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Risks and Risk Governance in Unconventional Shale Gas Development

Mitchell J. Small[1], Paul C. Stern[2], Elizabeth Bomberg[3], Susan M. Christopherson[4], Bernard R. Goldstein[5], Andrei L. Israel[6], Robert B. Jackson[7], Alan Krupnick[8], Meagan Mauter[9], Jennifer Nash[10], Warner North[11], Sheila M. Olmstead[12], Aseem Prakash[13], Barry Rabe[14], Nathan Richardson[15], Susan Tierney[16], Thomas Webler[17], Gabrielle Wong-Parodi[18], Barbara Zielinska[19]

[1]H. John Heinz III Professor of Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA

[2]Nation Research Council, Board on Environmental Change and Society, Washington, DC 20001, USA

[3]School of Social and Political Science, University of Edinburgh, Edinburgh UK EH8 9LD

[4]City & Regional Planning, Cornell University, Ithaca, NY 14853, USA

[5]University Professor Emeritus, University of Pittsburgh, Pittsburgh, PA 15260, USA

[6]Department of Geography, The Pennsylvania State University, University Park, PA 16802, USA

[7]School of Earth Sciences, Woods Institute for the Environment, and Precourt Institute for Energy, Stanford University, Stanford, CA 94305, USA

[8]Senior Fellow and Director, Center for Energy Economics and Policy, Resources for the Future, Washington, DC 20036, USA

[9]Chemical Engineering and Engineering & Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213, USA

[10]Mossavar-Rahmani Center for Business and Government, John F. Kennedy School of Government, Harvard University, Cambridge, MA 02138, USA

[11]President and Principal Scientist, NorthWorks, Inc., San Francisco, CA 94133, USA

[12]Lyndon B. Johnson School of Public Affairs, University of Texas, Austin, TX 78713, USA

[13]Department of Political Science, University of Washington, Seattle, WA 98195, USA

[14]Director, Center for Local, State, and Urban Policy, Gerald R. Ford School of Public Policy, University of Michigan, Ann Arbor, MI 48109, USA

[15]Resident Scholar, Resources for the Future, Washington, DC 20036, USA

[16]Senior Advisor, the Analysis Group, Boston, MA 02199, USA

[17]Research Fellow, Social and Environmental Research Institute, Amherst, MA 01002, USA

[18]Research Scientist, Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA 15213, USA

[19]Division of Atmospheric Sciences, Desert Research Institute, Reno, NV 89512, USA

Abstract

A broad assessment is provided of the current state of knowledge regarding the risks associated with shale gas development and their governance. For the principal domains of risk, we identify observed and potential hazards and promising mitigation options to address them, characterizing current knowledge and research needs. Important unresolved research questions are identified for each area of risk, however, certain domains exhibit especially acute deficits of knowledge and attention, including integrated studies of public health, ecosystems, air quality, socioeconomic impacts on communities, and climate change. For these, current research and analysis are insufficient to either confirm or preclude important impacts. The rapidly evolving landscape of shale gas governance in the U.S. is also assessed, noting challenges and opportunities associated with the current decentralized (state-focused) system of regulation. We briefly review emerging approaches to shale gas governance in other nations, and consider new governance initiatives and options in the U.S. involving voluntary industry certification, comprehensive development plans, financial instruments, and possible future federal roles. In order to address the multiple disciplines and complexities of the evolving shale gas system and reduce the many key uncertainties needed for improved management, a coordinated multiagency federal research effort will likely be needed.

1. Introduction

The recent US shale gas boom, in the view of proponents, has introduced a new era of cheap, clean domestic energy and widespread economic benefits. As unconventional extraction technology has evolved and its use has spread, however, opposing claims have been made on many of the purported benefits. There have been strong calls to assess the associated risks to human health and safety, the socioeconomic wellbeing of impacted communities, the impacts on ecosystem health, and the near and long-term effects on global climate. Associated questions concern society's capacity to control the risks through further technology development, appropriate environmental monitoring, stronger regulation, or collaborative partnerships with industry.

Controversy surrounding shale gas development should not be surprising. Although its technologies have been practiced since the 1950s, ongoing advances since that time in methods for exploration, drilling (e.g., horizontal drilling), chemical synthesis and application (for hydraulic fracturing fluids), and expanding scales and locations of operation have raised broader concerns. History indicates that when energy technologies emerge rapidly, their risks and governance are often contentious. [1-8] This history indicates the value of efforts at an early stage of technological development to understand the potential concerns of affected populations, to examine the risk concerns carefully, and to assess the capacity of the industry and the regulatory system to assess and manage the risks. This special issue attempts to advance decision-relevant understanding of unconventional shale gas development by presenting analyses of what is known in several key domains of risk and its governance, identifying those areas where further scientific knowledge and data are critically needed to support decision making.

This paper summarizes key elements of the technical-social system of shale gas development, its risks, and their governance. For each principal domain of risk, we identify hazards and promising mitigation options and we characterize the state of knowledge, including research needs. We also review the rapidly evolving landscape of shale gas governance in the US, noting the current condition of governance institutions and discussing new initiatives and options for voluntary certification, comprehensive development plans, financial instruments, and possible future federal roles. We conclude with an overall assessment of the state of knowledge and risk management.

2. The Technical-Social System of Shale Gas Development

Figure 1 depicts shale gas development as an integrated system encompassing: A) The oil and gas (O & G) and related industries; B) Technological methods and advancements that they employ; C) Risks and benefits to the environment, human health, and socioeconomic wellbeing; and D) Governance institutions that inform, coordinate, regulate or incentivize industry actions to mitigate risks. A number of the particular elements shown in Figure 1 reflect US conditions, especially as they relate to the nation-specific structure of the O & G industry and governance institutions. However, the more general functions of the interactions between the O & G industry and governance sectors are similar across nations – each building upon their knowledge of technology and risks to formulate and implement appropriate strategies to exploit their capabilities or address their implications. In a similar manner, information and influence are shared and exchanged across the operational and risk domains as shale gas development is planned and implemented.

The shale gas industry is made up of a wide range of firms of differing size, technical capability, and experience, with varying objectives of profitability, health, safety, community involvement, and environmental stewardship, and each operating in a dynamic environment of costs, market prices and regulation. [9] In many cases a principal firm (or operator) oversees the overall operations on a well pad, with many (sub)contractors performing specific tasks. Operators include large independent drillers, such as Chesapeake Energy, Williams Energy, and Range Resources, as well as a number of the largest international energy firms, including ExxonMobil, BP, Shell, ConocoPhillips and Chevron. Concurrently, hundreds of small companies populate the industry, some operating only a single well. Furthermore, while operators maintain overall responsibility at a site, much of the work is done by specialized contractors, including well drilling, hydraulic fracturing, and water, chemical and waste handling. While these activities can involve many of the most significant risks at a site and beyond, they often occur without direct responsibility to, or contact with, regulators and inspectors.

The technologies developed and applied for shale gas development are diverse. They include the provisioning of equipment, labor, water, chemicals, and many other materials along the supply chain. They also encompass industrial practices for drilling, well placement and completion; hydraulic fracturing; and the recovery, distribution, and use of natural gas. Industrial management, including waste disposal and the monitoring of safety, economic and environmental aspects of operations, is also important. Adoption and deployment of these technologies by the O & G industry is influenced in varying degrees by rules, guidance, and/or incentives put in place by public or private governance institutions. Different levels of operational, environmental, human health, and socioeconomic risk and risk mitigation result.

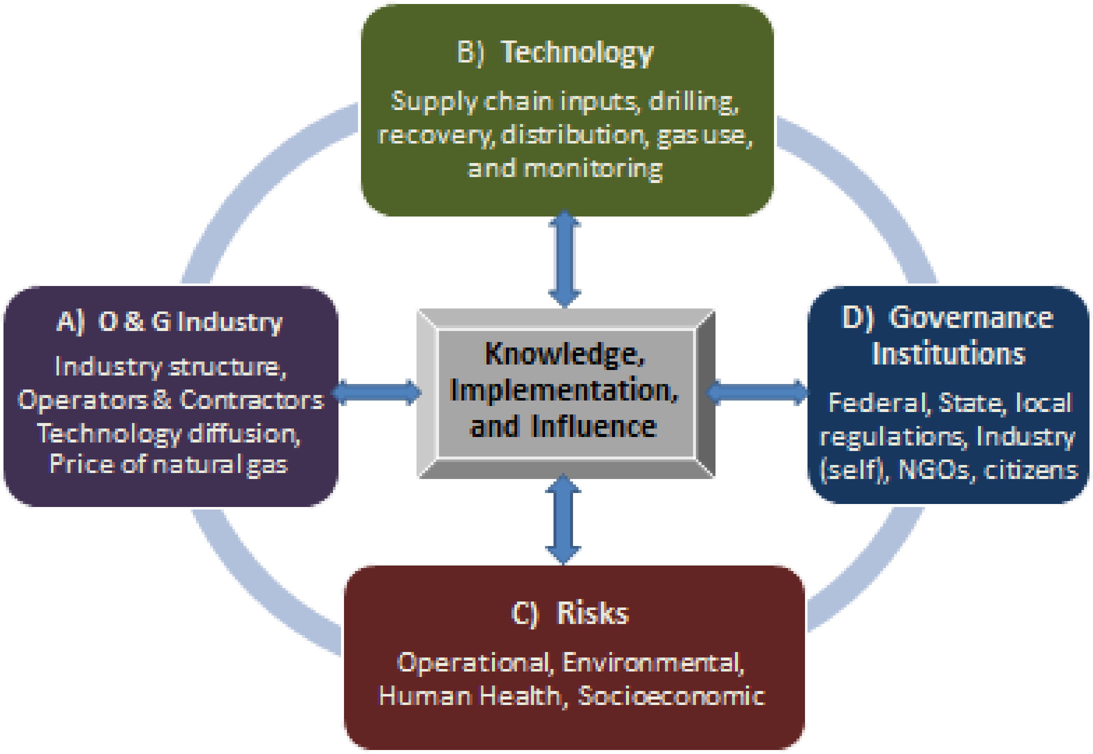

Figure 1. Elements of the Technical-Social Shale Gas Development System

3. Domains of Risk

This section considers the state of knowledge across the principal risk domains of concern, identifying important hazards, mitigation options, and research needs for each.

Operational Risks. Leaks, releases, and seismic events are key operational hazards whose mechanisms are relatively well understood. The risks of leaks and releases to the air, water, and soil environments can be mitigated considerably by implementation of operational safeguards and procedures, such as installation of impermeable liners and containment walls, real-time data collection, wastewater recycling, the addition of tracers to injection fluids, and the use of advanced technology to collect, manage, and interpret sensor data, including supervisory control and data acquisition (SCADA) systems similar to those now applied in a number of infrastructure, industrial, and O & G applications. [10-12] Many of these best practices are addressed in industry performance standards, such as those of the American Petroleum Institute.[13] Induced seismicity occurs when hydraulic fracturing fluid withdrawal or injection result in excessive pore pressures, brittle rock failure, and subsequent macro-seismicity. To date, induced seismicity events felt at the surface have been limited primarily to sites implementing deep well injection of wastewaters.[14] To prevent induced seismicity a protocol of subsurface characterization and seismic monitoring is recommended to avoid sites and operations (e.g., injection rates) with elevated seismic risk. [15-17]

Worker safety concerns are periodically heightened by major incidents, such as the recent well pad explosion at a Chevron site that resulted in the death of one contractor, a major injury, and a fire that burned for days near Dunkard, Pennsylvania. [18] Since 2010 three other significant gas well explosions and fires have occurred at wells operating in the Marcellus Shale play, injuring 11 workers, two of whom subsequently died. [19] Furthermore, elevated accident rates among vehicles and drivers servicing shale gas operations have been reported. [20] To minimize accidents, safety must be paramount in the corporate culture and procedures of operators and contractors, [4, 21, 22] and must include a combination of practices involving codification, communication, incentives, training, and the knowledge that employees are able and responsible to act on company commitments. [23] Especially in industries with companies of widely ranging size, experience, mobility, and profitability, well formulated corporate and industry programs are needed to ensure high levels of safety performance. [24-26] Nonetheless, the natural gas industry and its suppliers have been observed to exhibit a good record of safety relative to the coal and oil industries [27], and a number of industry leaders have put forth specific core principles for safe and responsible operations. [28-30]

<u>Risks to Water Resources</u>. The state of knowledge about surface water impacts and stress from shale gas development is relatively good, though less so for subsurface soil and groundwater contamination. The risks include contamination of shallow aquifers by “stray gases”, which can potentially evolve into salinization of shallow groundwater; contamination of surface water and shallow groundwater from land disturbance from infrastructure development, spills, leaks, and disposal of inadequately treated hydraulic fracturing fluids or hyper-saline wastewater, which often contains metals and low-level radioactivity; and accumulation of toxic and radioactive elements in soil or stream sediments. Land disturbance and inadequate waste treatment from Marcellus Shale development have affected surface water quality, but there is no systematic evidence of impacts from accidental releases. [31-33] Extraction of freshwater resources could also induce water shortages or conflicts with other water users. [34-37] Options to mitigate water stress are available, including the recycling of flowback waters – already very common among operators in the Marcellus Shale [38] – and the use of brackish and other impaired waters for hydraulic fracturing. [35]

The risks of over-extraction can best be countered by keeping public records of where withdrawals occur and limiting withdrawals locally, particularly from smaller streams, lakes, and rivers. Reducing the risk of ground- and surface-water contamination from chemicals and from stray gas migration is best addressed by providing good baseline data before drilling, maintaining a strong emphasis on well integrity, and minimizing leaks and spills from surface operations, including the chemicals used in drilling and hydraulic fracturing and the wastewater generated. [34, 37, 39, 40] Vengosh et al. (2014) [37] highlight the need to develop novel geochemical and isotopic tracers to delineate the sources and mechanisms of possible contamination.

Risks to air quality. The air pollutants associated with shale gas development include greenhouse gases (primarily methane), ozone precursors (volatile organic compounds and nitrogen oxides), air toxics, and particulate matter from flaring, compressors, and engines. [34, 41] Regulators primarily use generic emission inventories for air quality and health assessments that are often based on few measurements and are sometimes out of date. A full chemical classification of emissions, including air toxics, during all natural gas life-cycle stages is needed to properly perform source apportionment modeling and to understand all potential air quality and health impacts. Research needs include measurements of emissions before and during drilling and hydraulic fracturing, production, processing, transmission, storage and distribution, and from retired and abandoned wells. Opportunities to reduce risks to air quality arise from the use of vapor recovery technology; more extensive green completions; and frequent inspections of well pads, pipes, and connections.

Climate change impacts. Shale gas has been promoted as a “bridge” to a renewable energy future because gas can substitute for coal, particularly in power generation. Early reviews of releases from shale gas operations of methane, a highly potent though relatively short-lived greenhouse gas [42] questioned this claim, and climate risks from fugitive methane have subsequently received detailed analytic attention. [43-47] Studies based on monitoring of individual facilities tend to yield lower leakage rates but may have trouble capturing the heavy-tail effects of outlier (very leaky) sources unless sample sizes are large. Atmospheric mass balance studies are able to consider aggregate emissions over a region and tend to yield higher leakage estimates, but are prone to uncertainties due to contributions from natural or other unknown sources. Further studies to harmonize and resolve the direct and atmospheric mass balance estimates deserve priority.

The net effect of shale gas on climate change comes both from direct emissions of greenhouse gases and from the economic effects of increased gas supplies on energy consumption and fuel substitution. [48] Newell and Raimi (2014) [47] offer one of the first comprehensive analyses of the effects of these economic forces. They find that substituting cleaner-burning natural gas for coal in power production reduces CO_2 emissions substantially, but this benefit is offset by increased energy use overall and reduced renewable adoptions driven by lower energy prices. The findings suggest that shale gas may actually postpone the transition to a renewable energy future and increase the risks of not meeting multi-decadal emissions targets. Given the long residence time of CO_2 in the atmosphere, this postponement could lock in higher ambient concentrations and warming potential over many decades. Additional comprehensive analyses of the effects of shale gas development on global demand for fossil fuels and fuel switching are clearly needed.

Ecological Impacts. Principal ecological hazards include stress to streams and rivers from water withdrawals; toxic emissions to air, water, and soil from site operations; and habitat fragmentation due to the siting of well pads and their service roads, pipelines, and other support infrastructure systems. The effects of fragmentation on habitats and species are likely similar to those of conventional oil and gas operations for the same area and pattern of disturbance. However, research has only recently begun to study effects in areas where unconventional shale gas development is occurring. [49-52] Measurement and development of data on species location, abundance, and habitat use along with studies of species' responses to exposure to ecological hazards are necessary inputs to models that can provide predictive estimates of impacts.

Public health effects. Researchers are beginning to identify the various pathways that can link chemical and other stressors from shale gas development to health effects, as well as the major uncertainties about these effects. [53, 54] Workers are vulnerable to workplace hazards such as skin contamination, traffic accidents, explosions, and toxic vapors. [55] Residents are vulnerable to dermal, air, food, and water pathways, light and noise stress, and psychological distress associated with a wide scope of possible outcomes and with lack of trust in information sources. [56-59] The set of possible health outcomes is not fully identified, let alone the magnitude and distribution of the resulting risks. Determining the risks can be difficult due to uncertain exposures and possible long latency periods, however, the long-term studies needed to address these issues are not yet in place. Future health monitoring efforts will require increased collaboration between industry and researchers to identify endpoints and chemicals of concern, establish detection limits for existing instrumentation, and define risk pathways. Developing a strong link between exposure processes and emissions is critical to designing effective mitigation strategies and motivating their implementation.

Socioeconomic and Community Effects. It has long been recognized that rural communities can experience both positive and negative impacts from energy booms [60] and oil and gas extraction. [61] However, researchers are just beginning to analyze the effects of shale gas development on communities. [62-64] Expected hazards include boom-bust economic cycles; increased housing costs; impacts on preexisting local industries; demands on community infrastructure, police and social services; uneven distribution of private benefits, costs, and externalities; and community conflict and mistrust. In other contexts, some communities have mitigated risks thorough community planning with effective public participation and oversight, or through the allocation of impact fees or other streams of revenue allocated to community improvements. [65, 66] Research is critically needed in communities affected by shale gas development to understand the capture of wealth by local communities and its use to mitigate or compensate for harms; long-term economic/population/employment effects, including possible economic de-diversification and losses incurred by local industries and tourism from disruption or stigma; and the ability of communities to plan for a highly uncertain future level of drilling activity. [67] Effective risk mitigation will require longitudinal studies in affected and comparison communities and assistance to communities to participate in the associated data collection, mitigation and planning.

Synergistic and Cumulative Risks. Synergies across risk domains could amplify risks and produce cumulative effects, but knowledge of these amplification pathways is still quite limited. As an example of synergism, excessive or uncoordinated water withdrawals can harm aquatic habitat near the point of withdrawal, exacerbate toxic effects from leaks or spills downstream, affect the quality of local recreation, and reduce income from tourism services in nearby communities. Multiple effects can also trigger a cumulative response, for instance, a sudden demand for increased governmental oversight to manage risks. Coordination among regulatory bodies is key to identifying mitigation options that reduce multiple stressors, thereby reducing cumulative and synergistic risks. [68] Interdisciplinary case studies are needed to improve the knowledge base.

4. Challenges of Risk Governance

In addition to concerns about the risks associated with shale gas development, interested and affected parties have questioned the adequacy of the system of risk governance, including: the safety and environmental protection cultures and records of companies and of the industry overall; the adequacy of information for supporting risk governance choices; the ability, capacity, and independence of the governmental regulatory system at all levels from local to federal; the functioning of the legal system; and the adequacy of stakeholder participation to influence decisions that affect them. Public trust in risk governance is an important underlying issue in many places. [69-73] To assess current knowledge and research needs for shale gas governance we review the characteristics of the present decentralized (state-focused) regulatory approach in the U.S., briefly consider emerging shale gas governance in other nations, and consider new and proposed approaches for voluntary governance, comprehensive planning, financial incentives, and an expanded Federal role.

<u>The effectiveness of decentralized government regulation.</u> The evolving approach to shale gas governance in the United States reveals a distinctively decentralized regulatory approach, one that poses both opportunities and challenges in developing effective policy while lodging most authority at present in the hands of state and local authorities. In such a system states and localities may devise innovative environmental governance approaches carefully tailored to their unique circumstances or shirk environmental responsibilities to maximize rapid energy development in a competitive political economy.

Oil and gas development in the U.S. has typically been managed by states. The states with long track records of oil and gas production have developed significant regulatory capacities. However, in the recent shale gas boom, many other states have had to rapidly ramp up regulatory abilities. Wiseman [69, 73-76] has documented this transition in many states and has found that states often lack the staff and expertise to meet all of these tasks, especially as development expands. States also vary greatly in the extent of local land use and rulemaking autonomy they grant to city and county officials. As a result, fundamentally different local roles have emerged in various states. [39]

Since a number of the resource requirements and risk impacts of shale gas development do not respect state boundaries, especially for well pads located near state borders, some degree of coordination is necessary. Regional compacts and commissions can serve to facilitate these interactions. The Susquehanna River Basin Commission (SRBC) is a federal interstate compact responsible for managing the basin’s water resources. The SRBC regulates water withdrawals and consumptive use in the basin and must approve water withdrawals before shale gas drilling can be undertaken. [77] Established interstate compacts and commissions might play a similar role for water, air, or ecological resources; new ones could be established to focus specifically on shale gas.

In addition to standards and rules for shale gas operations and permitting, liability laws and requirements for financial assurance of well closure and environmental restoration can play an important role in mitigating risk. A common state financial mechanism is a severance tax on the production of oil or gas, which could compensate communities for damage or the public trust for depletion of a non-renewable resource. At present, however, the vast majority of revenue from such taxes is transferred into general state revenues or earmarked for other services such as public education. [78] Revenue from such taxes could be dedicated to environmental or community restoration and legacy funds for future issues, and some states have begun to explore such possibilities.   Other common approaches include an upfront impact fee, with funds distributed to affected communities, and cash bonds that are held and returned to the last owner of the well only after proper closure and restoration are completed. Mitchell and Casman (2011) [79] evaluate the relative advantages of these approaches and identify necessary tax, fee, or bond levels that could incentivize responsible parties for environmentally responsible practices rather than well abandonment and foreclosure.

Governance outside the USA. While the initial surge of shale gas development and concerns regarding its risks and risk governance have been focused in the United States, significant gas development potential exists in many other countries [16], including China, Argentina, Algeria, Mexico, Australia, Poland and South Africa. [80] Many of these countries are now watching to learn from the US experience and several have introduced risk governance policies or practices. [35]

In the United Kingdom centralized governance mechanisms predominate, as all mineral rights are owned by the Crown, and extensive national regulations have been developed for proposed shale gas extraction. Procedures are now in place for obtaining permits and permission for unconventional oil and gas operations, with the process coordinated by the Department of Energy & Climate Change (DECC), and consultations and permits required from the Environmental Agency (EA), the Health and Safety Executive (HSE), the British Geological Survey (BGS) and the local minerals planning authority (MPA). [69] Best practice requirements include a prior seismic survey at the site and regular seismic monitoring before, during and after development; submission of an environmental risk assessment (ERA); and full public disclosure of fracturing fluids and all monitoring data on the operator’s website. Moreover, under a new “community engagement charter” operators are expected to engage with affected communities before applying for planning permission and commit to a package of financial community benefits. [81]

The EU has also begun to establish general principles and recommendations for shale gas development designed to address significant differences in potential and perspectives across European countries. [82-85] Its actions thus far suggest EU shale policies are likely to include elements of the precautionary principle, an insistence on transparency, the need for consultation and stakeholder buy-in, and an emphasis on sustainability. [86]

Australia has recently developed extensive regulatory guidelines for coal seam methane extraction that are likely to guide regulatory oversight of the shale gas industry. Land use and water rights are the dominant concerns in Australia, but adoption of a nationally harmonized regulatory framework that supports robust, consistent and transparent regulation across all Australian jurisdictions is expected to accelerate development. [35] The governance structure for oil and gas resources in Argentina, on the other hand is concentrated at the provincial level.

Provinces have the authority to grant exploration permits, oversee operations, and modify the stringency of federal environmental regulations set by the Secretary of Energy. Argentina's most promising basin, the Neuquen, overlays four provinces, and there is some risk of inter-provincial conflict over water resources and environmental releases related to the unconventional extraction industry. [35] China also has significant shale gas potential, [87] though substantial challenges are imposed by formation depth and complex subsurface geology [35] and appropriate policies for shale gas governance are still under consideration. [88]

New governance opportunities. A number of innovative approaches for shale gas governance have been identified in the past few years. Not surprisingly, these proposals have generated both support and opposition. We briefly discuss four here to illustrate a potential range of initiatives and possible future governance scenarios that could emerge.

Voluntary best-practice standards and certification codes Prior research suggests that in some industries, firms tend to share a common reputation. Consequently, industrial accidents or pollution problems in one firm can harm the reputation of all firms. [89] In response, industry level codes or programs have been proposed which outline best practices which can prevent industrial accidents, and allow firms to collectively signal their commitment to high standards of safety and environmental performance. The oil and gas industry has developed more than 80 voluntary best-practice standards to address risks from their operations. [90] In the Marcellus, shale gas operators, national and regional environmental organizations, and foundations have formed the Center for Sustainable Shale Development (CSSD). [91] An initial set of CSSD performance standards addresses steps needed to manage air emissions, water recycling, wastewater disposal, groundwater monitoring, and reduced toxicity of fracturing fluid. CSSD recently established a protocol for compliance monitoring and certification, to be conducted by an independent third party. The emergence of voluntary programs is notable, showing that firms appreciate the long term payoffs of dispelling any notion of a regulatory void. Voluntary standards could set a floor for state regulations that would also apply to non-volunteering companies. They also might provide a basis for subsequent federal-level solutions designed to reduce industry costs of dealing with a patchwork of state and local regulations and requirements.

Comprehensive development plans Consideration of comprehensive development plans for shale gas drilling has occurred in the states of Colorado and Maryland. Under a voluntary program in Colorado gas operators may propose a Comprehensive Drilling Plan (CDP) for multiple drilling locations. This program is voluntary, though encouraged by the Colorado Oil and Gas Conservation Commission. Maryland has proposed a requirement for a mandatory Comprehensive Gas Development Plan (CGDP) prior to receiving a permit to drill. The plan must specify the locations of all planned well pads, roads, pipelines and supporting facilities over a period of five years and comply with all land use, location, and setback regulations. The objective of the Maryland CGDP proposal is to enable coordinated planning to maximize the use of existing infrastructure, reduce land surface disturbance, avoid sensitive areas, minimize cumulative effects, provide operators with decision support tools to help in their compliance planning and report preparation, and ensure a high degree of community and stakeholder participation in the site selection and implementation process. [92, 93] Far-reaching legislation enacted in Illinois in 2013 included some elements of this approach as well.

Innovative use of economic resources Some of the adverse risks of shale gas development could be addressed through use of severance tax revenues or funds from related impact fees to improve state and local governance capacity (for example, by employing and training regulatory staff and improving monitoring systems); to support public health facilities and other infrastructure in affected communities; and to help fund a transition to renewable energy systems. The liability system might also be used to create stronger incentives for an improved environmental and safety culture in the industry, for example, by requiring insurance for operators, establishing disclosure or strict liability rules, setting higher bonding requirements, or shifting burdens of proof.

Possible scenarios for expanded national risk governance While effective voluntary standards and better-informed state and local planning and regulation could help to bring better consistency and performance to shale gas governance, experience with previous environmental regulations suggests the likely emergence of an expanded federal government role to address interstate risk implications of shale development, provide for the formalization of best practices, and to incentivize more consistent and effective risk management across the industry through support for data collection and sharing. Under this scenario, as in other domains of environmental regulation, significant authority for implementation and enforcement is likely to be delegated to states with high levels of resources and expertise. Konschnik and Boling (2014) [94] argue that a combined federal-state approach for a “smart regulation framework” would include: an improved characterization of risks by regulators (i.e., the US EPA) and the industry; the determination of optimal mitigation strategies; the identification of appropriate regulations to ensure that optimal approaches are pursued; and enforcement to provide a level playing field for operators. The EPA would also assist in coordinating data collection, analysis and information dissemination.

5. Implications

The shale gas revolution has played out in the U.S. in a rapid and distributed manner, making it difficult to track and assess the nature, quantity, and distribution of economic benefits and losses, environmental impacts, potential human health and ecosystem risks, and social impacts to individuals and communities. There is strong evidence that shale gas has already yielded benefits to US energy costs and independence, but many of the risks remain under-analyzed and projections of long-term net effects on public health, community well-being, energy markets, greenhouse gas emissions, employment, and climate change trajectories remain contentious. Likewise, models for shale gas governance continue to evolve in a rapid and distributed manner, with many states still struggling to balance coordinated planning, best practices, voluntary industry certification, financial requirements, regulatory limits, and local government and stakeholder involvement, and the necessary capacity to implement their chosen regimes. What have we learned thus far about the evolving shale gas technical-social system, and where are the greatest needs for further research and data collection?

To date greater analytic attention has been given to some of the risks related to shale gas development than to others. The risk domains that have received the greatest focus include those associated with operational risks and accidents, induced seismicity, effects on water systems, and methane leakage from wells. By contrast, very little analysis has been done in a number of domains where significant risks may be present, such as public health, ecosystems, air quality, human communities, and climate change, but where current data collection, research and analysis are insufficient to either confirm or preclude important impacts. All the risk domains have important unresolved research questions, but some have been seriously neglected.

Our review suggests that governance of shale gas development in the U.S. has been essentially delegated to the states, many of which lack adequate resources to exercise the responsibility effectively. In many places, development is proceeding faster than the capacity to track and manage the associated risks. The effectiveness of current risk governance systems remains largely unknown. The current state-focused approach is resulting in variation between states in practices for siting, operations, monitoring, compliance, and compensation, and in the extent to which autonomy is granted to local governments to impose additional or different requirements for land use and operations. States also differ in their financial instruments and requirements for bonding and revenue generation and in their use of the revenues. Non-regulatory risk management approaches involving performance-based severance taxes and impact fees and markets based on air and water quality measurements may be promising but are only beginning to be considered.

A number of new proposals for shale gas governance have been put forth, including voluntary self-governance approaches and state proposals for comprehensive development plans. While efforts such as the voluntary CSSD certification and comprehensive gas development plans such as Maryland's have the potential to significantly improve industry and state shale gas governance, particularly when they incorporate best practices for public participation, some anticipate that an expanded federal role will eventually evolve to clearly incentivize strong and consistent risk management, to consider issues of sustainability, and to improve knowledge generation and transfer to stakeholders (industrial, regulatory, and public) who need it. Within current legislation, the federal government could help by collecting and disseminating available scientific knowledge in an easily accessible form; training state environmental employees; harmonizing measurement approaches; and providing databases to enable more uniform data collection across states. In order to address the complexities of the evolving shale gas system and reduce the many key uncertainties needed for improved management, a coordinated federal research effort involving agencies such the US National Science Foundation, the US EPA, Department of Energy, and Department of Interior should be considered.

Finally, shale gas development creates risk and risk governance issues globally. Along with the potential of low-cost energy to improve well-being for large populations comes the potential for locked-in dependence on fossil fuels and continued momentum toward climate change. However, given the realities of global markets, stricter regulations in one nation could shift production to others where controls are less stringent. These possibilities should command attention from multinational governance institutions concerned with climate change and other global environmental issues.

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