HEI energy

A Health Effects Institute Affiliate

HEI Energy

Health Effects Institute Energy
75 Federal St., Suite 1400
Boston, MA 02110, USA
+1-617-488-2300
www.HEIenergy.org

RESEARCH BRIEF 4

WINTER 2022

Abandoned and Orphaned Oil and Natural Gas Wells: Potential Human Exposures

This Research Brief is part of a series of periodic updates on the literature about potential human exposures and health effects associated with unconventional oil and natural gas development (UOGD) in the United States

Trusted Science, Clean Environment, Better Health

Abandoned and Orphaned Oil and Natural Gas Wells: Potential Human Exposures

Health Effects Institute Energy

Boston, MA

TRUSTED SCIENCE, CLEAN ENVIRONMENT, BETTER HEALTH

Publishing history: This document was posted at *www.heienergy.org* in February 2022.

Citation for document:
Elliott EG. 2022. Abandoned and Orphaned Oil and Natural Gas Wells: Potential Human Exposures. Research Brief 4. Boston, MA: Health Effects Institute Energy.

CONTENTS

About HEI Energy

The Health Effects Institute (HEI) Energy is a national research program formed to identify and conduct high-priority research on potential population exposures and health effects from development of oil and natural gas from shale and other unconventional resources across the United States. HEI Energy supports community exposure research in multiple regions. To enable exposure research planning, HEI Energy conducts periodic reviews of the relevant scientific literature. Once initial research is completed, HEI Energy will assess the results to identify additional exposure research priorities and, where feasible and appropriate, health research needs for funding in subsequent years.

The scientific review and research provided by HEI Energy will contribute high-quality and credible science that supports decisions about how best to protect public health. To achieve this goal, HEI Energy has put into place a governance structure that mirrors the one successfully employed for nearly forty years by its parent organization, the Health Effects Institute, with several critical features:

- HEI Energy receives joint funding from the U.S. Environmental Protection Agency under a contract that funds HEI Energy exclusively and from the oil and natural gas industry;
- HEI Energy's independent Board of Directors consists of leaders in science and policy who are committed to fostering the public–private partnership that is central to the organization;
- HEI Energy's research program is governed independently by individuals having no direct ties to, or interests in, sponsor organizations;
- HEI Energy's Research Committee consists of members who are internationally recognized experts in one or more subject areas relevant to the Committee's work, have demonstrated their ability to conduct and review scientific research impartially, and have been vetted to avoid conflicts of interest;
- All research undergoes rigorous peer review by HEI Energy's Review Committee;
- HEI Energy staff and committees engage in open and extensive stakeholder engagement before, during,and after research, and communicate all results in the context of other relevant research;
- HEI Energy makes publicly available all literature reviews and original research that it funds and provides summaries written for a general audience; and
- Without advocating policy positions, HEI Energy provides impartial science, targeted to make better-informed decisions.

HEI Energy is a separately funded affiliate of the Health Effects Institute (*www.healtheffects.org*).

AUTHORS

Elise G. Elliott, *Staff Scientist, HEI Energy*

ACKNOWLEDGMENTS

HEI ENERGY AND HEI PROJECT STAFF

Lee Ann Adelsheim, *Research Assistant, HEI Energy*

Kristin Eckles, *Senior Editorial Manager*

Daniel Greenbaum, *President, HEI*

Robert M. O'Keefe, *President, HEI Energy*

Allison Patton, *Senior Scientist, HEI and Quality Assurance Manager, HEI Energy*

Anna Rosofsky, *Staff Scientist, HEI Energy*

Donna J. Vorhees, *Vice President and CEO, HEI Energy*

HEI ENERGY RESEARCH COMMITTEE

George M. Hornberger, Chair, Director, Vanderbilt Institute for Energy & Environment, Vanderbilt University

Shari Dunn-Norman, Associate Professor, Missouri University of Science and Technology

Stefanie Ebelt, Associate Professor, Emory University

Howard Hu, Professor and Chair, Department of Preventive Medicine, Keck School of Medicine, University of Southern California

Judy S. LaKind, President, LaKind Associates, LLC, and Adjunct Associate Professor, University of Maryland School of Medicine

Christopher Paciorek, Adjunct Professor and Research Computing Consultant, University of California, Berkeley

Armistead (Ted) G. Russell, Howard T. Tellepsen Chair and Regents Professor of Civil and Environmental Engineering, Georgia Tech

Peter Thorne, Professor, Department of Occupational and Environmental Health, University of Iowa

PURPOSE OF THIS RESEARCH BRIEF

People living near unconventional oil and natural gas development (UOGD) can be exposed to chemical and non-chemical agents released to the environment from these operations. Both conventional and unconventional oil and natural gas wells may become inactive and, if not properly handled, may release chemicals to the environment, potentially resulting in human exposures. In the scientific literature, authors often refer to inactive wells as "abandoned" or, if the well has no known or solvent owner, "orphaned."

The U.S. Environmental Protection Agency (U.S. EPA) has estimated that 3.1 million wells are abandoned, of which 2.2 million require proper handling to limit releases to the environment (U.S. Environmental Protection Agency 2018). A collaboration between the Environmental Defense Fund and McGill University has estimated that 81,000 documented abandoned wells across the United States are unplugged, orphaned oil and natural gas wells (Environmental Defense Fund 2021). The purpose of this Research Brief is to summarize literature about the potential for releases to the environment and human exposures associated with abandoned and orphaned wells in the United States.

This document is part of a series of Research Briefs summarizing literature about potential exposures and health effects associated with UOGD.

OVERVIEW OF ABANDONED AND ORPHANED OIL AND NATURAL GAS WELLS

Both conventional and unconventional oil and natural gas wells may be currently operating ("active") or temporarily or permanently not operating ("inactive"). The most commonly used term to describe oil and natural gas wells that are inactive, that is, not producing or otherwise actively used for their intended purpose, is "abandoned wells." However, the term "abandoned well" may refer to plugged, unplugged, or both plugged and unplugged wells that are inactive, depending on the jurisdiction (Interstate Oil & Gas Compact Commission 2021; U.S. Environmental Protection Agency 2018). Other terms used to describe inactive wells include "idle," "temporarily abandoned," "shut-in," or "dormant." Inactive oil and natural gas wells that have no known or solvent owner are referred to as "orphaned" (Interstate Oil & Gas Compact Commission 2021).

Wells that are no longer economically viable may become permanently inactive and require proper handling, including plugging of the well. Well plugging typically requires filling the wellbore with cement or alternative materials to limit releases to the environment and prevent gas and fluid migration (Achang et al. 2020). Although few unconventional wells are inactive, thousands of conventional wells are no longer active and may or may not have been properly plugged according to current regulations. Improperly plugged wells may serve as a pathway for environmental releases to air, water, and the surface environment (Allison and Mandler 2018; Gass et al. 1977; Kell 2011; Wen et al. 2019; Wisen et al. 2019), including through "well-to-well" communication between existing and newly drilled wells (Interstate Oil & Gas Compact Commission 2021; Perra et al. 2021; Saint-Vincent et al. 2020). In turn, environmental releases could increase environmental exposures among those living near improperly plugged, inactive oil and natural gas wells.

Well maintenance, including plugging operations for inactive wells, is the responsibility of well operators (Interstate Oil & Gas Compact Commission 2021). However, governmental agencies carry the responsibility of plugging and properly decommissioning, or abandoning, orphaned wells (Interstate Oil

& Gas Compact Commission 2021). Orphaned wells are therefore not only of interest with regards to potential environmental releases, but also from a policy and economic perspective (Kang et al. 2021; Raimi et al. 2021). Under the Infrastructure Investment and Jobs Act, $4.7 billion is available for orphaned well plugging, remediation, and restoration activities (U.S. Department of the Interior 2021).

A challenge in better understanding the potential for environmental releases and any associated human exposures is the poor documentation and missing well records of oil and natural gas wells drilled prior to regulations introduced in the 1950s (Kang et al. 2016; Saint-Vincent et al. 2020a). Moreover, temporal and regional differences in the proper handling of inactive wells, along with the varying uses of terminology describing these different types of inactive oil and natural gas wells, further complicate synthesizing information on environmental releases from inactive oil and natural gas wells. Even if the locations of inactive wells are known, these wells differ in their potential for environmental releases and human exposures given changing operational practices over the long history of oil and natural gas extraction in the United States and the differing regulations for proper handling across the United States and over time. Thousands of wells were drilled prior to the introduction of new regulations in the 1950s and were therefore not properly plugged and abandoned based on current requirements (Achang et al. 2020; Interstate Oil & Gas Compact Commission 2021). Current plugging and abandonment practices primarily use cement to create stable, long-term seals at the entry points of wells; however, site-specific conditions may impact their durability (Achang et al. 2020).

Summary of the Review

Scope of the Review

We used the same search term and approach employed in the HEI Energy Research Committee's 2019 survey of the UOGD exposure literature (HEI-Energy Research Committee 2019) to identify publications for inclusion that assess potential human exposures associated with abandoned and orphaned oil and natural gas wells. The literature search included peer-reviewed and gray literature published between January 1, 2000 and December 1, 2021 that contributes to understanding how people might be exposed to chemical or non-chemical agents released directly from abandoned and orphaned oil and natural gas wells to the environment in the United States. All potentially informative studies of abandoned wells or orphaned wells were considered whether or not the authors set out to study human exposures.

Outside the United States, the potential for environmental exposures associated with abandoned wells is also an active area of research and regulation (Boothroyd et al. 2016; Taherdangkoo et al. 2018; Williams et al. 2019, 2021; Perra et al. 2021). For instance, in Germany concerns have been raised about potential groundwater contamination related to UOGD near abandoned wells (Taherdangkoo et al. 2018). However, given the extensive activity in North America, and geologic variations and policy differences between European and North American oil and gas development, this review focuses on and summarizes literature about abandoned and orphaned wells in the United States and Canada.

Overview of the Literature

The search returned a total of twenty publications that investigated abandoned oil and natural gas well locations; air emissions; potential releases to ground water; releases to soil, or combined release pathways; or a combination of these geospatial and environmental assessments. Four publications measured or estimated locations of abandoned oil and natural gas wells (Pekney et al. 2018; Saint-Vincent et al. 2020a, 2021; de Smet et al. 2021). Ten publications measured or reviewed air emissions (Kang et al. 2014, 2016; Lebel et al. 2020; Pekney et al. 2018; Riddick et al. 2019; Saint-Vincent et al. 2020b;

Townsend-Small et al. 2016; Townsend-Small and Hoschouer 2021; Williams et al. 2019, 2021). Six investigated potential releases to ground water (Brownlow et al. 2016, 2017, 2018; Kell 2011; McMahon et al. 2018; Nowamooz et al. 2018), three investigated releases to soil (McMahon et al. 2018; Townsend-Small and Hoschouer 2021; Williams et al. 2019), and one estimated combined leakage pathways (Kang et al. 2015). Additionally, the search returned several publications regarding policy (Interstate Oil & Gas Compact Commission 2021; U.S. Environmental Protection Agency 2018), economics (Raimi et al. 2021), and well handling technologies (Achang et al. 2020) that provided information and context on the terminology regarding abandoned and orphaned oil and natural gas wells. Although the literature search included search terms for both exposure and health publications, we did not identify any publications assessing associations between abandoned and orphaned oil and natural gas wells and adverse health outcomes.

The discussion of the abandoned and orphaned oil and natural gas well literature is organized in accordance with a conceptual model of exposure, which illustrates the exposure pathways assessed in the literature (Figure 1). This organization facilitates identification of links between potential UOGD sources of exposure and populations and gaps in our understanding of exposures. The abandoned and orphaned well literature includes only the first two elements of the conceptual model: identification of oil and natural gas well locations and characterization of environmental releases. No studies endeavored to quantify or otherwise assess human exposures.

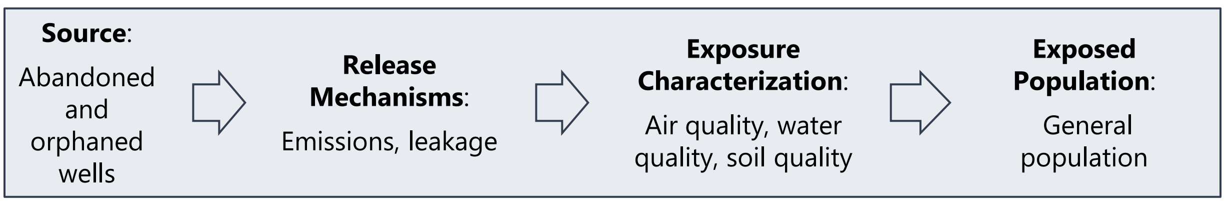

Figure 1. Conceptual model of potential exposure pathways associated with abandoned and orphaned oil and natural gas wells.

Abandoned and Orphaned Well Terminology Used in the Literature

This Research Brief summarizes all publications on inactive oil and natural gas wells that use the terms "abandoned" or "orphaned." As mentioned previously, the terminology related to these wells differs among jurisdictions (Interstate Oil & Gas Compact Commission 2021). The terminology also varies among the publications reviewed in this Brief. In the interest of clarity, we summarize how the authors of each publication define these terms in Table 1.

Table 1. Abandoned and orphaned oil and natural gas well terminology.

Author	Terminology	Well Status	Plugging Status	Other Descriptive
Abandoned Wells				
Achang et al. (2020)	Abandoned	Inactive	Unplugged	
Brownlow et al. (2016)	Leaky abandoned	Inactive	Not specified	Converted into water wells
Brownlow et al. (2017)	Abandoned and converted	Inactive	Not specified	Converted into water wells
Brownlow et al. (2018)	Leaky abandoned	Inactive	Not specified	Converted into water wells

Author	Terminology	Well Status	Plugging Status	Other Descriptive
Kang et al. (2014)	Abandoned	Inactive	Plugged and unplugged	
Kang et al. (2015)	Abandoned	Inactive	Plugged and unplugged	
Kang et al. (2016)	Abandoned	Inactive	Plugged and unplugged	
Kell (2011)	Abandoned	Not specified	Not specified	
Lebel et al. (2020)	Properly abandoned	Inactive	Plugged	
Lebel et al. (2020)	Improperly abandoned	Inactive	Unplugged	
McMahon et al. (2018)	Plugged and abandoned	Inactive	Plugged	
Nowamooz et al. (2018)	Improperly abandoned	Inactive	Unplugged	
Nowamooz et al. (2018)	Properly abandoned	Inactive	Plugged	
Pekney et al. (2018)	Abandoned	Inactive	Unplugged and improperly plugged	
Raimi et al. (2021)	Abandoned	Inactive	Unplugged	
Riddick et al. (2019)	Abandoned	Inactive	Plugged and unplugged	
Saint-Vincent et al. (2020a)	Abandoned	Inactive	Unplugged and improperly plugged	
Saint-Vincent et al. (2020b)	Abandoned	Inactive	Plugged and unplugged	
Saint-Vincent et al. (2021)	Abandoned	Inactive	Plugged and unplugged	
de Smet et al. (2021)	Abandoned	Not specified	Plugged, unplugged, and improperly plugged	
Townsend-Small et al. (2016)	Abandoned	Inactive	Plugged and unplugged	
Townsend-Small and Hoschouer (2021)	Abandoned	Inactive	Shut-in and canceled/abandoned	
U.S. Environmental Protection Agency (2018)	Abandoned	No recent production	Plugged and unplugged	
Williams et al. (2019)	Abandoned	Inactive	Unknown	
Williams et al. (2021)	Abandoned	No recent production	Plugged, unplugged, and compromised plug integrity	
Orphaned wells				
Kang et al. (2021)	Orphaned	Inactive	Unplugged	No responsible operator
Kell (2011)	Orphaned	Not specified	Not specified	No responsible owner
Raimi et al. (2021)	Orphaned	Inactive	Unplugged	
de Smet et al. (2021)	Orphaned	Not specified	Unplugged	No known owner
U.S. Environmental Protection Agency (2018)	Orphaned	No recent production	Not specified	No responsible operator
Williams et al. (2019)	Orphaned	Inactive	Unknown	
Other				
Interstate Oil & Gas Compact Commission (2021)	Idle	Inactive	Unplugged	
Lebel et al. (2020)	Idle	No recent production	Unplugged	
Saint-Vincent et al. (2020)	Legacy	Not specified	Not specified	
de Smet et al. (2021)	Legacy	Not specified	Not specified	
Williams et al. (2019)	Legacy	Inactive	Unknown	Inactive prior to 1952

Identification of Inactive Oil and Natural Gas Well Locations

Locating inactive oil and natural gas wells is a prerequisite to measuring environmental releases associated with these wells. Additionally, new UOGD operations may be sited in locations with inactive oil and natural gas wells, potentially creating new conduits for environmental releases from UOGD wells through "well-to-well" communication between existing and newly drilled wells (Interstate Oil & Gas Compact Commission 2021; Saint-Vincent et al. 2020).

Four publications measured or estimated locations of abandoned oil and natural gas wells (Pekney et al. 2018; Saint-Vincent et al. 2020a, 2021; de Smet et al. 2021).

Pekney et al. (2018) used a helicopter-based survey in southwestern Pennsylvania to detect magnetic anomalies that may indicate locations of improperly plugged or unplugged steel-cased wells.

In a follow-up study, Saint-Vincent et al. (2020a) used aeromagnetic surveys in Pennsylvania and Wyoming to compare magnetic anomalies to oil and natural gas well databases. At all study locations, the authors detected more magnetic points than recorded in databases. However, aeromagnetic survey methods are not able to differentiate between active and inactive oil and natural gas wells.

Saint-Vincent et al. (2021) employed a combination of two remote sensing techniques, airborne magnetometry and light detection and ranging (LiDAR), to detect abandoned wells in Pennsylvania in hilly locations with limited accessibility. Airborne magnetometry enables the detection of steel-cased oil and natural gas wells, while LiDAR enables the visualization of surface features that may be concealed using traditional satellite imaging methods. Compared to state database logs, the authors identified additional well locations of inactive wells, including wells without steel casings.

In contrast, de Smet et al. (2021) used drone-based aeromagnetic surveys to locate steel-cased wells in New York State. Compared to terrestrial and piloted surveys, the authors reported that drone-based aeromagnetic surveys were more operationally efficient, faster, lower cost, and safer compared to terrestrial or piloted aeromagnetic surveys. However, drone-based aeromagnetic surveys may have greater logistical challenges and are limited by battery power.

Potential for Environmental Releases

Abandoned oil and natural gas wells have the potential to release methane and other chemicals into the environment through multiple pathways, including inadequate plugging practices, compromised wellbore integrity, and subsurface fracture development (Williams et al. 2019). Methane released to the air serves as a potent greenhouse gas, while releases into the subsurface may lead to explosion hazards and the oxidation of subsurface methane can promote trace-element mobilization (McMahon et al. 2018).

Emissions Measurements and Models

Ten publications measured or reviewed air emissions related to inactive oil and natural gas wells (Kang et al. 2014, 2016; Lebel et al. 2020; Pekney et al. 2018; Riddick et al. 2019; Saint-Vincent et al. 2020b; Townsend-Small et al. 2016; Townsend-Small and Hoschouer 2021; Williams et al. 2019, 2021). All publications measured or reviewed methane emissions. One publication additionally measured benzene emissions (Lebel et al. 2020). No other type of chemical emissions was assessed in the identified literature.

Kang et al. (2014) made 42 methane measurements near 21 abandoned oil and natural gas wells in Pennsylvania and observed a chemical signature indicating a predominant origin from deeper geologic sources rather than microbial sources. The authors estimated that methane emissions from abandoned oil and natural gas wells contributed 4%–7% of the total anthropogenic methane emissions and could have cumulatively attributed 4%–13% of the total methane budget in Pennsylvania.

In a follow-up study, Kang et al. (2016) used repeated methane measurements over two years and chemical signatures from 163 abandoned oil and natural gas wells, noble gas isotope ratios, field investigations, and historical and state records to identify high methane-emitting abandoned oil and natural gas wells in Pennsylvania. The authors reported that unplugged gas wells and plugged but vented gas wells (a requirement for plugged wells in Pennsylvania in areas with coal) are the best predictors for high methane-emitting abandoned wells, independent of the presence of underground natural gas storage reservoirs or unconventional oil or gas production. They also reported that flow rates from the highest-emitting wells were consistent over a two-year sampling period. By coupling these field measurements with records about well attributes and numbers of wells, the authors estimated that methane emissions from abandoned oil and natural gas wells contributed 5%–8% of the annual anthropogenic methane emissions in Pennsylvania.

Lebel et al. (2020) measured methane emissions from oil and natural gas wells in California. They used a combination of ground-based methane measurement methods to measure emissions from 97 plugged and abandoned wells, one unplugged and abandoned well, 17 idle wells, and six active wells. The authors reported methane emissions at 35% of plugged and abandoned wells compared to 65%–67% of idle and active wells. Plugged and abandoned wells had the lowest methane emissions, while active wells had the highest methane emissions. The authors reported that most methane originated from deeper geologic sources rather than microbial sources. At one unplugged and abandoned well, the authors measured both methane and benzene emissions. Methane emissions were within the range observed at plugged and abandoned wells, and benzene emissions were below the detection limit.

Pekney et al. (2018) used aerial and multiple ground-based methane measurement methods in Hillman State Park, Pennsylvania, an area with historical records of currently inactive wells. Using a helicopter-based survey, the authors mapped methane concentrations and located wells by detecting magnetic anomalies. They successfully located wells via the aerial survey, but they did not detect elevated methane concentrations attributable to well emissions. The authors reported that methane emissions from abandoned wells were probably too small to detect by helicopter. Using a number of ground-based methods, the authors measured methane emissions from 31 wells. They used compared and evaluated the effectiveness of several measurement methods to inform future investigations. Nine of the 31 wells were buried (i.e. no surface expression), with methane flux measurements at the ground surface directly above them not significantly different from background methane soil flux. The authors reported a range of methane emission rates from the other 22 wells and recommended further study of factors that contribute to variability in the emissions, such as well characteristics, nearby horizontal drilling and hydraulic fracturing of new wells, and atmospheric conditions.

Riddick et al. (2019) measured methane emissions from 112 properly (plugged) abandoned, 147 improperly (unplugged) abandoned, and 79 active conventional oil and natural gas wells in West Virginia. The authors reported higher methane emissions for unplugged abandoned wells compared to plugged abandoned wells and higher methane emissions for more recently abandoned wells compared with wells that had been abandoned for a longer period of time. Methane emissions from active conventional wells were higher than those from plugged and unplugged abandoned wells. The authors further noted that their data for active wells exceeded U.S. EPA's emission factor for methane, citing the difference as evidence of important state-level variability that might not be reflected in a single national value.

Saint-Vincent et al. (2020b) measured methane emissions at 179 abandoned oil and natural gas wells in the Cherokee Platform of Oklahoma. The majority of wells did not leak methane; of those that leaked, the authors reported higher emissions from more shallow wells and unplugged wells. They did not detect correlations between methane emissions and distance from earthquake epicenters or active unconventional wells. They reported that only a small proportion of the wells contributed to the total observed emissions. Given the skewed distribution of methane emissions from the abandoned wells, the authors noted the importance of taking geographic location and plugging status into account when defining methane emission factors.

Townsend-Small et al. (2016) measured methane emissions from 19 unplugged and 119 plugged abandoned oil and natural gas wells across the Powder River Basin in Wyoming, the Denver-Julesburg Basin in Colorado, the Uintah Basin in Utah, and the Appalachian Basin in Ohio. The authors reported that one plugged well and eight unplugged wells were sources of atmospheric methane, with emissions from plugged abandoned wells significantly lower than emissions from unplugged abandoned wells. Their measured emission rates were highly skewed given the high proportion of wells that were not emitting methane. The authors estimated that abandoned wells contribute less than 1% to regional methane emissions in the study areas.

Townsend-Small and Hoschouer (2021) visited 41 inactive wells in Pecos County, Texas, in the Permian Basin and quantified methane emissions from 37 of them. Of the 41 wells, 5 inactive wells were leaking produced water onto the ground surface, which prevented the authors from measuring methane emissions at all but one of the wells. Emission results were similar to those reported by Townsend-Small et al. (2016) with most wells not being a large source of methane. The three highest emitting wells were responsible for 94% of the methane emissions observed throughout the study. At some of the wells leaking produced water, the authors noted a strong hydrogen sulfide odor but did not quantify hydrogen sulfide concentrations.

Williams et al. (2019) measured methane concentrations in the ambient air at a legacy oilfield in New Brunswick, Canada, with 10 legacy oil and natural gas wells. The wells were referred to as legacy wells because they were abandoned before abandonment protocols and regulations were established in 1952. The authors estimated that 11% of legacy oil and natural gas well sites were sources of methane emissions.

Williams et al. (2021) compiled 598 methane flow rate measurements for unplugged and plugged wells across seven U.S. states (Colorado, Ohio, Oklahoma, Pennsylvania, West Virginia, Wyoming, Utah) and two Canadian provinces (British Columbia and New Brunswick). In their analyses, the authors grouped the measurements by plugging status (i.e., unplugged and plugged) and well type (natural gas, combined oil and natural gas, and unknown). By combining these measurements with aggregate well counts from regional databases, the authors estimated the number of abandoned wells to be at least 4,000,000 in the United States and at least 370,000 in Canada. The authors estimated consistently higher annual methane emissions from abandoned wells by 20% in the United States and by 150% in Canada, compared to national inventory reports. They evaluated uncertainties in annual methane emission estimates from abandoned wells using Monte Carlo simulations of the emission factors and concluded that methane emissions from abandoned wells contribute substantially to uncertainty about anthropogenic methane sources in both countries.

Leakage and Potential for Groundwater Contamination

One study measured methane concentrations in groundwater in relation to inactive oil and natural gas wells (McMahon et al. 2018) and four studies simulated the potential for releases to overlying aquifers

(Brownlow et al. 2016, 2017, 2018; Nowamooz et al. 2018). In addition, one report characterized the findings of state groundwater investigations relative to oil and natural gas development (Kell 2011).

McMahon et al. (2018) collected groundwater samples from 15 monitoring wells in the Piceance Basin in Colorado. The authors reported evidence of shallow groundwater contamination with methane. Using groundwater measurements of multiple chemical tracers (i.e., major ions, trace elements, methane concentrations and isotopic compositions, and noble gases), they concluded that the methane contamination originated from a leaking inactive, plugged natural gas well.

Brownlow et al. (2016) simulated the potential for leakage from unconventional oil and natural gas wells to overlying aquifers in the presence of abandoned wells. The numerical model incorporated historical records and industry data for the Eagle Ford Shale in Texas. The authors reported that contaminant migration was possible through abandoned wells if certain spatial and hydraulic conditions exist. In a follow-up study using well data from the Eagle Ford Shale, Brownlow et al. (2017) estimated the probability of unconventional wells intersecting abandoned wells. The authors concluded that such intersections might occur, with the risk increasing as drilling and abandonment of oil and natural gas wells continues. Brownlow et al. (2018) investigated uncertainty associated with the model described by Brown et al. (2016) using sensitivity, linear, and nonlinear analyses. Based on these uncertainty analyses, the authors recommended data that would be useful for predicting the potential for leakage from abandoned wells (e.g., flowback and produced water volumes).

Nowamooz et al. (2018) assessed the potential of leakage from 85 abandoned wells in the St. Lawrence Lowlands basin in southern Quebec. They based the assessment on well attribute data compiled from drilling reports and abandonment programs. They estimated that the probability of leakage was greater than 50% for 65% of wells. The most important contributors to high leakage probability estimates were wellbore deviation (compared to a vertical wellbore direction) and lack of information on the construction and abandonment methods.

Kell (2011) summarized state groundwater investigations in relation to all phases of oil and natural gas development for Ohio and Texas between 1983 and 2007. The author reported that both states documented a significant number of groundwater contamination incidents linked to abandoned wells over the review period. During the 25-year review period (1983-2007) for Ohio, 41 of 185 documented groundwater contamination incidents resulted from orphaned well leakage. For the 16-year review period (1993-2008) for Texas, 30 of 211 documented groundwater contamination incidents were caused by orphaned wells or sites. The author noted that incidents were frequently linked to “insolvent or defunct operators and pre-regulated practices.”

Soil

Two studies measured shallow soil gas around inactive oil and natural gas sites (McMahon et al. 2018; Williams et al. 2019). One study reported release of produced water to the ground surface (Townsend-Small and Hoschouer 2021).

McMahon et al. (2018) observed evidence of shallow groundwater contamination near an inactive, plugged gas well in the Piceance Basin in Colorado using a multi-tracer approach. The authors also collected soil gas measurements near the observed leaking gas well and did not find evidence of methane emissions from soil to the atmosphere, indicating that methane leakage of inactive wells does not always manifest at the surface.

Williams et al. (2019) collected samples in New Brunswick, Canada at 12 legacy oil and natural gas sites. The sites included oil and natural gas wells that were abandoned before 1952 when abandonment protocols and regulations were implemented. The authors observed soil gas methane fluxes at one of the 12 sampled sites, describing the leakage rate as minimal.

Townsend-Small and Hoschouer (2021) visited 41 inactive wells in Pecos County, Texas, in the Permian Basin and observed that five wells were leaking produced water onto the ground surface. At some of these wells, the authors noted oily sheens, salt crust on the soil, or evidence of dead vegetation.

Combined leakage pathways

One study assessed the effective permeability of 42 plugged and unplugged inactive oil and natural gas wells in western Pennsylvania (Kang et al. 2015). Effective permeability is an overall estimate that captures all wellbore leakage pathways. The authors combined methane flow rate data with historical records on well depths to estimate the effective permeability of the wells. They reported a strong correlation between effective permeability estimates and measured methane flow rate. They explored the role of well plugging, geographic location, and well type in predicting effective permeabilities, concluding that, in general, well type appears to be the strongest predictor of effective permeability. They concluded that effective permeability estimates can be used to estimate methane emissions to the atmosphere or to evaluate the potential for fluid migration into groundwater.

SUMMARY AND NEXT STEPS

This Research Brief summarizes a growing body of literature about inactive oil and natural gas wells. The literature focused almost exclusively on determining the location of these wells and quantifying methane emissions. Inconsistent terminology complicates interpretation of the literature. More importantly, to our knowledge, the literature includes limited investigation of non-methane chemical releases from these wells and does not attempt to quantify human exposures of any kind.

Future research to improve the understanding of environmental releases and assessment of human exposures associated with abandoned and orphaned oil and natural gas wells would benefit from (1) more precise and consistent terminology describing wells and their characteristics, (2) application of remote sensing data to identify well locations and potentially exposed populations at various geographic scales, and (3) characterization of the full range of possible chemical releases from abandoned wells.

ACKNOWLEDGMENTS AND FUNDING

Although this document was produced with partial funding by the United States Environmental Protection Agency under Contract No. 68HERC19D0010 to the Health Effects Institute Energy, it has not been subject to the Agency's review and therefore does not necessarily reflect the views of the Agency, and no official endorsement by the Agency should be inferred. Oil and natural gas companies also provided funding to produce this document; however, it has not been subject to their review and therefore does not necessarily reflect the views of any of the oil and natural gas companies, and no endorsement by them should be inferred.

REFERENCES

Achang M, Yanyao L, Radonjic M. 2020. A Review of Past, Present, and Future Technologies for Permanent Plugging and Abandonment of Wellbores and Restoration of Subsurface Geologic Barriers. Environ Eng Sci; doi:10.1089/ees.2019.0333.

Allison E, Mandler B. 2018. Petroleum and the Environment. Am Geosci Inst. Available: https://www.americangeosciences.org/critical-issues/petroleum-environment [accessed 13 December 2021].

Boothroyd IM, Almond S, Qassim SM, Worrall F, Davies RJ. 2016. Fugitive emissions of methane from abandoned, decommissioned oil and gas wells. Sci Total Env 547:461–469; doi:10.1016/j.scitotenv.2015.12.096.

Brownlow JW, James SC, Yelderman JC. 2016. Influence of Hydraulic Fracturing on Overlying Aquifers in the Presence of Leaky Abandoned Wells. Groundwater 54:781–792; doi:10.1111/gwat.12431.

Brownlow JW, James SC, Yelderman JC. 2018. Uncertainty analysis: influence of hydraulic fracturing on overlying aquifers in the presence of leaky abandoned wells. Environ Earth Sci 77:16; doi:10.1007/s12665-018-7586-0.

Brownlow JW, Yelderman JC, James SC. 2017. Spatial Risk Analysis of Hydraulic Fracturing near Abandoned and Converted Oil and Gas Wells. Groundwater 55:268–280; doi:10.1111/gwat.12471.

de Smet TS, Nikulin A, Romanzo N, Graber N, Dietrich C, Puliaiev A. 2021. Successful application of drone-based aeromagnetic surveys to locate legacy oil and gas wells in Cattaraugus county, New York. J Appl Geophys 186:104250; doi:10.1016/j.jappgeo.2020.104250.

Environmental Defense Fund. 2021. Documenting orphan wells across the United States. Environ Def Fund. Available: https://www.edf.org/orphanwellmap [accessed 7 December 2021].

HEI-Energy Research Committee. 2019. Human exposure to unconventional oil and gas development: A literature survey for research planning. Boston, MA: Health Effects Institute.

Interstate Oil & Gas Compact Commission. 2021. Idle and Orphan oil and gas wells: State and provincial regulatory strategies. Available: *https://iogcc.ok.gov/sites/g/files/gmc836/f/documents/2021/2020_03_04_updated_idle_and_orphan_oil_and_gas_wells_report.pdf* [accessed 7 December 2021].

Kang M, Baik E, Miller AR, Bandilla KW, Celia MA. 2015. Effective permeabilities of abandoned oil and gas wells: analysis of data from Pennsylvania. Env Sci Technol 49:4757–4764; doi:10.1021/acs.est.5b00132.

Kang M, Brandt AR, Zheng Z, Boutot J, Yung C, Peltz AS, et al. 2021. Orphaned oil and gas well stimulus—Maximizing economic and environmental benefits. Elem Sci Anthr 9:00161; doi:10.1525/elementa.2020.20.00161.

Kang M, Christian S, Celia MA, Mauzerall DL, Bill M, Miller AR, et al. 2016. Identification and characterization of high methane-emitting abandoned oil and gas wells. Proc Natl Acad Sci 113:13636–13641; doi:10.1073/pnas.1605913113.

Kang M, Kanno CM, Reid MC, Zhang X, Mauzerall DL, Celia MA, et al. 2014. Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania. Proc Natl Acad Sci U A 111:18173–18177; doi:10.1073/pnas.1408315111.

Kell S. 2011. State Oil and Gas Agency Groundwater Investigations, And Their Role in Advancing Regulatory Reforms, A Two-State Review: Ohio and Texas. Available: *http://www.atlanticaenergy.org/pdfs/natural_gas/Environment/State%20Oil%20&%20Gas%20Agency%20Groundwater%20Investigations_US_GWProCoucil.pdf* [accessed 7 December 2021].

Lebel ED, Lu HS, Vielstädte L, Kang M, Banner P, Fischer ML, et al. 2020. Methane Emissions from Abandoned Oil and Gas Wells in California. Environ Sci Technol 54:14617–14626; doi:10.1021/acs.est.0c05279.

McMahon PB, Thomas JC, Crawford JT, Dornblaser MM, Hunt AG. 2018. Methane in groundwater from a leaking gas well, Piceance Basin, Colorado, USA. Sci Total Environ 634:791–801; doi:10.1016/j.scitotenv.2018.03.371.

Nowamooz A, Comeau FA, Lemieux JM. 2018. Evaluation of the potential for gas leakage along wellbores in the St. Lawrence Lowlands basin, Quebec, Canada. Environ Earth Sci 77:17; doi:10.1007/s12665-018-7483-6.

Pekney NJ, Diehl JR, Ruehl D, Sams J, Veloski G, Patel A, et al. 2018. Measurement of methane emissions from abandoned oil and gas wells in Hillman State Park, Pennsylvania. Carbon Manag 9:165–175; doi:10.1080/17583004.2018.1443642.

Perra C, McIntosh JC, Watson T, Ferguson G. 2021. Commingled Fluids in Abandoned Boreholes: Proximity Analysis of a Hidden Liability. Groundwater; doi:10.1111/gwat.13140.

Raimi D, Krupnick AJ, Shah J-S, Thompson A. 2021. Decommissioning Orphaned and Abandoned Oil and Gas Wells: New Estimates and Cost Drivers. Environ Sci Technol 55:10224–10230; doi:10.1021/acs.est.1c02234.

Riddick SN, Mauzerall DL, Celia MA, Kang M, Bressler K, Chu C, et al. 2019. Measuring methane emissions from abandoned and active oil and gas wells in West Virginia. Sci Total Environ 651:1849–1856; doi:10.1016/j.scitotenv.2018.10.082.

Saint-Vincent PMB, Sams JI, Hammack RW, Veloski GA, Pekney N. 2020. Identifying abandoned well sites using database records and aeromagnetic surveys. Environ Sci Technol acs.est.0c00044; doi:10.1021/acs.est.0c00044.

Saint-Vincent PMB, Sams JI, Reeder MD, Mundia-Howe M, Veloski GA, Pekney NJ. 2021. Historic and modern approaches for discovery of abandoned wells for methane emissions mitigation in Oil Creek State Park, Pennsylvania. J Environ Manage 280:111856; doi:10.1016/j.jenvman.2020.111856.

Taherdangkoo R, Tatomir A, Anighoro T, Sauter M. 2018. Modeling fate and transport of hydraulic fracturing fluid in the presence of abandoned wells. J Contam Hydrol; doi:10.1016/j.jconhyd.2018.12.003.

Townsend-Small A, Ferrara TW, Lyon DR, Fries AE, Lamb BK. 2016. Emissions of coalbed and natural gas methane from abandoned oil and gas wells in the United States. Geophys Res Lett 43:2283–2290; doi:10.1002/2015GL067623.

U.S. Department of the Interior. 2021. Bipartisan Infrastructure Deal Will Clean Up Legacy Pollution, Protect Public Health. Available: https://www.doi.gov/pressreleases/bipartisan-infrastructure-deal-will-clean-legacy-pollution-protect-public-health [accessed 7 December 2021].

U.S. Environmental Protection Agency. 2018. Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Abandoned Oil and Gas Wells. Available*:* *https://www.epa.gov/sites/default/files/2018-04/documents/ghgemissions_abandoned_wells.pdf* [accessed 7 December 2021].

Williams JP, Regehr A, Kang M. 2021. Methane Emissions from Abandoned Oil and Gas Wells in Canada and the United States. Environ Sci Technol 55:563–570; doi:10.1021/acs.est.0c04265.

Williams JP, Risk D, Marshall A, Nickerson N, Martell A, Creelman C, et al. 2019. Methane emissions from abandoned coal and oil and gas developments in New Brunswick and Nova Scotia. Environ Monit Assess 191:479; doi:10.1007/s10661-019-7602-1.

Wisen J, Chesnaux R, Werring J, Wendling G, Baudron P, Barbecot F. 2019. A portrait of wellbore leakage in northeastern British Columbia, Canada. Proc Natl Acad Sci 201817929; doi:10.1073/pnas.1817929116.

HEI ENERGY BOARD, RESEARCH COMMITTEE, AND STAFF