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Policy Analysis

Documented Orphaned Oil and Gas Wells Across the United States

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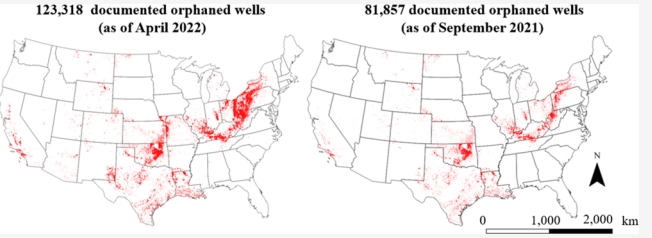
ABSTRACT: Orphaned oil and gas wells are unplugged nonproducing wells with no solvent owner of record to plug and mitigate them, such that the responsibility often falls on government agencies and the general public. Unplugged wells pose risks to the environment, climate, and human health. To develop a national framework to quantify the environmental benefits of plugging and optimize mitigation, we analyze oil and gas well data from state agencies across the United States to estimate the number of documented orphaned wells over time and evaluate their attributes. We find at least 81,857 documented orphaned wells as of September 2021 and 123,318 as of April 2022, representing 2% and 3%, respectively, of all estimated abandoned wells in the United States. We identify at least 20,286 potentially documented orphaned wells as of September 2021 (0.5% of all estimated abandoned wells in the country), of which 8% became documented orphaned wells as of April 2022. We estimate annual methane emissions to average 0.016 ± 0.001 MMt of CH_4 for the 123,318 documented orphaned wells as of April 2022, corresponding to 5−6% of the total methane emissions estimated by the U.S. EPA for all abandoned wells. Although well type (i.e., oil vs gas) is generally available (83% of the 81,857 documented orphaned wells as of September 2021), only 49% and 16% of the wells have information on depth and last production date, respectively. Overall, documented orphaned wells and their attributes, including location, well type, depth, and last production date, require additional characterization and studies to constrain the uncertainties. Nevertheless, our identification and analysis of documented orphaned wells represent the first steps toward characterizing the full set of wells eligible to be plugged and remediated with the federal funding available in the U.S. via the Infrastructure Investment and Jobs Act. Our results can also be useful for the management of the hundreds of thousands, potentially a million, undocumented orphaned wells likely to exist across the nation.



KEYWORDS: *orphaned wells, abandoned wells, oil and gas, methane, environmental impacts*

INTRODUCTION

Orphaned oil and gas wells are a category of unplugged nonproducing wells for which the operator is unknown, unavailable, or insolvent, leaving no responsible party to plug the well and restore the well site other than government agencies and the general public. Orphaned wells can pose a wide range of environmental risks by acting as leakage pathways connecting oil and gas reservoirs to groundwater aquifers and the atmosphere.[1−3] As such, they can be a potential source of groundwater contamination, air pollution, ecosystem degradation, human health impacts, and greenhouse gas emissions, in particular, methane, a potent greenhouse gas.[4−6]

Every year in the United States (U.S.), governments inherit the responsibility to plug and remediate a growing inventory of orphaned wells, for which state funding has been insufficient.[7,8] Therefore, in November 2021, the U.S. federal government committed $4.7 billion through the Infrastructure Investment and Jobs Act (IIJA), also known as the Bipartisan Infrastructure Law (BIL), to plug documented orphaned oil and gas wells and remediate and restore well sites across the country. However, there is currently a shortfall of available information to quantify and maximize the environmental benefits of plugging.

The definition of documented orphaned wells is important for the determination of the wells that are eligible for plugging and remediation through the IIJA funding. Orphaned oil and gas wells are a subcategory of unplugged abandoned oil and gas wells. In the U.S. Environmental Protection Agency's greenhouse gas inventory, abandoned wells are defined as unplugged or plugged wells with no recent production.[9] The main difference between an abandoned and an orphaned well is that an orphaned well has no responsible operator, leaving the financial responsibility to plug and remediate the wells to states, other government agencies, and the general public (Table 1). In addition, an orphaned well can have the meaning or term used by a state to describe a well in need of plugging, remediation, or reclamation. Only "documented" orphaned

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Table 1. Summary of Orphaned and Abandoned Oil and Gas Well Definitions

Well status	Production	Plugging status	Legal responsible operator	Financial responsibility	Examples of other terms used by states[a]
Abandoned	Nonproducing or not authorized for production	Plugged or unplugged	Active and able to plug and remediate the well	Operator	Suspended, shut-in, temporarily abandoned, inactive, idle
Orphaned	Nonproducing or not authorized for production	Unplugged	Unknown, unavailable, or insolvent and is unable to plug or remediate the well	State, other government agency, and/or the general public	Abandoned, revoked, forfeited, unknown, shut-in

[a]The terms are based on documented orphaned well data compiled as of January to April 2022. State-specific terms can be found in Table S4.

wells will be addressed through the IIJA. In general, a documented orphaned well is a well that is documented in state databases and that has gone through some internal state verification process to determine the well as being orphaned. However, these verification processes vary substantially among states, creating inconsistencies in documented orphaned well definitions across the U.S. On the other hand, the Interstate Oil and Gas Compact Commission (IOGCC) refers to an "undocumented orphaned well" as a well that is typically unknown to the state or a well that requires further verification to determine the well as being orphaned.[10]

Although oil and gas well locations and some attributes are recorded in state databases, orphaned well definitions and statuses, as well as the content of the well databases, vary widely among states, making it challenging to compile a national orphaned well data set. As of June 2022, the U.S. Geological Survey (USGS) identified 117,672 documented orphaned oil and gas wells across 27 states in the U.S.[11] Although the data set contains well type (e.g., oil, gas, or combined oil and gas) and geographic location information, well type data is only available for 49% of the documented orphaned wells, and the data set does not provide other well attributes such as well depth or the date on which the well last produced (or "last production date"). Moreover, the dates for each state vary substantially from July 2019 to June 2022 and are not well suited to analyze temporal variations. Other recent efforts to document the number of orphaned wells in the U.S. have relied on state survey responses and state databases that are unmapped. The IOGCC places the total number of documented orphaned wells in the U.S. to be 92,198 as of December 31st, 2020 and 131,227 as of November 15th, 2021.[10] Despite the 40% increase in orphaned well numbers in the order of months, no additional information is provided on orphaned well attributes (e.g., geographic location, well type, well depth, or last production date). However, the IOGCC provides high level explanations behind the increase in documented orphaned well numbers for a few states (Table S1). For most states, the increase is due to the review of existing databases and of new well inventories, additional field inspections, and bankruptcy of oil and gas companies. Overall, there is a need to analyze documented orphaned well locations and their attributes and evaluate how they may change over time.

The analysis of well attributes is important for estimating the cost of well plugging, determining leakage and emission potential, and better understanding the extent of environmental impacts.[5,12−14] For example, for all abandoned wells, gas wells have been shown to emit methane at higher rates than oil or combined oil and gas wells.[6] However, well attributes such as well type (e.g., oil, gas, or combined oil and gas), well depth, or date on which the well last produced (or "last production date") have not been analyzed specifically for orphaned wells. Therefore, there is a need to understand the extent to which our knowledge of the broader category of abandoned wells can be applied to orphaned wells.

Understanding the role of well attributes and other factors, such as oil/gas prices, on the number of newly orphaned wells may provide insight into why and when wells are becoming orphaned. For example, a study found a large spike in orphan well numbers in Alberta when oil prices dropped in 2016 to 2018.[3] To our knowledge, state oil and gas agencies or other data sources do not track the number of documented orphaned wells over time. As such, the relationship of well attributes and other factors (e.g., bankruptcy of oil and gas companies and introduction of new policies) on the number of newly orphaned wells is poorly understood. Therefore, there is a need to better understand when and at what time scale wells become orphaned to optimize policies and mitigation strategies to limit the number of wells becoming orphaned in the future.

In this paper, we provide two previously unavailable national geospatial data sets for documented orphaned oil and gas wells in the U.S., along with (1) a comparison of the numbers and geographical distribution of documented orphaned oil and gas wells over time, including before and after the IIJA enactment; (2) the number and location of potentially documented orphaned oil and gas wells before the IIJA enactment that may provide insight into future increases in the number of documented orphaned wells; (3) estimates of methane emissions from documented orphaned and potentially documented orphaned wells; (4) an analysis of documented orphaned well attributes (well type, well depth, and last production date); and (5) a comparison of oil prices with changes in the number of newly orphaned wells. This data set and the associated results can lead to the development of cost-effective mitigation strategies, inform government policies, and improve our understanding of the environmental impacts of orphaned wells.

Importantly, there are likely hundreds of thousands of orphaned wells, if not millions, in the U.S. alone that remain undocumented. Therefore, the development of effective policies and understanding the environmental impacts of documented orphaned wells are needed to develop long-term management plans for the ∼100,000 to ∼1,000,000 undocumented orphaned wells in the U.S. and many millions around the world.

MATERIALS AND METHODS

We define documented orphaned oil and gas wells as unplugged, nonproducing or abandoned wells identified by states as orphaned, thereby indicating that there is no associated responsible party other than the state (Tables 1 and S2). Depending on state's definitions and statuses, orphaned wells can encompass wells that are deemed

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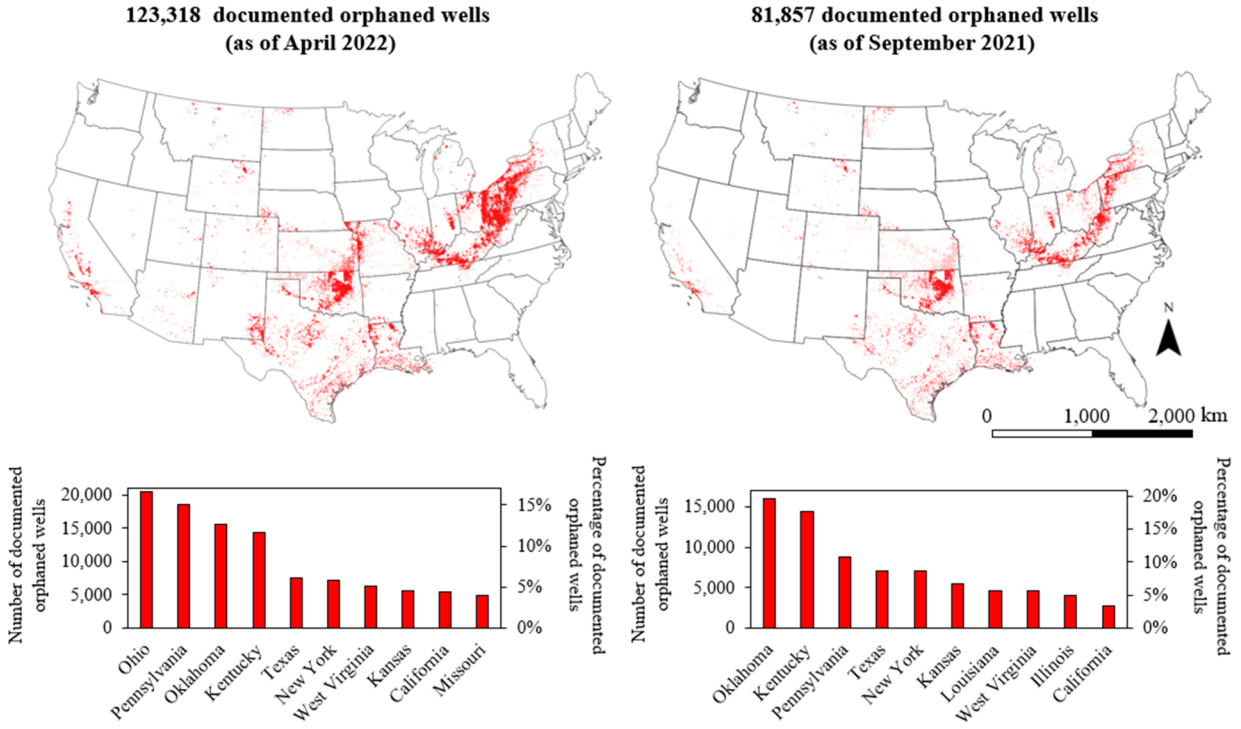

Figure 1. Distribution of documented orphaned oil and gas wells across the U.S. based on state databases as of April 2022 (left) and September 2021 (right).

"abandoned", "revoked", "unknown", "shut-in", or "forfeited" by states (Tables S3 and S4). Orphaned wells on federal or tribal lands not in state databases were not considered in this study.

To determine the number and attributes of documented orphaned wells, we collect information from online state databases. The source of each of these databases is provided in Tables S3 and S4. Even if they cannot be located exactly (i.e., with latitude/longitude coordinates), the wells are considered to be "documented orphaned" because the state agency has knowledge of the well's existence and has undergone some internal verification process such as database analysis. When information on documented orphaned well definitions, statuses, or geographic locations could not be retrieved from state online databases, we contacted the corresponding state oil and gas agency to obtain the required information. Where possible, we verified the plugging status of the documented orphaned wells as "unplugged" by consulting the well's plugging status and/or plugging date information.

The documented orphaned and potentially documented orphaned wells with available geographic locations are mapped using *ArcMap*. We quality control the data sets using *ArcMap* to verify that the wells are located within state boundaries and through comparison with available coordinates in the *Enverus* well database for wells with corresponding American Petroleum Institute (API) numbers. We identify duplicate wells on the basis of geographic locations and well attributes and API numbers representing different well events. Detailed steps taken to quality control the data sets are described in Figure S3 and Tables S15−S20.

We identify potentially documented orphaned wells as wells recorded in state databases as "potentially orphaned" or as "abandoned" wells with "unknown" or "unavailable" operator status but not officially considered orphaned by the state as of September 2021 (Table S5). These wells are not considered "documented orphaned wells" and are not in our 2021 data set. However, we determine the number of potentially documented orphaned wells as of September 2021 that are now in the April 2022 data set.

When geographic location, well type, well depth, or last production date was unavailable from state databases, we obtained the data from the proprietary *Enverus* well database using API numbers. In this study, only data on well locations and attributes unavailable from public state databases were supplied from the *Enverus* well database. The *Enverus* well database does not identify wells that have been verified by states and that can be considered as "documented orphaned wells". For Kansas, the well locations are approximated on the basis of the geographic centroid of the section, township, and range information provided by the oil and gas regulatory agency.

We estimate the annual methane emissions for the 123,318 documented orphaned wells (as of April 2022), the 81,857 documented orphaned wells (as of September 2021), and the potentially documented orphaned wells (as of September 2021) by using methane emission factors for unplugged oil and gas wells in the U.S. developed by Williams et al.[6] Methane emissions are estimated for five different scenarios with region-, basin-, and well type-specific emission factors on the basis of available well type information (oil and combined oil and gas, gas, and unknown) (Tables S8 and S9). We do not directly account for time-variant emission factors in our estimate and assume that the measurements used in developing the emission factors are taken at different times and average out at the national scale. The five scenarios developed in Williams et al.[6] assign emission factors on the basis of various regions with each region having three different emission factors based on the well type category (gas, oil, combined oil and gas, and unknown). The first "Total" scenario includes nationwide emission factors, while the second "Region" scenario assigns

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emission factors from region-specific studies for five states (Oklahoma, Pennsylvania, Utah, West Virginia, Colorado) and nationwide emission factors to the remaining states. In the third "East/West" scenario, emission factors are attributed to broad eastern and western regions in the U.S., while the fourth "North/South" scenario assigns emission factors to broad northern and southern regions in the U.S. Lastly, in the fifth "Basin" scenario, emission factors are assigned to states on the basis of their location in five different oil and gas basins.

Finally, we evaluate how the number of wells orphaned in Texas, Louisiana, Pennsylvania, and Wyoming vary with annual (2000 to 2021) and monthly (January 2020 to May 2021) oil prices by determining the correlation coefficients. We retrieve annual and monthly oil price data from the U.S. Energy Information Administration.[15]

RESULTS

Number of Documented Orphaned and Potentially Documented Orphaned Wells. We find the total number of documented orphaned wells in the U.S. to be 81,857 as of June to September 2021 and 123,318 as of January to April 2022, representing 2% and 3%, respectively, of all estimated abandoned wells in the United States.[6,9] Of the 81,857 documented orphaned wells as of September 2021, 96% (78,685) have location information and 814 of these locations were unavailable from state databases and provided by the *Enverus* well database. Similarly, for the 123,318 documented orphaned wells as of April 2022, 98% (120,481) have location information and 4,916 of these locations were unavailable from state databases and provided by the *Enverus* well database. Our documented orphaned well counts only include wells considered to be documented orphaned by states and eligible for IIJA funding, meaning that our number does not include potentially orphaned wells, undocumented orphaned wells, or estimates based on expert opinion. Furthermore, compared to the number of documented orphaned wells reported by the IOGCC, our compilation does not rely on state surveys and instead relies on state databases and records with documentation on each orphaned well. Furthermore, our data set contains a larger number of documented orphaned wells and spans more states compared to the USGS documented orphaned well data set.

The overall spatial trends for both the September 2021 and the April 2022 data sets are similar (Figure 1). On the basis of the most recent estimate of 123,318 documented orphaned wells (as of April 2022), states with the highest number of documented orphaned wells are Ohio (17%), Pennsylvania (15%), Oklahoma (13%), and Kentucky (12%), which collectively account for 56% of the total number of documented orphaned wells in the U.S. (Table S4). On the basis of the 81,857 documented orphaned wells (as of September 2021), Oklahoma (20%), Kentucky (18%), Pennsylvania (11%), and Texas (9%) collectively account for 56% of the September 2021 count of documented orphaned wells (Figure S1 and Table S3). The main change is the large increase in the number of documented orphaned wells in Ohio (+19,649) between September 2021 and April 2022. Furthermore, Pennsylvania and Kentucky collectively contain 28% of the September 2021 and the April 2022 count of documented orphaned wells.

We find an increase of 41,461 (51%) documented orphaned wells in the six months between September 2021 and April 2022. We presume that the main driver for the increase in orphaned well numbers was the announcement of the IIJA in November 2021, which may have incentivized states to identify documented orphaned wells eligible for federal funds for plugging and remediation. However, there may be other drivers for the increase in orphan well numbers such as bankruptcies,[3] which may be related to oil and gas prices. The states with the largest increase in documented orphaned wells are Ohio (+19,649), Pennsylvania (+9,673), Missouri (+4,812), California (+2,579), New Mexico (+1,771), and West Virginia (+1,723). The increase in the number of documented orphaned wells is most noticeable across the Appalachian Region (Figure 1). Furthermore, Arizona and South Dakota, which were not included in the first documented orphaned well count due to lack of data, are included in the April 2022 well count. As such, we identify documented orphaned wells across 28 states as of September 2021 and across 30 states as of April 2022.

As of September 2021, we estimate the total number of potentially documented orphaned wells (which are wells identified as "potentially orphaned" or as "abandoned" wells with "unknown" operators by states) in the U.S. to be 20,286 across 10 states on the basis of our analysis of state oil and gas databases. Potentially documented orphaned wells represent 0.5% of all estimated abandoned wells in the country (Table S13).[6,9] These are wells that are not considered orphaned by the state and for which federal funding (IIJA) to plug them are not applicable. California and Alabama contain 79% of all potentially documented orphaned wells in the nation. The remaining potentially documented orphaned wells are located in eight other states including Pennsylvania, Kentucky, and Kansas (Figure S1 and Table S5).

Only 8% (1,683) of the potentially documented orphaned wells identified in September 2021 became documented orphaned wells as of April 2022. These wells are mostly located in California (75%) and Pennsylvania (21%), while the remaining wells are located in Kentucky (38), Colorado (16), Nebraska (4), Alabama (3), and Montana (1) (Table S5). In Pennsylvania, 30% (351) of the potentially documented orphaned wells are documented orphaned wells as of April 2022. Similarly, in California, 11% (1,270) of the potentially documented orphaned wells are documented orphaned wells as of April 2022. Therefore, 18,603 (92%) potentially documented orphaned wells as of September 2021 remain potentially documented orphaned wells in April 2022, indicating that our definition of potentially documented orphaned wells may only be a good indicator of wells in Pennsylvania and California to be documented orphaned wells in the future.

Methane Emissions. Annual methane emissions for the 81,857 documented orphaned wells as of September 2021 average at 0.0096 MMt of CH_4 and range between 0.0093 MMt of CH_4 (North/South Scenario) and 0.0103 MMt of CH_4 (Region Scenario) using the emission factors and scenarios developed in Williams et al. (Figure 2 and Table S10).[6] For the 123,318 documented orphaned wells as of April 2022, we find annual methane emissions to average at 0.016 MMt of CH_4 and range between 0.015 MMt of CH_4 (North/South Scenario) and 0.017 MMt of CH_4 (Region Scenario) (Table S11). For the 20,286 potentially documented orphaned wells as of September 2021, annual methane emissions average 0.0025 MMt of CH_4 and range between 0.0024 MMt of CH_4 (Basins Scenario) and 0.0027 MMt of CH_4 (North/South Scenario) (Table S12). The U.S. Environmental Protection

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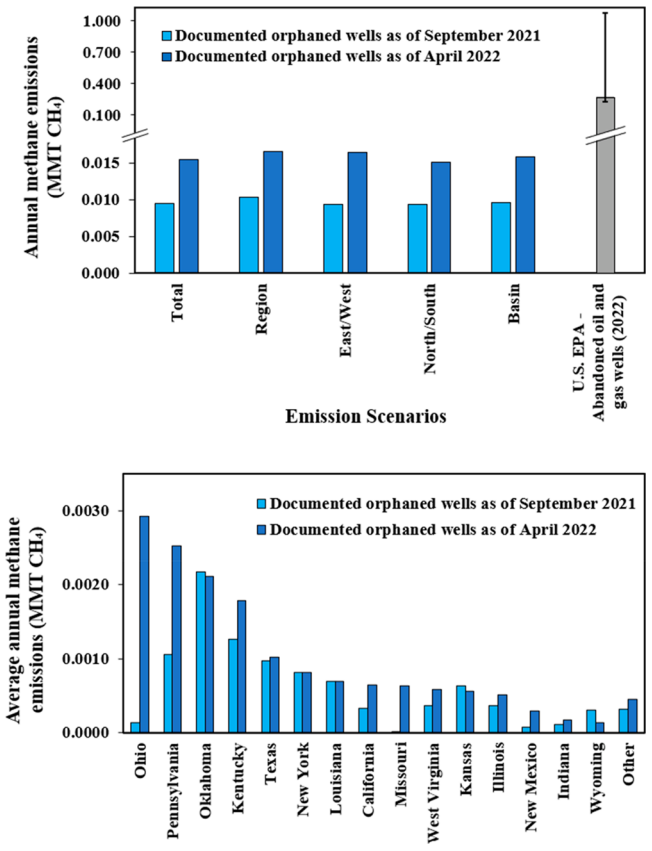

Figure 2. Total annual methane emissions by scenarios developed in Williams et al.[6] with methane emissions and emissions uncertainty for abandoned wells by the U.S. EPA[9] (top) and distribution of annual methane emissions by state for the average of all five scenarios (bottom). All emission scenarios are described in Table S8.

Agency (EPA) estimates total methane emissions from abandoned oil and gas wells to be 0.276 MMt of CH_4.[9] Therefore, documented orphaned wells as of April 2022 represent 5−6% and potentially documented orphaned wells represent 0.9% of the total methane emissions estimated by the U.S. EPA for all abandoned oil and gas wells. If we include undocumented orphaned wells, methane emissions from orphaned wells may contribute as high as 36% of the total methane emissions from abandoned wells (Table S13). We note that the states with the highest proportion of methane emitted annually correspond to the states with the highest number of orphaned wells.

Well Attributes. On the basis of the available information from state databases and the *Enverus* well database, we determine the well type, well depth, and last production date for the documented orphaned wells compiled as of September 2021. Of the total number of documented orphaned wells as of September 2021 (81,857), 83% (67,866) have information on well type, 49% (40,108) on well depth, and 16% (13,286) on last production date (Figures 3 and S2 and Table S6). No state provides information on all three well attributes for all documented orphaned wells in a state. Out of the 28 states with documented orphaned wells, 26 states have well type information, 23 states have well depth information, and 19 states have last production date information.

Last production date information is available for only 16% of the documented orphaned wells. However, the last production date information may reflect when the orphaned well was documented in the state databases instead of indicating when the well last produced. The most recent last production date is September 2021 and the earliest is February 1931. The average last production date is December 2005, and the median is December 2008. The largest proportion of documented orphaned wells (5,582 or 42% of documented orphaned wells with available information) has a last production date after 2010. The year with the largest number of last production dates for documented orphaned wells (750) is 2018. Therefore, available last production dates may be biased toward more recent dates.

We combine well status date information (date the status of the well was last updated to orphaned) (available for 23% (19,021) of the documented orphaned wells) and last production date information to determine when these wells may have become orphaned (or "orphaned date"). Orphaned date information likely reflects changes in data management and record keeping practices and might not reflect when the well was orphaned. The most recently documented orphaned well was in September 2021 and the oldest, in January 1911, which is earlier than the oldest production date of February 1931 by 20 years. The largest proportion of documented orphaned wells with orphaned date information were orphaned after 2010, accounting for 29% of all documented orphaned wells. Approximately 14% of the documented orphaned wells were orphaned between 2016 and 2020, while the largest number of newly documented orphaned wells (10%) in any year was recorded in 2013. About 92% of the wells newly orphaned in 2013 were orphaned in Pennsylvania on January 1st. This corresponds to the orphaned date of 89% of the documented orphaned wells in Pennsylvania and the earliest orphaned date in the state. As such, the high number of wells orphaned on January 1, 2013, in Pennsylvania most likely reflects data management practices within the state. Therefore, our results indicate that combining well status date and last production date information may not accurately reflect the orphaned date of a well. However, even if well status dates and last production dates are not widely available and may be highly uncertain, they may be useful in better understanding documented orphaned well characteristics.

We compare annual (2000 to 2021) and monthly (January 2020 to May 2021) oil prices[15] with available orphaned date information for Texas, Louisiana, Pennsylvania, and Wyoming (Figure 4). By visual inspection, the available data does not consistently show that low oil prices lead to more wells becoming orphaned. However, in Texas and Louisiana, the highest proportion of wells became orphaned between 2016 and 2020 when annual oil prices were low compared to the average 2000−2021 oil price. In Wyoming, the highest proportion of wells became orphaned in 2009, which coincides with a sharp decline in oil prices. At both the annual and monthly time scale, we do not find statistically significant relationships ($-0.4 <$ Spearman correlation coefficient < 0.4) between oil price and changes in the number of orphaned wells (Table S14). However, additional data and analysis is needed to understand the role of oil price on changes in the number of orphaned wells as our data is limited to a few years and does not cover all states. Moreover, other factors may be impacting the number of orphaned wells such as gas prices, bankruptcies of oil and gas companies, and policies. Overall, there is a need to better understand the relationship between the temporal variation in the number of newly orphaned wells and factors potentially contributing to wells becoming orphaned.

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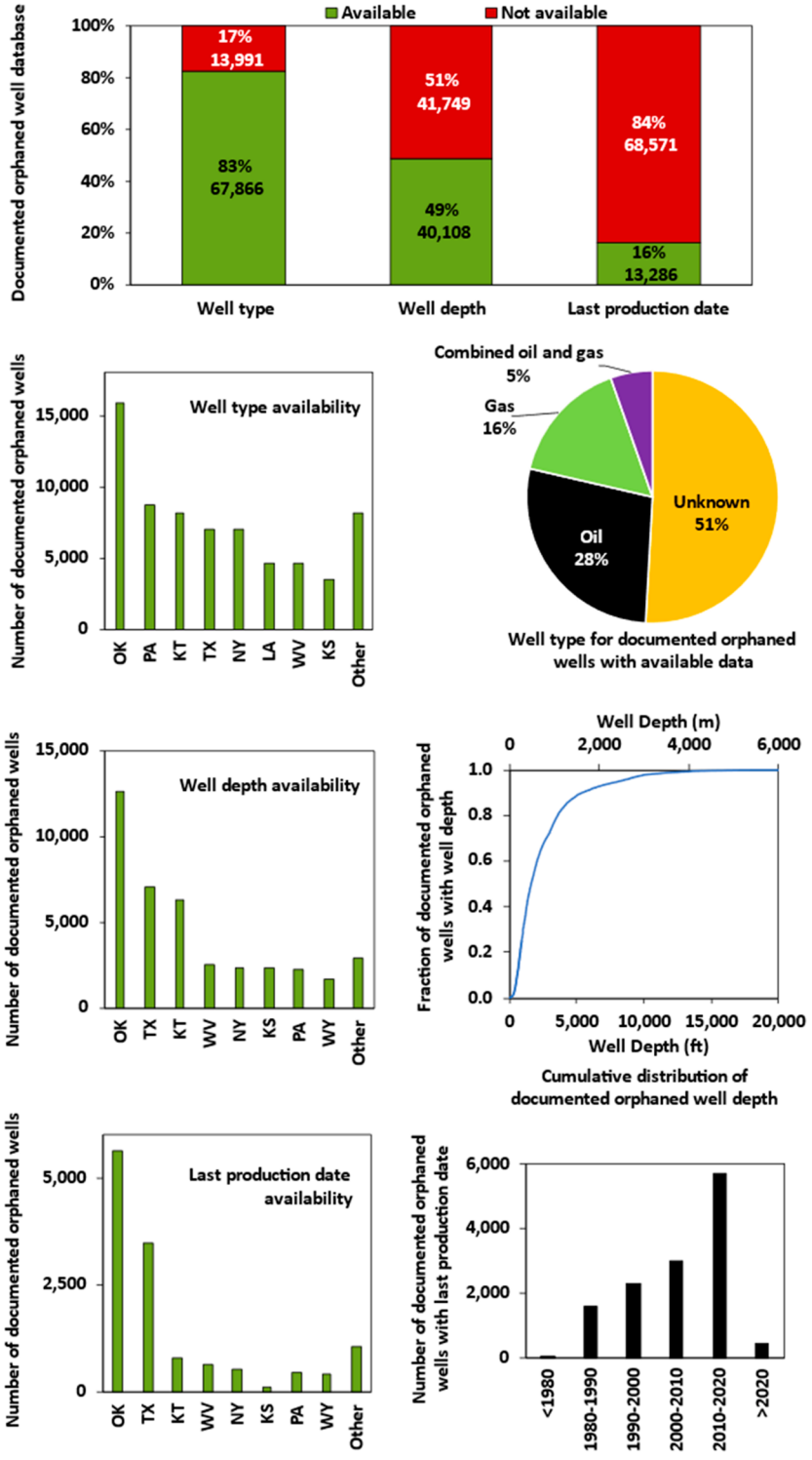

Figure 3. Well attribute availability for the 81,857 documented orphaned oil and gas wells as of September 2021 (top); availability of well type, well depth, and last production date per state (left column); pie chart of well type distribution (top right column); cumulative distribution of well depth (middle right column); histogram of last production date (bottom right column).

On the basis of the well depth information available for 49% of the documented orphaned wells, the depths of documented orphaned wells range from as deep as 4.4 mi (7.1 km) to as shallow as 20 ft (6 m), while the average depth is 2,474 ft (754 m) and the median depth is 1,606 ft (490 m) (see Table S7 for quality control of depth data). The deepest well is a well of unknown type in Oklahoma, while the next deepest well is a 4.3 mi (7.0 km) deep gas well in Texas. Only 5% of the documented orphaned wells are deeper than a mile with the largest proportion of these deeper wells located in Texas (55%) and Oklahoma (25%).

We estimate from the total number of documented orphaned wells with well type information (67,866) that 16% are gas wells, 28% are oil wells, 5% are combined oil and

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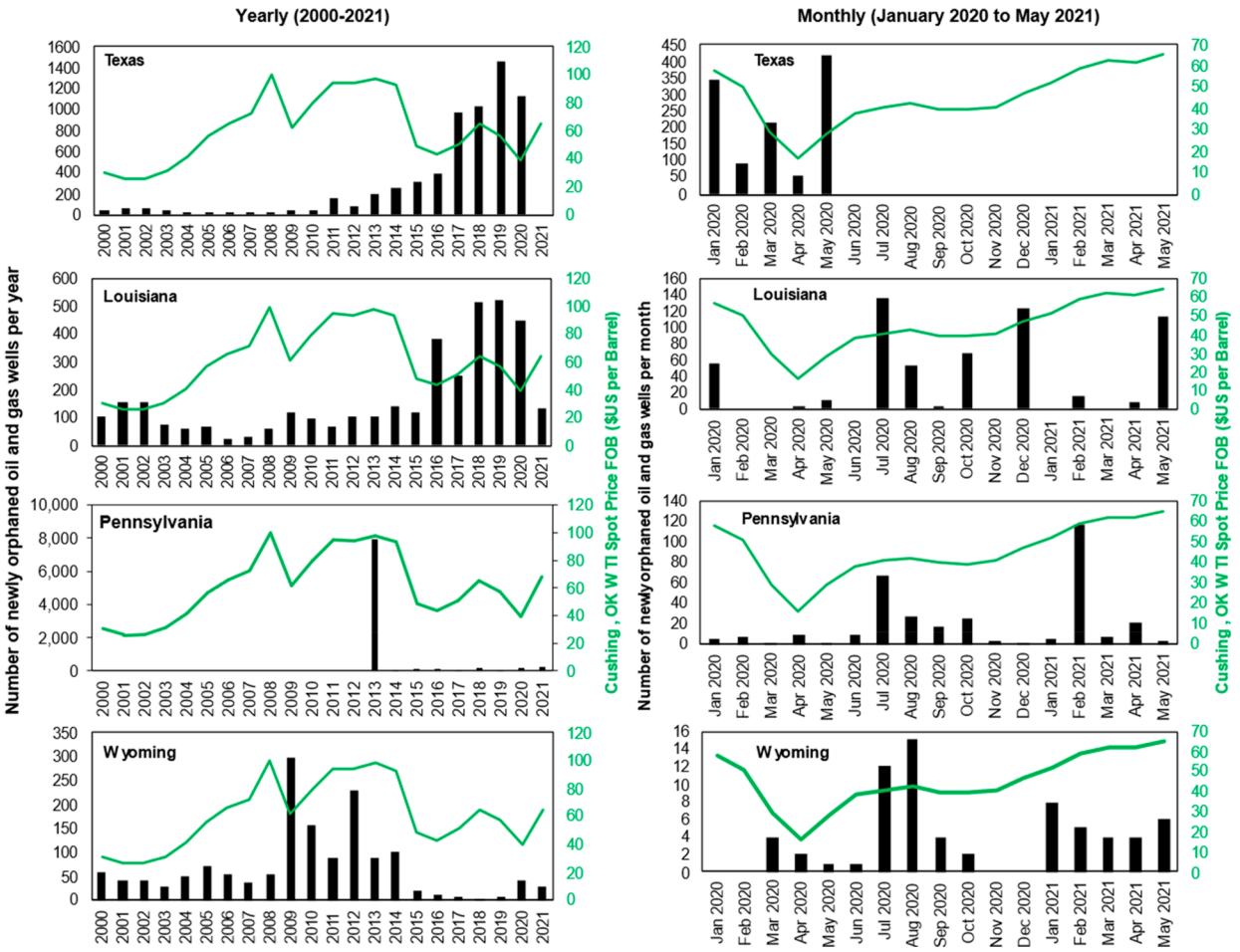

Figure 4. Orphaned dates by year (left column) and month (right column) for documented orphaned oil and gas wells in Texas, Louisiana, Pennsylvania, and Wyoming with available orphaned date information as of September 2021. Years/months indicating no wells orphaned are years/months with no available data.

gas wells, and 51% are of unknown well type. Compared to the well type distribution of all abandoned oil and gas wells in the U.S., there are 13% more documented orphaned wells with an unknown well type, 8% fewer gas wells, and 5% fewer oil and combined oil and gas wells.[6]

DISCUSSION

The number of documented orphaned and potentially documented orphaned wells found in this study most likely represents a lower bound of the total number of existing orphaned oil and gas wells in the U.S., mainly because they do not include undocumented orphaned wells. The IOGCC estimates the total number of undocumented orphaned wells to be between 310,000 and 800,000,[10] while other studies suggest much higher numbers.[16] Undocumented orphaned wells were likely orphaned before the existence of regulatory oversight from state oil and gas agencies. Thus, it is critical to find and document orphaned wells that are not in current state databases so that they can be addressed through plugging and site remediation. However, understanding the role of documented orphaned well attributes on environmental impacts is useful for developing policies and long-term management strategies for both documented and undocumented orphaned wells that exist today and will exist in the future.

Our results suggest that newly documented orphaned wells as of April 2022 are located near documented orphaned wells as of September 2021 and in regions of known historical oil and gas activity (e.g., Pennsylvania, New York, Ohio). As such, it may be beneficial to prioritize regions with a high density of documented orphaned wells or regions containing legacy wells when identifying undocumented orphaned wells across the U.S. Furthermore, our identification of more than a thousand potentially documented orphaned wells (wells identified in state databases as "potentially orphaned" or "abandoned" wells with an "unknown" or "unavailable" operator status) that became documented orphaned wells within a few months could provide guidance to states and policymakers for the identification of wells at risk of becoming orphaned.

We find that documented orphaned well attributes, specifically well type, last production date, orphaned date, and well depth, remain unavailable for many documented orphaned oil and gas wells across the U.S. These well attributes may not have been recorded by states or may be available in nondigitized records. Even when well type information is available, the well type of many documented orphaned wells is reported as "unknown". Moreover, the shallower depths of orphaned wells may mean that plugging costs may be lower for orphaned wells than other abandoned wells; however, this may change as deeper active wells become orphaned, and orphaned wells may be more challenging to plug due to other reasons

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such as access and well condition. A large fraction of documented orphaned wells with date information have orphaned dates and last production dates in the past decade. However, the last production date is missing for a vast majority of the documented orphaned wells, and thus, the observed trend in dates likely indicates a bias toward newly documented wells. Although last production dates and orphaned dates are difficult to obtain and may be highly uncertain, these dates may provide helpful insight on documented orphaned well characteristics and guide future efforts to compile date information.

The determination of the well attributes explored in this paper (well type, last production date, orphaned date, and well depth) along with others, such as gas-to-oil ratio, wellbore deviation, geology, operator, and density of wells,[14] is needed to develop strategies to optimize wells for mitigation. Moreover, the role of many of these factors on methane emissions and broader environmental impacts of orphaned wells needs further research. Overall, there is a lack of knowledge on orphaned wells, even those that are documented, due to incomplete government databases. In other words, in addition to finding undocumented orphaned wells, there is a need to better characterize documented orphaned wells.

The number of documented orphaned wells and their attributes can be affected by various factors including the introduction of new policies, improvements in state data management, bankruptcies of oil and gas companies, and oil and gas prices. Our data sets of documented orphaned wells only provide snapshots in time, and we may be missing important temporal trends. Therefore, we cannot yet fully understand when and at what time scale wells may become orphaned. Although one study found a large spike in orphan well numbers in Alberta when oil prices dropped in 2016 to 2018,[3] we do not find similar trends in our data set. There is a need for more studies to understand why and how wells are becoming orphaned so that appropriate policies can be developed to limit the number of wells becoming orphaned in the future. However, there are also many undocumented orphaned wells that already exist, and the documentation of these wells are less likely to be affected by oil price and more likely to be driven by IIJA and the federal funding provided to the U.S. Department of Energy to find and characterize documented orphaned wells. Overall, additional data compilation and analysis are needed to understand temporal variations and to quantify benefits of policies and government spending.

Hundreds of thousands of oil and gas wells, if not over a million, may be orphaned in the U.S. alone. As society transitions away from fossil fuels, the tens of millions of oil and gas wells in the U.S. and around the world are at risk of becoming orphaned, and thus, it is necessary to understand and mitigate the environmental and climate impacts associated with orphaned wells to protect our water, air, ecosystems, and human health.

Policy Implication. In April 2022, the U.S. Department of the Interior (DOI) released guidance to states on activities permissible to be carried out under the grants provided by the IIJA and recommended practices for plugging, remediating, and reclaiming orphaned wells.[17] In the IIJA, while the term "orphaned well" is defined, there are no definitions for "documented orphaned wells", which are wells eligible for plugging, remediation, and reclamation funding, and "undocumented orphaned wells", which are recommended to be identified and characterized by states.

The Interstate Oil and Gas Compact Commission (IOGCC) refers to a "documented orphaned well" as a well for which states have an inspection or other record establishing the existence of the well. In addition, the IOGCC refers to an "undocumented orphaned well" as a well that is entirely unknown to the state or a well that requires further record and field verification. An inventory of wells "at risk of becoming orphaned", which is a term not currently defined in the IIJA, will have to be reported annually to Congress by the Department of the Interior. Here, we define potentially documented orphaned wells, which may be one of several categories of wells at risk of being added to the list of documented orphaned wells.

Among the activities eligible for funding under the IIJA, states may prioritize orphaned wells for plugging and remediation on the basis of factors such as public health/safety, environmental impacts, and land use priorities. As such, ranking systems including factors and associated weights will be state-specific to meet the states' particular needs. Furthermore, under the permissible activities of the grants, states can measure and track surface and groundwater contamination and greenhouse gas emissions, including methane. States are encouraged to follow a third-party methodology for measurement and verification, such as the American Carbon Registry's methodology.[18] However, using methodologies developed for carbon offset registries may be too costly and beyond what is needed to understand state level emissions reductions achieved through plugging. As a complement to the measurement effort, understanding attributes of documented orphaned wells may be useful to cost-effectively estimate methane emissions and design monitoring programs for groundwater contamination and methane emissions.

In 2022, the U.S. Department of Energy (DOE) created a research consortium to identify and characterize undocumented orphaned wells and mitigate their environmental risks. This consortium was provided $30 million USD over 5 years. However, the timeline and funding are unlikely to be sufficient to identify and characterize the estimated 310,000 to 800,000,[10] and possibly million, undocumented orphaned wells across the U.S. The research consortium plans to determine the location, ownership, wellbore integrity, methane emissions, water contamination, and other environmental impacts of undocumented orphaned wells, each of which is challenging and expensive to determine. Our data on documented orphaned wells and analysis of their attributes can be used to develop an efficient and cost-effective framework for the identification and characterization of undocumented orphaned wells. For example, documented orphaned well attributes might provide useful information and a test bed for the development of detection approaches and methodologies for undocumented orphaned wells. Moreover, as with documented orphaned wells, it is important to understand well attributes (e.g., type, depth, age) of undocumented wells. When an undocumented orphaned well is found, the only information likely to be available is its location. However, by looking at the nearby documented orphaned well attributes, we may be able to infer undocumented orphaned well attributes, especially those related to geology. Therefore, our analysis of documented orphaned wells and their attributes can contribute to the characterization of undocumented orphaned wells and lay the

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foundation for long-term management of the growing number of orphaned wells in the U.S. and abroad.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c03268.

Additional data and methods on the number, attributes, methane emissions, and quality control steps for the documented orphaned and potentially documented orphaned wells (XLSX)

2021 Documented orphaned oil and gas well data set (XLSX)

2022 Documented orphaned oil and gas well data set (XLSX)

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Notes

The authors declare no competing financial interest.

The 2021 and 2022 documented orphaned well data sets are available on the McGill Dataverse at https://doi.org/10.5683/SP3/PLAOIX.

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