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POLICY BRIDGE

Orphaned oil and gas well stimulus—Maximizing economic and environmental benefits

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Orphaned oil and gas wells are abandoned wells for which the cost of environmental impacts usually falls on governments and the general public. Government agencies responsible for well plugging often face funding shortfalls and many orphaned wells remain unplugged. To address this and support the oil and natural gas industry, federal governments are already spending, or considering spending, billions of dollars to plug orphaned oil and gas wells. Here, we analyze oil and gas data for the United States and Canada and identify policy recommendations that can best address environmental impacts of abandoned and orphaned wells. At least 116,245 wells across 32 states and four Canadian provinces/territories are operated by companies filing for bankruptcy in the first half of 2020, which may be an indication that many wells will be orphaned in the near future. Moreover, there are 4,700,000 historic and active oil and gas wells in the United States and another 790,000 in Canada. Of these, 2,000,000 and 310,000 wells are active in the United States and Canada, respectively. Thus, three of five wells ever drilled in the United States are currently inactive (2,700,000 wells), but only one in three are plugged (1,500,000 wells). Plugging involves isolating zones containing oil, gas, and water and is the main strategy for well abandonment. If the orphaned well stimulus funding comes through, tens of thousands of wells will be plugged within a few years. Well plugging at this scale far exceeds current rates of plugging, and it is important that we work to ensure long-term environmental benefits of well abandonment to water, air, climate, ecosystems, and human health. Minimizing environmental impacts of the millions of abandoned and orphaned wells in the United States, Canada, and abroad will allow for an economically beneficial and environmentally safe transition to a carbon-neutral economy.

Keywords: Oil and gas policy, Abandoned and orphaned wells, Well leakage, Environmental impacts, Groundwater contamination, Methane emissions

1. Introduction

There are 4 million historic and active oil and gas wells in the United States alone. As society transitions away from fossil fuels to renewables (Höök and Tang, 2013; Brandt et al., 2013), most of these wells will eventually be abandoned, and some will be orphaned. Orphaned wells are abandoned oil and gas wells for which a responsible party no longer exists, for instance, through bankruptcy. In the next few years, the number of wells abandoned and orphaned may increase rapidly, given the sharp decline in oil prices in 2020, coinciding with the COVID-19 pandemic. Therefore, it is important to develop policies that can best reduce the environmental impacts of the growing inventory of abandoned and orphaned oil and gas wells in the short and long term.

Many environmental impacts can occur when abandoned oil and gas wells leak gas, oil, saline water, and/or other fluids (Jackson et al., 2014; **Figure 1**). The impacts include air pollution, greenhouse gas emissions, groundwater contamination, soil degradation, damage to ecosystems, and risk of explosions, all of which pose threats to human health. To eliminate these risks, when a well is no longer economically viable, wells are supposed to be plugged according to procedures dictated by regulation (Environmental Defense Fund, 2019). In 2018, the industry paid for the plugging of 16,153 wells in the United

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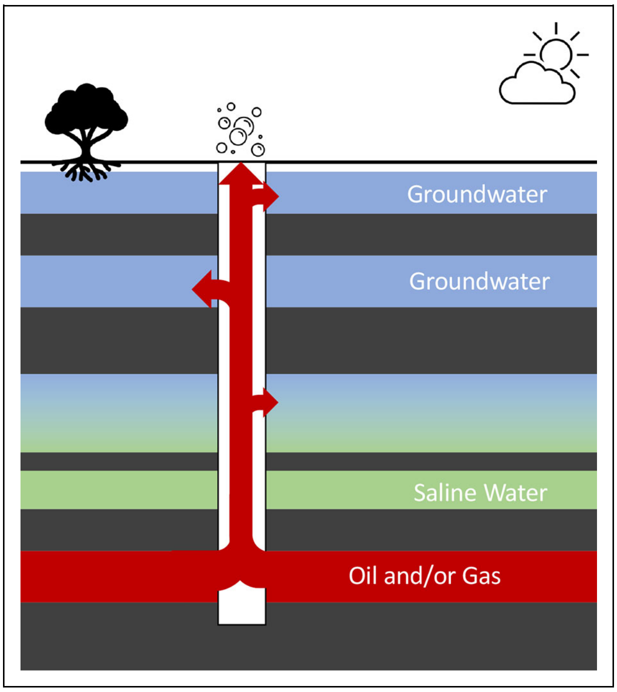

Figure 1. Cross-sectional schematic of an unplugged abandoned well acting as a subsurface leakage pathway connecting oil and gas reservoirs to aquifers and the ground surface. The dark gray zones represent lower permeability layers that act as barriers for vertical flow of groundwater and oil and gas. Groundwater is defined here as protected water of sufficient quality to be used for drinking, agriculture, industrial, or other uses. The red zone represents the formation containing oil and/or gas (and water) from which oil/gas will migrate upward due to buoyancy. As the oil/gas migrates upward, it can leak into aquifers and cause groundwater contamination or emit gases to the atmosphere. Plugged wells can also act as leakage pathways if the plugging was performed inadequately or the plug deteriorates. DOI: https://doi.org/10.1525/elementa.2020.20.00161.f1

States that are not orphaned, while state governments paid for the plugging of 2,372 wells (IOGCC, 2019). Government funds to plug orphaned wells are perpetually in shortfall (Ho et al., 2018; Schuwerk and Rogers, 2020; Abboud et al., 2020) and many remain unplugged. The downturn in the oil and gas industry and recent bankruptcies of dozens of companies pose the risk of pushing an increasing number of wells into overloaded government queues (Schuwerk and Rogers, 2020).

In efforts to reduce environmental impacts while supporting the oil and natural gas industry economically, several U.S. politicians and other stakeholders have proposed spending billions of dollars of federal stimulus funding to plug orphaned oil and gas wells across the country (Raimi et al., 2020). In September 2020, U.S. Senator Michael Bennet of Colorado announced bills to plug orphaned wells and increase federal bonding requirements to reflect the true cost of plugging and site reclamation. Other federal bills for orphan well plugging, bonding reform, and capacity building of state agencies are expected to be announced in 2021. In Canada, the federal government already committed $1.7 billion CAD to plug orphaned wells and support oil and gas workers in April 2020. With federal funding, tens of thousands of orphaned wells are being and will be plugged, providing environmental benefits. However, it is difficult to quantify these benefits using currently available information.

To quantify and maximize the environmental benefits of such programs and determine beneficial policy strategies, policy makers need to evaluate the scale of the problem, understand well leakage, and implement monitoring of environmental impacts of abandoned oil and gas wells. Therefore, we address four questions: (1) Will there be more orphaned wells because of the current COVID-19 economic downturn? (2) What are the barriers and limitations to well plugging? (3) What are the environmental impacts of leaky orphaned and abandoned wells? and (4) How can proposed federal orphaned well stimulus programs best address environmental impacts of abandoned wells?

2. The problem of orphaned and abandoned wells now and in the future

2.1. Potential role of bankruptcies on the number of orphaned wells

We compile data on oil and gas companies filing for bankruptcy or other defaults (e.g., Chapter 11: missed interest, distressed exchange) in the United States and Canada (Tables S1 and S2). We then use Enverus's DrillingInfo and state/provincial/territorial databases (Tables S3 and S4) to estimate the number of oil and gas wells associated with the financially distressed companies (**Figure 2**). We include active and inactive (including abandoned, idle, suspended, and orphaned) oil and gas wells in these counts.

In the first half of 2020, 30 oil and gas exploration and production companies filed for bankruptcy or receivership in the United States and Canada (Tables S1 and S2). Across the United States and Canada, these companies operate 116,245 wells in 32 states and four Canadian provinces/territories, with the most in California (37,620), Texas (16,529), and Oklahoma (12,258; **Figure 2**). Wells operated by companies going bankrupt are not necessarily orphaned but may change ownership or continue to produce within the restructured company (Schuwerk and Rogers, 2020). In some cases, wells change hands multiple times before being abandoned. As a result, available data cannot yet be used to understand precisely how many of the wells operated by bankrupt companies are being, or will be, orphaned across the United States and at what timescale (Figure S2). Nevertheless, data from Alberta show that a drop in oil price leads to an increase in the number of orphaned wells in the following approximately 3 years (Figure S3).

2.2. Number of active and inactive oil and gas wells

We compile the number of drilled, active, and plugged oil and gas wells across the United States and Canada (Figure S1) available in state/provincial/territorial databases (Tables S3 and S4). To determine whether a well is active or not, we use the definition for abandoned wells

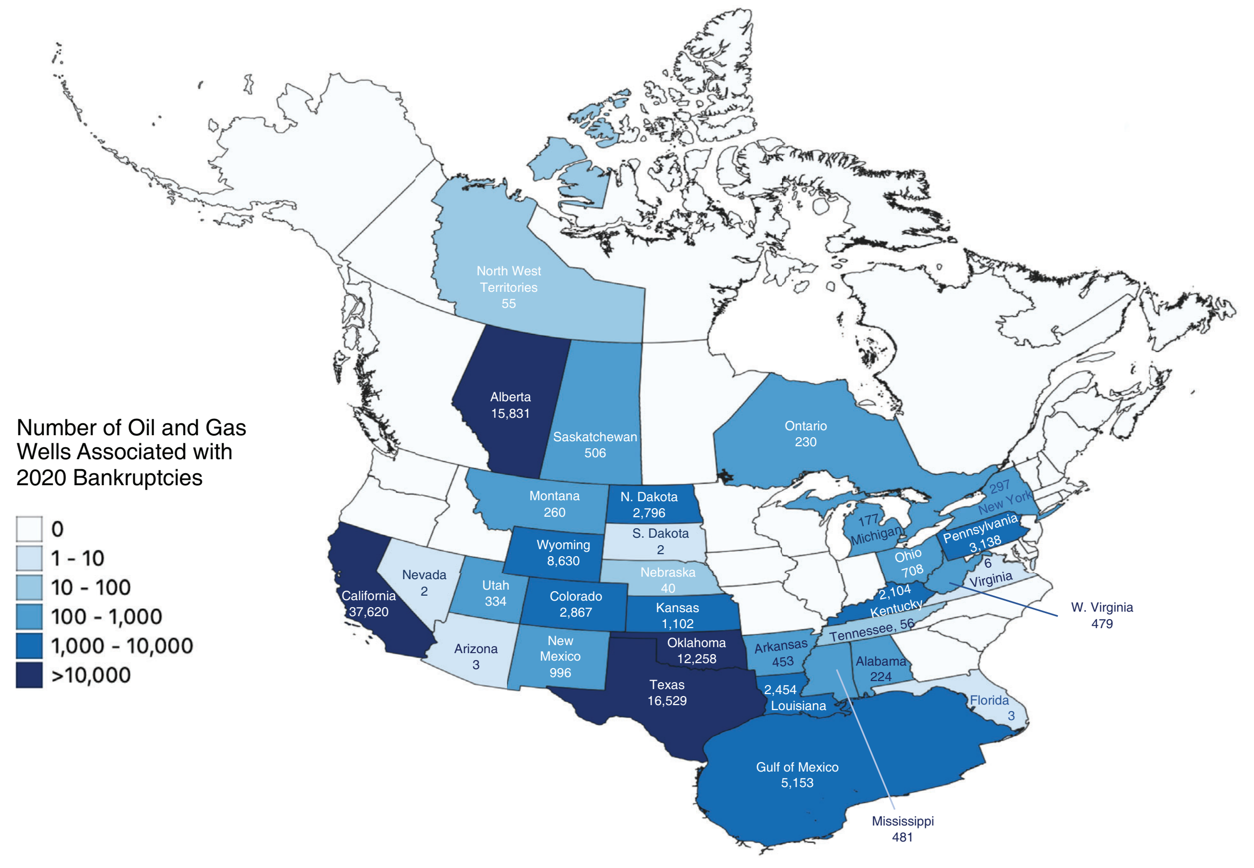

Figure 2. Map of the number of oil and gas wells in each state/province operated by companies that filed for bankruptcy in 2020 in the United States and Canada (as of July 2020). DOI: https://doi.org/10.1525/elementa.2020.20.00161.f2

employed by the U.S. Environmental Protection Agency (2019). Using a key word search, we categorize wells with the terms "inactive," "temporarily abandoned," "shut-in," "suspended," "dormant," "junked," "idle," and "plugged" as abandoned. The number of orphaned wells is analyzed separately (Figure S2). To present the number of wells drilled over time in the United States, we compile the number of wells drilled per year from Brandt et al. (2014) for 1859–1989 and the U.S. Environmental Protection Agency (2019) for 1990–2018 (Figure S4).

According to state and provincial/territorial records, there are 4,653,000 historic and active oil and gas wells in the United States and another 788,000 in Canada (Tables S3 and S4). Of these, 1,954,000 (42%) and 313,000 (40%) wells are active in the United States and Canada, respectively. In the active well counts, we include wells drilled for enhanced recovery (e.g., injection wells) and disposal wells (e.g., salt water disposal well that was formerly producing gas) in addition to those drilled to produce oil and gas. In the United States, 1,519,000 (33%) wells are plugged; while in Canada, 351,000 (45%) are plugged. Thus, two of three wells ever drilled in the United States are currently inactive, but only one in three are plugged (Tables S3 and S4).

Using well counts from Brandt et al. (2014) and the U.S. Environmental Protection Agency (2019) for the United States, the number of drilled oil and gas wells is 4,072,000 as of 2018 (Figure S4), which is lower than the 4,765,000 wells in state databases (Table S3). In addition, discrepancies between state databases and Enverus's DrillingInfo have been documented (Schuwerk and Rogers, 2020).

The numbers of oil and gas wells presented here may be underestimated due to poor recordkeeping of older wells. Oil was first produced commercially in the United States in 1859 in Pennsylvania. The state records show 214,337 wells in Pennsylvania (Table S3), but published estimates show that the number of wells drilled in the state is likely to be much higher, ranging from 305,000 to 750,000 (Dilmore et al., 2015; Kang et al., 2016). Across the United States, there are many states with oil production dating back to the 19th century, including California (Brandt, 2011) and Texas. A recent study scaling up results from database records and aeromagnetic surveys estimates that the average number of drilled wells in the United States is 6,037,587, with 1,159,689 being abandoned (Saint-Vincent et al., 2020b).

3. Considerations for mitigating abandoned and orphaned wells

3.1. Barriers and limitations of well plugging

State and provincial regulations require oil and gas companies to formally abandon wells that are no longer producing and will not be producing again in the future (Environmental Defense Fund, 2019). At abandonment, wells are required to be plugged such that fluids cannot migrate from oil and gas reservoirs to aquifers or the ground surface (Gasda et al., 2004; Watson and Bachu, 2009; King and Valencia, 2014). Well plugging involves identifying formations bearing protected waters, oil, and/or gas and isolating these zones (Gasda et al., 2004; Watson and Bachu, 2009; Environmental Defense Fund, 2019) using cement, mechanical plugs, and other packing materials (King and Valencia, 2014). Regulations specify the type of material that can be used for plugging and the vertical intervals to be plugged, which generally extend above and below formations to be isolated. There are several barriers and limitations to well plugging, and here, we discuss the following: high plugging costs, well/plug integrity failures, and protected water definitions.

Abandonment involves plugging wells and restoring sites, which typically have average costs in the orders of $10,000 CAD to $100,000 CAD per well (IOGCC, 2019; Kang et al., 2019b; Raimi et al., 2020). Because of the greater depths of hydraulically fractured wells producing from shale and other tight rocks, the plugging costs of these wells may be much higher (Andersen and Coupal, 2009; Mitchell and Casman, 2011; Schuwerk and Rogers, 2020). However, there are many conventional, vertical wells that may be as expensive to plug due to the condition of the well and their remoteness.

Plugging should limit any gas emissions to the atmosphere. However, reducing methane or other greenhouse gas emissions is not an explicit goal of most abandonment regulations. In some cases, as in some coal-producing regions of the United States and in Canada, plugged wells are vented, by regulation, for reasons of safety, and they emit as much methane as the highest emitting unplugged abandoned wells (Kang et al., 2016). Moreover, plugging regulations and technology have evolved with time from nonexistent to modern standards over the course of 160 years (King and King, 2013). Although the conditions of well plugs may be assessed by knowledge of the age of the well, a clear relationship between leakage and well age has not been observed (Riddick et al., 2019). In addition, government databases do not provide sufficient information to assess whether a well is plugged properly. Overall, aside from vented plugged wells, measurements show lower average rates of methane emissions from plugged wells than unplugged wells (Kang et al., 2016; Townsend-Small et al., 2016; Saint-Vincent et al., 2020a; Williams et al., 2020); nonetheless, leakage to groundwater and/or to the atmosphere can occur at unplugged and deteriorating or poorly plugged wells (Kell, 2011; McMahon et al., 2018).

In addition to how well an abandoned well is plugged, leakage occurrence and rate depend on the integrity of the well (Gasda et al., 2004; King and King, 2013; King and Valencia, 2014; Davies et al., 2014; Lackey et al., 2017; Wisen et al., 2019; Ingraffea et al., 2020; Hammond et al., 2020; Abboud et al., 2020). Surface casing vent flows, surface casing pressures, and gas migration—all indicators of subsurface leakage—at active and unplugged abandoned wells—have been observed at 5.6% of wells in Pennsylvania (Ingraffea et al., 2020), 6.9% of wells in Colorado (Lackey et al., 2017), and 10.8% of wells in British Columbia (Wisen et al., 2019). The most common pathway for fluids to leak has been identified as uncemented or poorly cemented annular space between casings (Watson and Bachu, 2009; Dusseault and Jackson, 2014; Hammond et al., 2020). However, identifying attributes linked to higher leakage frequencies has been found to be challenging due to incomplete databases (Montague et al., 2018). Moreover, subsurface gas migration pathways are “rarely clear,” and “not all remedial operations will be completely successful” (Abboud et al., 2020).

State definition for groundwater to be protected varies, and oil and gas activities are widespread in underground sources of drinking water (Kang and Jackson, 2016; DiGiulio et al., 2018; Kang et al., 2019a; Kang et al., 2020), defined by the U.S. Environmental Protection Agency as waters that may be usable with treatment (DiGiulio et al., 2018). Groundwater wells in the United States are increasingly being drilled deeper (Perrone and Jasechko, 2019), and brackish water previously considered too saline to be used is being treated or blended with fresher water (Kan and Rapaport-Rom, 2012) to meet water quality requirements. However, the depth interval designed to protect groundwater is set by the definition of protected water at the time of plugging and may not protect groundwater that may be used in the future. Nevertheless, the majority of the millions of groundwater wells already drilled and being used today likely exist within the protected zones.

The bulk of the proposed national stimulus funds will likely be used for plugging and site remediation in efforts to create jobs. The observation that methane emission rates are lower at individual plugged wells (Kang et al., 2016; Townsend-Small et al., 2016; Saint-Vincent et al., 2020a; Williams et al., 2020) has been used as an environmental argument supporting well plugging. However, large variabilities in methane emissions rates have been observed (Erno, 1996; Riddick et al., 2020), and plugs can degrade or be poorly installed (King and King, 2013). In other words, the science on benefits and impacts of individual wells and at the broader system level in decadal and centennial timescales is understudied and it is difficult to quantify the environmental benefits of plugging. In rare cases, plugging wells may even increase the likelihood of contaminating groundwater (Jackson et al., 2020) because of the complex subsurface pathways that effectively connect neighboring wells. In these cases, plugging could lead to leakage occurring through a different pathway or even to a different surface location. Therefore, the leakage potential of plugged wells requires further research, and this research needs to be conducted within a short time frame to meaningfully inform how potential bills are implemented.

3.2. Leakage means likely groundwater contamination and possibly gas emissions to the atmosphere

Abandoned wells can leak underground even if methane emissions are not occurring at the surface (McMahon et al., 2018; Schout et al., 2019). In sedimentary basins where oil and gas are typically produced, the subsurface environment holds layers of rocks with different properties and

Table 1. Physical environmental components affected by abandoned and orphaned oil and gas wells. DOI: https://doi.org/10.1525/elementa.2020.20.00161.t1

Environmental Component	Availability of Direct Measurements	Strategies to Reduce Environmental Impacts	Ability of Plugging and Site Restoration to Reduce Impacts
Surface water	Wen et al. (2019)	Plugging; site restoration; dilution/mixing	Depends on interactions with groundwater
Groundwater	Kell (2011); McMahon et al. (2018); Wen et al. (2019)	Plugging; groundwater remediation; natural attenuation	Unclear
Air	Lebel et al. (2020)	Plugging; dilution/mixing	Assumed to reduce emissions
Climate (methane emissions)	Kang et al. (2014, 2016); Townsend-Small et al. (2016); Boothroyd et al. (2016); Pekney et al. (2018); Riddick et al. (2019); Lebel et al. (2020); Saint-Vincent et al. (2020a); Williams et al. (2020)	Plugging; flaring; gas usage	Appears to reduce emissions
Ecosystems	Nallur et al. (2020)	Plugging; site restoration; natural attenuation	Site restoration to predevelopment conditions likely to reduce impacts. Plugging may reduce impacts depending on the reliance on groundwater and sensitivity to air quality
Human health	Not available	Plugging; site restoration; natural attenuation	Depends on reliance on groundwater. Depends on air pollutant and exposure limits

"Availability of direct measurements" include publications that, to our knowledge, link impacts to the environmental component to abandoned or orphaned oil and gas wells. We do not include studies that focus on impacts due to shale gas development or other active oil and gas development.

fluids (**Figure 1**). Leaking fluids can be saline water, hydrocarbons in liquid or gas form (e.g., methane, a strong greenhouse gas), radionuclides, and other anthropogenic and naturally occurring contaminants found in deep subsurface environments (Jackson et al., 2013). Some of the rock layers are relatively permeable and allow fluids to move easily, while others such as shale are less permeable. Fluids are often trapped beneath lower permeability layers. However, if a highly permeable conduit such as an unplugged or poorly plugged well exists, fluid movement driven by buoyancy and/or pressure can cause fluids to leak rapidly to overlying aquifers. As the leaking fluids migrate upward, some may enter overlying aquifers. This process has been referred to as the "elevator model," using the analogy of a full elevator at the ground floor becoming emptier as the elevator goes up and people exit at various floors (Nordbotten et al., 2004). Pressures are a function of natural hydraulic and geothermal gradients but can be increased by anthropogenic activities such as fluid injections for enhanced oil and gas recovery or waste disposal. Overall, leakage, driven by a combination of natural and anthropogenic activities, can result in groundwater contamination and possibly a wide range of impacts to surface water, ecosystems, air, and climate (**Table 1**), all of which can be long-lasting.

Groundwater contamination has been linked to leakage from unplugged and plugged wells. A study of documented groundwater contamination incidents in Ohio from 1983 to 2007 found that 41 of 185 (22%) incidents were caused by orphaned well leakage (Kell, 2011). In another study of one well in Colorado, groundwater was found to be contaminated by a gas well, which was plugged in 1990 (McMahon et al., 2018). We analyze available data from Alberta on surface casing vent flow and gas migration reports (Alberta Energy Regulator, 2020) to understand how leakage potential may have changed with time (Figure S5). In 2008, Alberta changed their regulations so that well caps were vented rather than sealed due to concerns of elevated gas concentrations in local groundwater (Boyer, 2015). Even though no changes were made to regulations specifying how wells are plugged in the subsurface, leakage "considered nonserious" increased two-fold (Figure S5). The implication is that prior to 2008, leaks were likely occurring but not detected at the ground surface. The two studies (Kell, 2011; McMahon et al., 2018) and our analysis described here are the only available studies linking groundwater contamination to abandoned wells. Reasons for the lack of case studies include limitations to sampling subsurface environments, complexities and uncertainties in subsurface pathways and fluids, and a general lack of monitoring (Darrah et al., 2014; Wen et al., 2019).

3.3. Environmental impacts of abandoned and orphaned wells

Impacts of abandoned and orphaned wells to other environmental components including air, ecosystems, and human health (**Table 1**) are understudied. However, in the past decade, there have been numerous studies on environmental impacts due to active oil and gas development, particularly those relating to shale gas or hydraulically fractured horizontal wells (Jackson et al., 2014). Some of these findings are likely to be broadly applicable to the abandoned and orphaned well leakage problem. However, there are important differences in the physical conditions (e.g., fluid pressures) and surface and subsurface activities, and studies focused on abandoned and orphaned wells are needed.

Oil and gas production has been found to impact air quality through emissions of volatile organic compounds, nitrogen oxides, sulfur dioxide, ammonia, and particulate matter (Pétron et al., 2014; Jaramillo and Muller, 2016; Caron-Beaudoin et al., 2018; Caron-Beaudoin et al., 2021). To our knowledge, there is only one published study measuring air pollution from abandoned wells. Lebel et al. (2020) measured benzene from one high-emitting unplugged gas well and found concentrations to be below detection. However, results from one well are not sufficient to evaluate air quality impacts, and additional measurements are needed to understand air quality impacts of abandoned wells. Nevertheless, it is reasonable to assume that methods such as plugging are effective at reducing emissions of air pollutants in addition to methane.

Ecosystem impacts attributed to oil and gas development include land cover change, forest fragmentation, habitat loss, farmland conversion, and soil degradation (Drohan et al., 2012; Brittingham et al., 2014; Matthees et al., 2018; Nallur et al., 2020). For ecosystems, site restoration is likely as important, if not more important, than plugging itself. Site restoration is defined as "removal of equipment, trash and debris; repair of erosion; removal of hydrocarbons and closure of pits; and associated activities" (IOGCC, 2019, p. 17) and often does not mean restoring the land to predevelopment conditions. For example, in Arkansas, most of the areas disturbed by oil and gas development were restored to pastureland even though half of the land was originally forested (Nallur et al., 2020). In contrast, well abandonment in Alberta includes restoring surface conditions to the original state (Erno, 1996). Although plugging may reduce some of the impacts to ecosystems through improved air and water quality, site restoration, especially to predevelopment conditions, likely produces substantial positive benefits to ecosystems.

A few studies have found positive associations between the proximity to shale gas development activities and birth outcomes or respiratory diagnoses (Bamber et al., 2019), while results of other studies are inclusive (Caron-Beaudoin et al., 2021). Overall, a recent review finds that "the epidemiologic literature on the potential health effects of oil and natural gas operations is still inadequate to definitively guide policy" (Bamber et al., 2019, p. 15). There currently are, to our knowledge, no published studies on the relationship between abandoned or orphaned oil and gas wells and human health.

4. Policy implications

4.1. Plugging costs, carbon credit pricing, and the social cost of carbon/methane

We estimate the cost per carbon emissions avoided through well plugging and compare these prices to carbon prices and the social cost of carbon and methane (**Figure 3**; Table S6). The methane emission rates used are 10,000 mg/h/well and greater, following the definition of high methane-emitting abandoned oil and gas wells by Kang et al. (2019b). These high emitters likely represent <10% of all abandoned wells (Williams et al., 2020), and thus, there will be additional costs for finding the high-emitting wells. These additional costs are not included in the plugging costs presented here.

Considering plugging costs alone, the cost can be covered by carbon pricing at some wells and by the social cost of carbon and methane at many wells (**Figure 3**). Carbon prices may be able to cover the cost of plugging high methane-emitting wells, especially if costs of plugging and identifying high-emitting wells can be reduced and kept below $ 10,000 CAD per well. Although air quality impacts are included in the social cost of emitting methane (Shindell et al., 2017), it is important to note that we are not considering the full environmental costs of abandoned wells such as those related to groundwater contamination and ecosystem degradation. As a result, the benefits of plugging wells at $ 100,000 CAD per well or more are still likely to outweigh the costs.

4.2. The utility of environmental monitoring requirements in orphan well stimulus funding

Orphaned well stimulus funds can be implemented such that states, provinces, and territories focus on economic benefits and spend the bulk of the funds on plugging (i.e., Canada's approach), aim to maximize environmental benefits through monitoring and science-based mitigation strategies, or implement aspects of both. The potential U.S. stimulus programs, as they currently stand, aim to allocate funding for federal agencies to conduct some research (**Table 2**).

Monitoring of pre- and postplugging conditions is useful for designing appropriate mitigation strategies and for quantifying the environmental benefits of plugging and abandonment. Monitoring can also fill current gaps in our understanding of wellbore and well plug integrity and leakage processes and associated impacts (**Table 1**). However, other than California's Assembly Bill 1328 approved in 2019, we know of no requirement to monitor plugged oil and gas wells in any other state, province, or territory for environmental impacts.

4.3. Monitoring and management of abandoned wells including orphaned wells

The development of policies and workforce to monitor and manage environmental impacts of abandoned and orphaned wells is timely due to the recent downturn in the oil and gas industry. Monitoring and studies of environmental impacts should consider all components of the environment (air, water, and ecosystems) and human health. Moreover, policies developed around careful plugging and worker training will provide a valuable

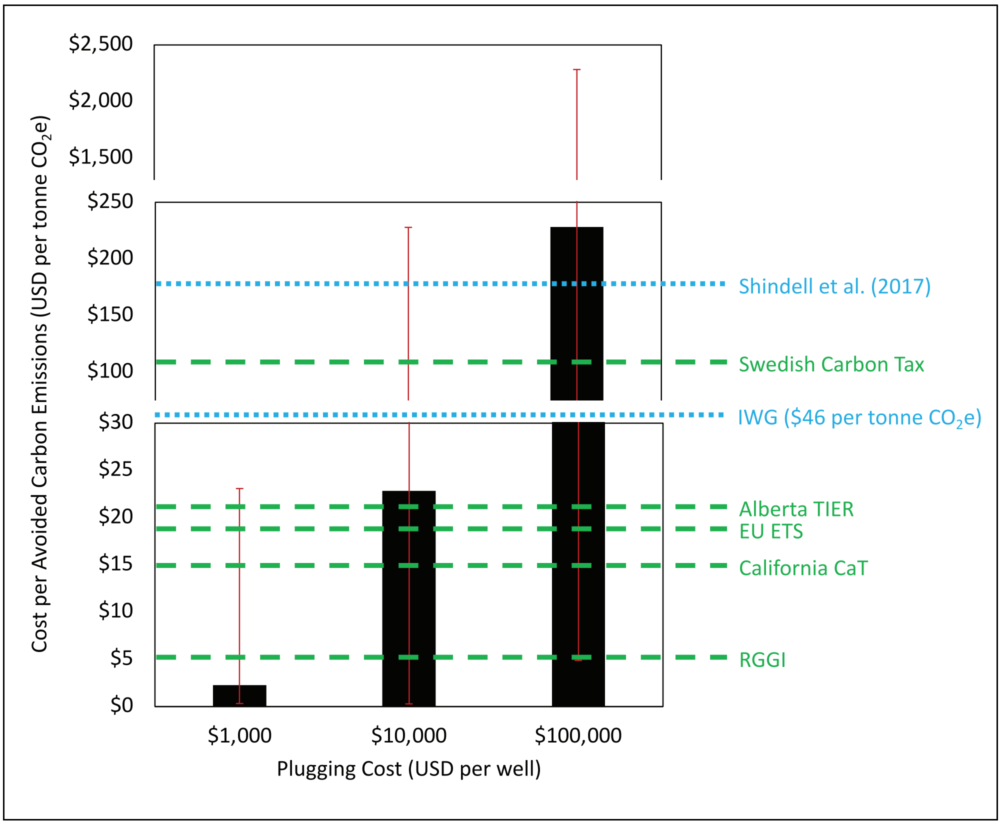

Figure 3. Costs per tonne of avoided carbon emissions achieved through plugging, compared to carbon prices and the social cost of emitting carbon/methane. We assume plug lifetimes of 20, 50, and 100 years (Kang et al., 2019b) and consider methane emission rates of 10,000 mg/h/well, 100,000 mg/h/well, and 1,000,000 mg/h/well (Table S6). The black bar represents estimates for a 20-year plug lifetime and a methane emission rate of 100,000 mg/h/well. The red lines represent the full range of costs estimated in Table S6 for the three plugging costs. The green dashed lines represent selected carbon prices (World Bank, 2020). The Swedish Carbon Tax of $119 CAD per tonne CO2e is the highest carbon price listed in a recent report by the World Bank (2020). The other prices shown are the Alberta Technology Innovation and Emissions Reduction Regulation, the European Union Emissions Trading System, California Cap and Trade, and the Regional Greenhouse Gas Initiative (World Bank, 2020). Shown in blue dotted lines, the social cost of carbon is obtained from the Interagency Working Group on Social Cost of Greenhouse Gases, U.S. Government (2016), and the social cost of emitting methane is from Shindell et al. (2017). DOI: https://doi.org/10.1525/elementa.2020.20.00161.f3

Table 2. Potential components of orphaned well plugging stimulus funding. DOI: https://doi.org/10.1525/elementa.2020.20.00161.t2

Activity	U.S. Potential Orphaned Well Stimulus Bills[a]	Canada Orphaned Well Stimulus Program in Effect Since April 2020
Orphaned well plugging	Funds to be provided to states, tribes, and the Department of the Interior for federal lands	Funds provided to provinces
Increase state/provincial capacity for regulatory oversight on plugging activities	Funds to be provided to states, tribes, and federal agencies through the Department of the Interior	Not required
Research on characterizing methane emissions from abandoned wells and finding historic wells	Funds to be provided to federal agencies (e.g., Department of Energy) but also funding to states is permitted to be used for this purpose	Not required
Monitoring of plugged and unplugged abandoned wells	Not required, but state and federal funds are permitted to be used for this purpose	Not required
Training of environmental monitoring workers	Not required	Not required

See supplementary material for additional details on the Canadian Orphan Well Stimulus program.

[a] The potential bills reviewed are under development and have not been finalized. Therefore, they are subject to change.

foundation to manage the increasing number of abandoned wells in the oil and gas industry for decades to come. Here, we outline six policy recommendations for monitoring and managing abandoned oil and gas wells including orphaned wells:

1. Monitor representative populations of plugged and unplugged abandoned wells across multiple basins to understand the ability of plugging to address the full suite and interdependency of environmental risks (**Table 1**). Ongoing analysis of monitoring results and well attributes are needed to identify representative populations of wells. Moreover, it is important to perform pre- and postplugging monitoring and understand short-term variations (i.e., daily and seasonal).
2. Study the long-term—decadal to century-scale—impacts of abandoned wells. Such studies should include monitoring at the same wells over decades.
3. Monitor and manage abandoned wells regionally to account for interwellbore communication and complex subsurface leakage pathways. The region to investigate will depend on the geology, hydrogeology, and the history of oil and gas and other subsurface activities. Additional research involving field and modeling work is needed to develop a framework for selecting these regions.
4. Find and document wells that are not in current databases so that they can be addressed through plugging and site restoration in a systematic manner.
5. Develop national and international standards for documenting historical and modern wells to improve the long-term maintenance and usability of databases.
6. Train workers on well plugging, site restoration, environmental monitoring, and other jobs that will remain available during and after the transition to clean energy.

The cost of monitoring, especially for surface methane emissions, is likely to be small compared to the cost of plugging (Kang et al., 2019b; Riddick et al., 2020) and the full environmental costs. However, there are opportunities to reduce monitoring costs even further. Rather than monitoring all wells, monitoring can be conducted at representative sites, and the results can be used to develop models that can evaluate impacts inexpensively. To do this, some monitoring is necessary as the data currently available are insufficient to constrain such models. Database analysis of well attributes such as plugging status, well type, and geographic location is important for identifying leakage scenarios and representative sites (Kang et al., 2016; Williams et al., 2020).

Methods for finding and locating wells include "electromagnetic surveys, old records, pressure transient response, stressed vegetation, site disturbance surveys and other methods" (King and Valencia, 2014, p. 8). There have also been recent advances in remote sensing and aerial surveys (Saint-Vincent et al., 2020b), which have been tested at six fields in Pennsylvania and Wyoming. However, additional studies are needed to evaluate the potential for such technologies to be scaled up to the United States. Alternatively, there are cost-effective opportunities using grassroots-based approaches (Brantley et al., 2018) to find, locate, and document abandoned wells.

There is a need for national and international standards for documenting historical and modern wells as the form and content of databases vary substantially among regions (states, provinces, territories, and federal governments). Well attributes reported include location, depths, direction of drilling, permit number, operating company, drilled/completion/abandonment dates, status (e.g., active, abandoned, suspended), well type or gas-to-oil ratio, and producing formation/pool/field/reservoir. These attributes may be important predictors for leakage and understanding the extent of potential environmental impacts.

Moving forward, the current strategy of relying on oil and gas industry fees and bonds to fund future environmental liabilities (including monitoring) is likely to lead to shortfalls in funding (Ho et al., 2018; Schuwerk and Rogers, 2020). Possible additional sources of funding are carbon credits, fees to other subsurface users (e.g., natural resource developers, groundwater users) and revenue from repurposing existing wells for geothermal energy, waste disposal, and other energy or mineral development. Moreover, there are opportunities to repurpose the land for wind and solar.

Despite gaps in our understanding of environmental impacts and benefits of abandoned and orphaned wells and plugging them, action, taking the precautionary approach (Foster et al., 2000; Kriebel et al., 2001), is needed now. Action should include plugging and monitoring and a framework for integrating new knowledge as it becomes available (Williams, 2011). Stakeholders, objectives, management alternatives, models, and monitoring protocols need to be clearly outlined along with strategies to build capacity for monitoring and adaptive management (Foster et al., 2000; Williams, 2011).

Although the primary goal of the orphaned well stimulus is economic, many stakeholders, policy makers, and legislators are supportive of the stimulus funding because of the potential environmental outcomes. If the orphaned well stimulus funding comes through, tens of thousands of wells will be plugged within a few years. Well abandonment and plugging at this scale far exceeds current rates of plugging, and it is important that we understand how to ensure long-term environmental benefits of well abandonment.

5. Conclusions

There are millions of abandoned oil and gas wells in the United States, Canada, and abroad. As society transitions away from fossil fuels, the number of abandoned and orphaned wells will likely grow. Therefore, it is important to develop policies that lead to effective well plugging and abandonment and that incorporate monitoring and management of the growing inventory of abandoned wells. Additional studies on environmental impacts of abandoned and orphaned wells and benefits to plugging these wells are needed, particularly for impacts to groundwater, air, ecosystems, and human health. Protecting the environment can translate into large economic benefits as we eliminate the high costs of remediating our water, soil, and air and combating climate change.

Data accessibility statement

All of the data used in this study are included in Supplementary material of this article.

Supplemental files

Supplemental files for this article are available online.

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Competing interests

The authors declare that they have no conflict of interest.

Author contributions

Contributed to conception and design: MK, ARB, ZZ, ASP, RBJ.

Contributed to acquisition of data: MK, JB, CY.

Contributed to analysis and interpretation of data: MK, JB, CY.

Drafted and/or revised the article: MK, ARB, ZZ, ASP, RBJ.

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