Characterization and renewable energy potential of abandoned and orphaned oil and gas wells across Canada and the United States

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Abstract

There are millions of abandoned and orphaned oil and gas wells across Canada and the United States. Abandoned wells no longer produce oil and/or gas, and thus, in general, operators are not financially incentivized to plug and remediate the wells and associated sites. As a result, there are many orphaned wells, which are a subset of abandoned wells that have no responsible party, leaving the financial responsibility to plug and remediate the wells to government agencies and the general public. Abandoned and orphaned wells can degrade ecosystems, contaminate water sources, impact human health, and emit air pollutants including methane, a potent greenhouse gas. However, the risks posed by abandoned and orphaned wells can be reduced by plugging and remediation. Converting abandoned and orphaned wells to solar, wind, or geothermal energy production could provide funding for mitigation, which is needed to repurpose the land, remove and restore existing infrastructures and plug the well, all of which provide environmental benefits and stimulate the economy. However, there is currently a shortfall of available information on abandoned and orphaned wells and their characteristics to mitigate their environmental impacts and determine how they could be converted for clean energy production.

First, we analyzed 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 found 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. Furthermore, we estimated annual methane emissions to average 0.016 MMt of methane for the 123,318 documented orphaned wells as of April 2022, corresponding to 5% of the total methane emissions estimated by the U.S. Environmental Protection Agency for all abandoned wells. For the attributes of the 81,857 documented orphaned wells as of September 2021, we find that although well type (i.e., oil vs gas) is available for 83% of the wells, about half (51%) of the available well type are reported as “unknown”, meaning that well type is only known for 41% of the 81,857 documented orphaned wells. Furthermore, only 49% and 16% of the documented orphaned wells as of September 2021 have information on depth and last

production date, respectively. Our analysis revealed that documented orphaned wells require additional characterization and studies to constrain the uncertainties and optimize mitigation.

Second, we analyzed maps of renewable energy potential and oil and gas well data across Canada and the United States to assess the nation-wide potential for wind, solar, and geothermal energy production at abandoned and orphaned well locations. We estimated the total number of abandoned and orphaned wells in Canada and the United States to be 3,746,078, of which 3% are orphaned and in need of government funding. We find that abandoned and orphaned wells differ in spatial patterns and renewable energy potential. We show large wind (> 400 W/m^2) and solar (> 1,600 kWh/kWp) energy potential at more than one million abandoned and orphaned well sites. More than 90% of abandoned and orphaned wells with available depth are better suited for hydrothermal systems, yet enhanced geothermal is possible at up to 10% of the wells. Repurposing these wells can help fulfill national energy transition goals and emission reduction targets, while providing additional funding for mitigation.

Overall, additional studies are required to further identify and characterize the millions of abandoned and orphaned wells that exist across Canada and the United States. Nonetheless, our identification and analysis of documented orphaned wells in the United States represent the first steps toward characterizing the full set of wells eligible to be plugged and remediated with the federal funding available via the Bipartisan Infrastructure Law in the United States. Furthermore, our assessment of the nation-wide potential for wind, solar, and geothermal energy production at abandoned and orphaned well locations can help fulfill and finance the U.S. and Canada's energy transition goals – shifting away from polluting fossil fuel resources and providing funding for managing the legacy of the millions of non-producing wells across the two nations and the world.

Résumé

Il existe des millions de puits pétroliers et gaziers abandonnés et orphelins au Canada et aux États-Unis. Les puits abandonnés ne produisent plus de pétrole et/ou de gaz et donc, en général, les propriétaires ne sont pas incités financièrement à sceller et nettoyer les puits et à remettre en état les sites connexes. Par conséquent, il existe de nombreux puits orphelins, qui représente un sous-ensemble de puits abandonnés ayant des propriétaires introuvables ou incapables de nettoyer les puits, laissant la responsabilité financière du colmatage et de la remise en état aux gouvernements et au grand public. Les puits abandonnés et orphelins posent des risques environnementaux puisqu'ils sont susceptibles de contaminer les sources d'eau, de détériorer les écosystèmes et d'émettre du méthane et d'autres polluants atmosphériques. Cependant, les risques posés par les puits abandonnés et orphelins peuvent être réduits grâce au colmatage des puits et la remise en état des terrains. La réaffectation des puits abandonnés et orphelins à la production d'énergie solaire, éolienne ou géothermique pourrait fournir un flux de financement pour la fermeture définitive des puits, ce qui inclut la décontamination des terrains, la restauration d'infrastructures existantes et le scellement des puits. Cependant, il existe actuellement un manque d'information sur les caractéristiques des puits abandonnés et orphelins pour nous permettre de réduire leurs impacts environnementaux et déterminer la façon dont on pourrait y installer des structures à production d'énergie renouvelable.

Premièrement, nous avons analysé des données publiques sur les puits de pétrole et de gaz provenant d'organismes gouvernementaux à travers les États-Unis afin d'estimer le nombre de puits orphelins répertoriés au fil du temps et d'évaluer leurs attributs. Nous avons trouvé 81,857 puits orphelins répertoriés en date de septembre 2021 et 123,318 en date d'avril 2022, ce qui représente 2% et 3% respectivement de tous les puits abandonnés estimés aux États-Unis. De plus, nous avons estimé que les émissions annuelles de méthane s'élevaient en moyenne à 0.016 MMt de méthane pour les 123,318 puits orphelins répertoriés en avril 2022, ce qui correspond à 5% des émissions totales de méthane estimées par l'Environmental Protection Agency des États-Unis pour tous les puits abandonnés. En ce qui concerne les attributs des 81,857 puits orphelins répertoriés en date de septembre 2021, nous constatons que le type de puits (pétrole et/ou gaz) est généralement disponible (83%), tandis que la profondeur et la

dernière date de production est disponible pour seulement 49% et 16% des puits respectivement. Notre analyse révèle que les puits orphelins répertoriés nécessitent une caractérisation et des études supplémentaires pour limiter les incertitudes et accélérer leur remise en état.

Deuxièmement, nous avons analysé des cartes de potentiel d'énergie renouvelable et des données publiques sur les puits pétroliers et gaziers à travers le Canada et les États-Unis afin d'évaluer le potentiel pour la production d'énergie éolienne, solaire et géothermique aux emplacements de puits abandonnés et orphelins. Nous avons estimé que le nombre total de puits abandonnés et orphelins au Canada et aux États-Unis s'élève à 3,746,078, dont 3% sont orphelins et ont besoin de financement gouvernemental pour la remise en état. Nous constatons que les puits abandonnés et orphelins diffèrent dans leurs distributions spatiales et leurs potentiel en production d'énergie renouvelable. Nous montrons un grand potentiel énergétique éolien (> 400 W/m^2) et solaire (> 1,600 kWh/kWp) pour plus d'un million de puits abandonnés et orphelins. Plus de 90% des puits abandonnés et orphelins avec une profondeur connue sont mieux adaptés aux systèmes géothermiques hydrothermaux, mais un système de géothermie améliorée (EGS) est possible pour 10% des puits. La réaffectation de ces puits à la production d'énergie renouvelable peut aider à atteindre les objectifs nationaux de transition énergétique et les cibles de réduction d'émissions de gaz à effet de serre tout en fournissant un flux de financement supplémentaire pour la remise en état.

Pour conclure, des études supplémentaires sont nécessaires pour mieux identifier et caractériser les millions de puits abandonnés et orphelins qui existent au Canada et aux États-Unis. Néanmoins, notre identification et analyse des puits orphelins répertoriés aux États-Unis représentent un premier pas vers la caractérisation de l'ensemble des puits admissibles à être colmaté grâce au financement fédéral disponible via le Bipartisan Infrastructure Law. De plus, notre évaluation du potentiel de la production d'énergie renouvelable à l'emplacement de puits abandonnés et orphelins peut contribuer à atteindre et à financer les objectifs de transition énergétique des États-Unis et du Canada – s'éloigner des ressources polluantes tel que le pétrole et le gaz et fournir des fonds pour gérer l'héritage des millions de puits inactifs au Canada, aux États-Unis et ailleurs dans le monde.

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Contributions of Authors

Chapter 3 of this thesis corresponds to the paper “Documented orphaned oil and gas wells across the United States”, which was published in *Environmental Science and Technology* in September 2022. It is co-authored by Adam S. Peltz and Renee McVay from the Environmental Defense Fund and my supervisor, Prof. Mary Kang, from the Department of Civil Engineering at McGill University. Chapter 4 of this thesis, named “Converting abandoned and orphaned oil and gas wells for renewable energy production in Canada and the United States” is in preparation for submission to a peer-reviewed scientific journal. This work is co-authored by Prof. Mary Kang. In Chapter 3 and 4, the research, analysis, and writing are my own, with Prof. Mary Kang assisting in the conceptualization, analysis, and writing of the papers.

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1. Introduction

1.1. Importance of analyzing abandoned and orphaned oil and gas wells

Oil and natural gas are one the world's primary sources of fuel and are used to propel vehicles, heat buildings, and produce electricity around the world (International Energy Agency, 2023). As society transitions away from polluting and depleting oil and gas sources and towards renewable energy, there will be an increasing number of oil and gas wells that will cease to produce oil and gas and thus, becoming abandoned or orphaned. Abandoned wells no longer produce oil and/or gas, and thus, in general, operators are not financially incentivized to plug and remediate abandoned wells and associated sites. As a result, there are many orphaned wells, which are a subset of abandoned wells that lack a financial responsible party other than government agencies and taxpayers. All oil and gas wells pose a threat to the environment and climate; non-producing oil and gas wells pose a risk to our water, air, and ecosystems, and can emit methane, a potent greenhouse gas. There is a need to analyze and characterize abandoned and orphaned oil and gas wells to better understand the extent of their environmental impacts, develop strategies for mitigation, and find opportunities to repurpose the wells and sites for renewable energy production. Therefore, research on abandoned and orphaned oil and gas wells will become increasingly important as governments seek to limit greenhouse gas emissions and expand the use of renewable energy. In this thesis, we compile and analyze geospatial data on abandoned and orphaned wells across Canada and the United States (U.S.) to inform policy makers, mitigation strategies, and federal spending.

1.1.1. Mitigating abandoned and orphaned oil and gas wells in the context of climate change

The impacts of climate change are being felt around the world and are expected to increase in intensity and frequency with continued emissions of greenhouse gas emissions to the atmosphere (Intergovernmental Panel on Climate Change, 2021). Anthropogenic activities, such as oil and gas production, are major contributors of greenhouse gas emissions and can exacerbate the impacts of climate change, which include rising temperatures, extreme weather events, natural disasters, ecosystem degradation, biodiversity loss, and scarcity of natural resources. Oil and gas currently supply more than 50% of the world's energy (International Energy Agency, 2023) and are one of the largest contributors to climate change (Intergovernmental Panel on Climate Change, 2022). According to the Intergovernmental Panel on Climate Change (IPCC), emissions from fossil fuels must be halved within the next decade if global warming is to be limited to 1.5°C above pre-industrial levels (IPCC, 2018). Therefore, reducing methane emissions from abandoned and orphaned oil and gas wells will be an important step towards tackling climate change. Determining the location and characteristics of abandoned and orphaned wells can help develop mitigation strategies and frameworks to limit greenhouse gas emissions from the millions of non-producing oil and gas wells that exist in Canada, the United States, and around the world.

1.1.2. Opportunities for abandoned and orphaned oil and gas wells in the face of the renewable energy transition

As called for in the Paris Agreement, global emissions need to be reduced by 45% by 2030 and reach net-zero by 2050 in order to curb the worst effects of climate change. Transitioning to net-zero will require a complete transformation of the global energy system. Replacing oil and gas with renewable energy sources such as wind, solar, and geothermal would drastically reduce emissions. A growing number of countries around the world, including Canada and the United States, are committing to a significant reduction in emissions by 2030 and net-zero emissions by 2050.

In 2022, the Government of Canada published an emissions reduction plan with goals to reduce methane emissions from its largest emitting sector, the oil and gas industry, by at least 40% by 2025 and replace oil and gas with renewable energy (Environment and Climate Change Canada (ECCC), 2022). Similarly, the United States published a sustainability plan with goals of reducing greenhouse gas emissions by 50% before 2030 and reaching net-zero emissions by 2050 (Office of the Federal Chief of Sustainability Officer, 2021). In addition, the U.S. plans to reduce methane emissions from the oil and gas sector, invest in the remediation of abandoned and orphaned oil and gas wells, and replace oil and gas with sources of renewable energy. To achieve these targets, the governments of Canada and the U.S. have recently released tax credits and made some important investments in clean energy infrastructures, such as solar, wind, and geothermal, through the U.S. Inflation Reduction Act of 2022 (Internal Revenue Service, 2022) and the 2023 Canadian Federal Budget (Department of Finance Canada, 2023).

As the governments of Canada and the U.S. plan to reduce emissions from the oil and gas sector and transition towards clean energy, it is becoming increasingly important to address and mitigate non-producing oil and gas wells, which represent both a source of greenhouse gas emissions and of potential renewable energy production. Therefore, it is crucial to analyze and characterize abandoned and orphaned wells not only to mitigate their environmental and climate impacts, but also to determine how they could be converted to sustainable sources of energy.

1.2. Objectives and approach

To limit the environmental and climate impacts of abandoned and orphaned wells and repurpose the wells and sites for renewable energy development, it is important to characterize and analyze their attributes and estimate their potential for clean energy production. In this thesis, we compile inventories of abandoned and orphaned wells across Canada and the United States based on public well data from regulatory oil and gas agencies. In the first study, we focus solely on documented orphaned wells in the United States and analyze their spatial and temporal distribution and well attributes (depth, last production date, and well type) and estimate their methane emissions. In the second study, we expand our inventory and compile all abandoned and orphaned wells across Canada and the United States and analyze their spatial distribution and depth (important in assessing geothermal potential). Using national maps of land cover and renewable energy potential, we then determine the potential for solar, wind, and geothermal energy production at abandoned and orphaned well sites across the two nations. Both studies show the lack of data on abandoned and orphaned wells from regulatory oil and gas agencies and identify uncertainties in well counts and well attributes. Furthermore, these studies highlight the need for plugging and remediating abandoned and orphaned wells and their potential for solar, wind, and geothermal energy production. Our compilations and associated results lay the foundation for future research on quantifying the impacts and opportunities of abandoned and orphaned wells across Canada, the United States, and around the world.

1.3. Organization of the thesis

The first chapter introduces the importance of analyzing and characterizing abandoned and orphaned wells in the context of climate change and the renewable energy transition. The second chapter provides an overview of the definitions, inventories, and environmental impacts of abandoned and orphaned wells in Canada and the United States and reviews the challenges and benefits of solar, wind, and geothermal energy development at abandoned and orphaned well locations based on the current literature. In the third chapter, we compile and characterize documented orphaned wells in the United States, analyze their well attributes, and estimate their methane emissions. In the fourth chapter, we provide a continental scale inventory of all abandoned and orphaned wells across Canada and the United States and estimate their potential for wind, solar, and geothermal energy production. The fifth and sixth chapters discuss the significance of our findings in the context of climate change and the renewable energy transition in addition to providing limitations and recommendations for future work.

2. Literature review

2.1. Oil and gas well statuses and definitions

Many statuses and definitions are associated with oil and gas wells. For example, wells may be “completed”, “active”, “suspended”, “abandoned”, “plugged”, or “orphaned”. The life cycle of an oil and gas well begins with well drilling and ends when production stops, after which the well and well site is generally, although not always, plugged, remediated, and restored. Oil and gas well statuses and definitions vary across states, provinces, territories, and countries. Therefore, to compile inventories of abandoned and orphaned wells, it is important to understand how non-producing oil and gas wells are defined and labeled across the different oil and gas regulatory agencies in Canada and the United States.

2.1.1. Life cycle of an oil and gas well: from drilling to abandonment

Before a well is drilled, the site is prepared (e.g., cleared and leveled) and supporting infrastructure is built, such as a well pad and access roads. Then, the well is drilled and encased by steel and cement to prevent leakage of fluids or gas to the surface and subsurface. During completion operations, the well is prepared for production, which usually involves connecting the well to oil and gas reservoirs. After these initial phases, the well is considered active. Active wells include those that produce oil and gas, but also include enhanced recovery wells (e.g., injection wells) and disposal wells (e.g., salt water disposal well formerly producing gas). Once production stops, typically when operations are no longer economically viable, the well is considered to be “abandoned” (U.S. Environmental Protection Agency, 2023). To limit environmental risks and greenhouse gas emissions, abandoned wells are typically plugged (or sealed) with cement and the land is restored, sometimes to its original condition (Interstate Oil and Gas Compact Commission, 2021). However, due to the high cost of plugging and remediation, insufficient bond requirements, and lack of government funding, many abandoned wells remain unplugged. In instances when the operator declares bankruptcy or is financially unable to plug and remediate the well, the well is considered to be “orphaned”. As such, the responsibility of plugging and restoring orphaned wells falls on government agencies and taxpayers (Raimi *et al.*, 2021; Kang *et al.*, 2021; Merrill *et al.*, 2023).

2.1.2. Abandoned and orphaned well definitions in Canada and the United States

Definitions of abandoned and orphaned oil and gas wells vary from countries, states, provinces, and territories, making it challenging to compile national/continental inventories of abandoned and orphaned oil and gas wells in Canada and the United States. In their greenhouse gas inventory, the United States Environmental Protection Agency (EPA, 2023) defines “abandoned wells” as wells with no recent production, including plugged and unplugged wells, and wells with, or without, a responsible operator. State oil and gas agencies may use other terms to define an abandoned well, such as “inactive”, “temporarily abandoned”, “shut-in”, “dormant”, or “idle”.

Orphaned wells are a subcategory of unplugged abandoned wells and may be defined by states/provinces/territories as "deserted", "long-term idle", and even "abandoned" (EPA, 2023). The main difference between abandoned and orphaned wells is that orphaned wells have no responsible party to plug and remediate the wells other than government agencies and the general public (Raimi *et al.*, 2021; Kang *et al.*, 2021; Merrill *et al.*, 2023). Orphaned wells documented in public databases are defined as "documented orphaned wells" and have gone through some internal verification process by oil and gas regulatory agencies to determine that the wells are orphaned (IOGCC, 2021; U.S. Department of the Interior (DOI), 2023). However, these verification processes can vary substantially among government agencies. In contrast, "undocumented orphaned wells" are wells typically unknown to government agencies or are wells that require further verification to determine the well as being orphaned (IOGCC, 2021; DOI, 2023).

In their most recent greenhouse gas inventory, Environment and Climate Change Canada (ECCC, 2023) defines two main categories of abandoned wells: plugged and unplugged abandoned wells. Plugged abandoned wells have a well status of "abandoned", "downhole abandoned", or "junked and abandoned". In contrast, unplugged abandoned wells are wells without recent production and include "inactive", "temporarily abandoned", "suspended", "dormant", and "orphaned" wells. Well statuses such as "temporarily abandoned" and "suspended" imply that the well, although with no recent production, will likely resume production. In some instances, operators get non-producing wells classified as "suspended" to avoid decommissioning costs and requirements associated with abandoning wells (El Hachem and Kang, 2023). Although various definitions and statuses of abandoned and orphaned wells are used by oil and gas agencies, it is important to establish a consistent definition and understand the different statuses for regulations, policies, and federal spending.

2.2. Environmental impacts of abandoned and orphaned oil and gas wells

Abandoned and orphaned wells can act as subsurface leakage channels connecting oil and gas reservoirs to groundwater aquifers, the surface, and the atmosphere (Jackson *et al.*, 2014; Cahill *et al.*, 2019). As such, abandoned and orphaned wells have the potential to contaminate water sources, degrade ecosystems, impact human health, and emit air pollutants and methane, a potent greenhouse gas (Kang *et al.*, 2021; Kang *et al.*, 2023). These impacts can be exacerbated if the well is unplugged or if the integrity of the well and/or plug is compromised.

Most studies on the environmental and climate impacts of oil and gas wells have been conducted for active wells, especially for hydraulically fractured wells (Jackson *et al.*, 2014). As such, the impacts of abandoned and orphaned wells on the air, water, ecosystems, and human health are largely understudied. The findings for active wells may be applicable to abandoned and orphaned wells. However, due to their physical and operational differences, more studies and direct measurements focused on abandoned and orphaned wells are needed to better understand how the impacts of abandoned and orphaned wells compare to active wells.

Kang *et al.* (2021) reviewed the available literature on the environmental and climate impacts of abandoned and orphaned wells. They found that the majority of direct measurements at abandoned and orphaned wells are focused on methane emissions (Kang *et al.*, 2014; Kang *et al.*, 2016), while a smaller number of direct measurements are available for surface water and groundwater (Kell, 2011; McMahon *et al.*, 2018; Wen *et al.*, 2019), and ecosystems (Nallur *et al.*, 2020). However, no studies have analysed the impacts of abandoned or orphaned wells on human health. A more recent study by Kang *et al.* (2023) quantified the environmental risks of documented orphaned wells across the United States by analyzing available data on population, domestic groundwater production wells, groundwater and surface water quality, methane emissions, air pollutant emissions, and health and environmental studies. The authors specify that available monitoring data are not extensive enough to quantify the environmental risks of orphaned wells and that more direct measurements are needed. The following section provides an overview of methane emissions and land use impacts of abandoned and orphaned wells.

2.2.1. Methane emissions

Abandoned and orphaned wells are a source of methane emissions. Methane is a potent greenhouse gas, with a global warming potential 29.8 times stronger than that of carbon dioxide over a 100 year timeframe and 82.5 times stronger over a 20 year timeframe (IPCC, 2021). While direct measurements of methane emissions have been conducted at abandoned wells (Kang *et al.*, 2014, 2016; Townsend-Small *et al.*, 2016; Pekney *et al.*, 2018; Riddick *et al.*, 2019; Lebel *et al.*, 2020; Saint-Vincent *et al.*, 2020; Williams *et al.*, 2021; Townsend-Small and Hoschouer, 2021; El Hachem and Kang, 2023), to our knowledge, only one study has conducted methane emission measurements at orphaned wells (Nivitanont *et al.*, 2023).

Methane emission from abandoned and orphaned wells can originate from the aboveground wellhead infrastructure, surface casing vent (SCV), or surrounding soil and equipment (storage tanks, pipelines, etc.) (Bowman *et al.*, 2023). Multiple methods can be used to measure methane emissions and the choice of the appropriate method will depend on the characteristics of the emission source. Previous measurements of methane emissions at abandoned wells have been conducted using chambers or enclosures (Kang *et al.*, 2014), atmospheric modeling (Riddick *et al.*, 2019, Lebel *et al.*, 2020), Hi-Flow samplers (Pekney *et al.*, 2018), mobile surveys (Lebel *et al.*, 2020, Vogt *et al.*, 2022), and soil gas sampling (Boothroyd *et al.*, 2016, Schout *et al.*, 2019). Although aerial surveys using helicopters and drones have been used to locate abandoned and orphaned wells, they have not been used to quantify emission rates (Saint-Vincent *et al.*, 2020, 2021; de Smet *et al.*, 2021). Detecting and quantifying emissions using vehicles, aircrafts, and satellites requires attributing emission plumes to the correct source (Atherton *et al.*, 2017, MacKay *et al.*, 2021). However, when multiple sources exist, this process can be challenging and can create uncertainties. Furthermore, vehicles, aircrafts, and satellites are designed to measure relatively high emission rates (>100 g h^{-1}) (Peischl *et al.*, 2018, Cusworth *et al.*, 2022) and thus, might miss smaller emission rates from abandoned wells. Enclosure or chamber-based methods are directly applied to the emission source and are able to detect relatively low emission rates (Williams *et al.*, 2023), therefore limiting uncertainties and removing the need to attribute emission sources. However, methane emissions have only been measured at relatively few abandoned well locations and the available datasets are not likely to be representative of all wells. Therefore, more research and measurements are needed to better characterize and constrain the uncertainties of methane emissions from abandoned and orphaned wells.

To estimate emissions, measurements of methane emission rates are used to determine emission factors, which are multiplied by the total number of abandoned and orphaned wells. However, large uncertainties are associated with methane emissions from abandoned and orphaned wells, ranging as high as 60% for Canada (ECCC, 2023) and 204% for the U.S. (EPA, 2023). These uncertainties arise due to the potentially large number of undocumented wells and the scarcity of direct measurements of methane emissions, which have only been conducted at 1,136 abandoned wells across nine states in the U.S. (Kang *et al.*, 2023). Methane emission estimates can be improved by refining geospatial inventories of abandoned and orphaned wells across Canada and the U.S.

Methane emissions vary depending on the attributes of abandoned and orphaned wells, such as the location, plugging status (e.g., plugged or unplugged), and well type (e.g., oil, gas, or combined oil and gas). For example, it has been showed that plugged wells emit less methane than unplugged wells and that gas wells emit more than oil or combined oil/ gas wells (Kang *et al.*, 2016; Townsend-Small *et al.*, 2016; Peckney *et al.*, 2018; Riddick *et al.* 2019; Williams *et al.*, 2021). A recent review of factors linked to oil and gas well leakage found geographic location to consistently be a predictor of high methane-emitting wells; however, the role of many factors remains understudied (El Hachem and Kang, 2023). Therefore, there is a need to characterize abandoned and orphaned wells across Canada and the U.S. to better understand how well attributes can impact methane emissions.

2.2.2. Ecosystem degradation and land use impacts

Oil and gas development can cause land cover changes and fragmentation, noise disturbances, habitat destruction, ecosystem and soil degradation, and biodiversity loss (Drohan *et al.*, 2012; Moran *et al.*, 2015; Pickell *et al.*, 2015; Brittingham *et al.*, 2014; Matthees *et al.*, 2018; Nallur *et al.*, 2020). Adverse ecosystem impacts can occur when abandoned and orphaned well sites remain unrestored and can remain long after abandonment.

Site restoration is a crucial step in decommissioning abandoned and orphaned wells. Although well plugging may reduce some ecosystem impacts, restoring abandoned and orphaned well sites, especially to their original condition, may produce significant benefits.

Generally, site restoration involves the removal of equipment, debris, hydrocarbons or pits (IOGCC, 2021). However, it does not always include groundwater remediation or restoration of the land to pre-development conditions. Restoration activities can vary widely depending on the well's age, condition, location, accessibility, and other factors. Most regulatory agencies have requirements for the restoration of abandoned wells and require bonds to cover restoration costs. However, bonds almost never meet the full costs of restoration, especially if the site is restored to its original condition (Ho *et al.*, 2018; Raimi *et al.*, 2021).

A recent study showed that the ecosystem service benefits of restoring the lands of abandoned and orphaned wells (based on agricultural sales and carbon sequestration) far outweigh restoration costs (Haden Chomphosy *et al.*, 2021). Restoring abandoned and orphaned well sites can bring many benefits at the regional and national scale, including food security and biodiversity conservation. Abandoned and orphaned wells no longer offer economic benefits, but their impacts on the land and ecosystems can continue decades after their abandonment, unless the well and associated site is restored. As more oil and gas wells are being abandoned and orphaned, restoring these non-producing wells can provide long-term benefits not only to local ecosystems, but also at the regional and national scale.

2.3 Inventories of abandoned and orphaned oil and gas wells

Various datasets of abandoned and orphaned wells have been compiled for Canada and the United States, mainly to inform national greenhouse gas inventories and federal spending. These inventories are challenging to compile due to a lack of a uniform definition for abandoned and orphaned wells and lack of public data from state, provincial, and territorial oil and gas agencies. As such, discrepancies exist between the various datasets. The following section includes an overview of existing abandoned and orphaned well inventories in Canada and the U.S.

2.3.1. <u>Documented orphaned oil and gas wells in the United States</u>

In November 2021, the United States Department of the Interior (DOI) provided $4.7 billion USD to states through the Bipartisan Infrastructure Law (BIL or Infrastructure and

Investment Jobs Act) to plug, remediate, and reclaim orphaned wells (Public Law 117-58, 135 Stat. 429). According to the BIL, only documented orphaned wells, which are orphaned wells the regulatory agency has a record (for example, drilling or inspection report) establishing the existence of the well, will be eligible for funding (DOI, 2023). The Interstate Oil and Gas Compact Commission (IOGCC), a multi-state government agency, estimated the number of documented orphaned wells based on state surveys before and after the BIL was passed. The IOGCC reported a total of 92,198 and 131,227 documented orphaned wells before and after the BIL was signed into law respectively, which represents a 42% increase in the number of documented orphaned wells (IOGCC, 2021). Based on explanations offered by states, the increase in documented orphaned well numbers are mostly attributed to additional database verifications and field investigations. However, not all documented orphaned wells had available location information. For example, 34% and 17% of the reported documented orphaned wells in Pennsylvania and Illinois respectively had no geographic coordinates.

Following the announcement of federal funding to plug and remediate documented orphaned wells across states, Merrill *et al.* (2023) and Fellow Environmental Partners (2023) compiled geospatial inventories of documented orphaned oil and gas wells based on public state oil and gas well databases. Although both sources do not compare the number of documented orphaned wells before and after the enactment of the BIL, they estimated a similar number of documented orphaned wells. Merrill *et al.* (2023) estimated 117,672 documented orphaned wells based on data collected from 2019 to 2022, while Fellow Environmental Partners reported 117,553 documented orphaned wells based on data collected from 2021 to 2023. In addition, Merrill *et al.* (2023) analyzed available documented orphaned well depth and completion year data, which was obtained from IHS Markit, a proprietary database. In contrast, Fellow Environmental Partners conducted a socio-economic analysis by attributing a socio-economic factor (SIV) to documented orphaned wells and estimating the proximity of documented orphaned wells to zones at risk (e.g., public schools, endangered species areas). Importantly, both of these inventories only provide one dataset and were compiled over a long-time frame (e.g., up to three years in Merril *et al.* (2023)). Therefore, they cannot be used to evaluate temporal changes in the number of documented orphaned wells.

2.3.2. Undocumented orphaned oil and gas wells in Canada and the United States

"Undocumented orphaned wells" are wells that are typically unknown to oil and gas regulatory agencies, or wells that require further verification to determine the wells as being orphaned (DOI, 2023; IOGCC, 2021). As such, undocumented orphaned wells are not included in current public oil and gas well databases. However, based on surveys from oil and gas producing states in the U.S., the number of undocumented orphaned wells can range between 310,000 and 800,000 (IOGCC, 2021). In Ontario, Canada, the number of undocumented orphaned wells could be as high as 30,000 (El Hachem, 2022). However, the actual number of undocumented orphaned wells in Canada and the U.S. may be much higher.

Since limited information exists about undocumented orphaned wells, they will need to be identified through various means, including historical records, remote sensing techniques, or predictive modeling. Furthermore, inventories of abandoned and orphaned wells can be a useful starting point to locate undocumented orphaned wells. Already, projects are aiming to locate undocumented orphaned wells through satellite imagery and machine learning (Lin and Rolnick, 2021). Over the next five years, the U.S. Department of Energy (DOE, 2022) aims to locate and characterize undocumented orphaned wells through remote sensing, data analytics, geophysical characterization, and advanced sensors and monitoring.

2.3.3. Abandoned oil and gas wells in Canada and the United States

Determining the number of abandoned wells in Canada and the U.S. is important to estimate methane emissions, determine well leakage potential, prioritize plugging and remediation, and inform policies and regulations. The number of abandoned wells in Canada and the United States is highly uncertain due to lack of public oil and gas well data, poor recordkeeping, and undigitized records, especially for older abandoned wells. As such, there are discrepancies between various sources of abandoned well counts. Importantly, current inventories of abandoned wells do not distinguish between abandoned and orphaned wells, which is an important distinction for funding, regulations, policies, and mitigation.

Abandoned wells are included in the United States and Canada's greenhouse gas inventory (GHGI) as a source of methane emission. To estimate the number of abandoned wells, both countries combine data from different sources and report large uncertainties in the number of abandoned wells. As of 2021, Environment and Climate Change Canada (ECCC) estimates that there are 405,000 abandoned wells across Canada based on a combination of data from provincial/territorial databases and data from the Canadian Association of Petroleum Producers (CAPP) (ECCC, 2023). In contrast, as of 2021, the U.S. EPA estimates the total number of abandoned wells in the U.S. to be 3.7 million based on proprietary data from Enverus, historical records, and online state databases (EPA, 2023). Due to the complexity of estimating the number of abandoned wells, the greenhouse gas inventories of Canada and the U.S. report the need for improved abandoned well count estimates.

Recent studies have compiled geospatial inventories of abandoned wells for Canada and the U.S. (Williams *et al.*, 2021; Kang *et al.*, 2021) and highlight the lack of data and discrepancies between sources. Williams *et al.* (2021) estimate the total number of abandoned wells in the U.S. to be 2.5 million based on regional databases alone and 4 million based on a compilation of state databases, research articles, and national well repositories. As such, they estimate that 1.5 million abandoned wells are undocumented by state agencies. Similarly for Canada, they find 0.32 million abandoned wells based on regional databases. By comparison with the CAPP well database, they estimate that 60,000 abandoned wells are undocumented in provincial/territorial databases in Canada. In contrast, Kang *et al.* (2021) estimate the total number of abandoned wells in Canada and the U.S. to be 3 million based on state, provincial, and territorial records. The inventories in Williams *et al.* (2021) and Kang *et al.* (2021) underline the challenges of compiling geospatial inventories of abandoned wells and the discrepancy between various sources.

There appears to be strong potential for aerial surveys such as aeromagnetic surveys and LiDAR to determine the precise location of abandoned wells (Saint-Vincent *et al.*, 2020; Saint-Vincent *et al.*, 2021; de Smet *et al.*, 2021). For example, a study scaling well counts from database records and aeromagnetic surveys estimate the average number of drilled wells in the United States to be 6 million, of which 1 million are abandoned (Saint-Vincent *et al.*, 2020). However, aerial surveys can be expensive and cannot distinguish between active, abandoned, and orphaned wells. LiDAR can be used to identify flat areas that indicate well pads, but can misidentify fallen trees as well sites. In contrast, aeromagnetic surveys can identify the ferromagnetic material of well casings even in regions with dense foliage or with no aboveground evidence of wells, but cannot detect wells without metal casings and can be hindered by other ferromagnetic material on the ground.

2.4. Benefits and challenges of converting abandoned and orphaned wells for renewable energy production

2.4.1. Geothermal energy

Similar to drilling an oil and gas well, drilling a geothermal well is typically expensive and time-consuming. A significant portion of the cost associated with geothermal energy development comes from well drilling, which can represent 42% - 95% of the total project costs (Hance, 2005). Drilling a geothermal well can take from 25 to more than 100 days and the cost can range between $1 - $15 million per well, with the average estimated between $4 - $6 million per well (Shevenell, 2012). The most expensive drilling operations involve deep geothermal wells located in hard rock formations (Hance, 2005). By repurposing abandoned and orphaned oil and gas wells, the time and cost associated with drilling a geothermal well can be avoided. Abandoned and orphaned wells can even be extended vertically to deeper depths or laterally to improve heat extraction. Repurposing existing wells can reduce project costs by 50% (Bu *et al.*, 2012). Therefore, converting abandoned and orphaned oil and gas wells to geothermal energy production can reduce the cost and time associated with drilling geothermal wells, while providing a revenue stream for managing wells in the long term.

Converting abandoned wells for geothermal energy production has gathered increasing attention over the years. Notably, in 2022, the U.S. Department of Energy (DOE) awarded $8.4 million USD to projects repurposing oil and gas wells for geothermal energy production (DOE, 2022). These projects located in Texas, Oklahoma, Utah, Colorado, and Nevada are partnering with existing well owners to power commercial buildings, a school, and an electric vehicle charging infrastructure. Repurposing abandoned and orphaned wells for geothermal energy could provide an additional revenue stream for mitigation, reduce environmental and climate risks, and create jobs. Furthermore, converting abandoned and orphaned wells can make use of existing infrastructures and proximity to local energy demand. To date, only a few small-scale pilot projects are currently repurposing abandoned wells for geothermal energy production (U.S. Department of Energy, 2022; Szekszárdi *et al.*, 2022). Most feasibility studies have focused on technical feasibility (Gharibi *et al.*, 2018; Weijermars *et al.*, 2018; Moore and Hollander, 2020), risk assessments (Wilson *et al.*, 2007; Wang *et al.*, 2018), or economic and regulatory assessments (Westphal and Weijermars, 2018; Kurnia *et al.*, 2022). To our knowledge, no research has been conducted at the national/continental scale. Nonetheless, while studies have confirmed the viability of converting abandoned wells to geothermal energy production, more research is needed to assess feasibility at a larger scale.

In 2022, the first closed-loop geothermal well was successfully converted from an abandoned oil well in Hungary (Szekszárdi *et al.*, 2022). In closed-loop geothermal systems, fluids continuously circulate through a single well in a closed circuit. The main challenge for closed-loop systems is the high cost of well drilling and the low power generation, which typically does not justify the investment. Therefore, repurposing abandoned or orphaned wells can be a solution to reduce project costs (Wang *et al.*, 2010). Numerous studies have analyzed closed-loop geothermal energy systems using abandoned oil and gas wells, but these studies are primarily based on numerical models (Davis and Michaelides, 2009; Gharibi *et al.*, 2018; Wang *et al.*, 2018; Hu *et al.*, 2020; Singh, 2020). As such, more pilot projects are needed to determine the feasibility of converting abandoned and orphaned wells to closed-loop geothermal systems, especially at the regional or national scale.

To our knowledge, there are no pilot projects that have attempted to repurpose abandoned or orphaned wells to enhanced/engineered geothermal systems (EGS). In EGS, a made-man reservoir is created to increase the natural permeability of the rock. As such, water is injected into the reservoir where it is heated from the surrounding rocks and circulates to the production well where it is brought back to the surface. Due to the creation of fractures in the subsurface, more heat can be extracted with EGS compared to other geothermal systems (Lu, 2018). However, the greatest challenge of EGS is ensuring the productivity and longevity of the reservoir. Therefore, it is an area of active research and has not yet been deployed for large-scale applications (Ziagos *et al.*, 2013). Similar to closed-loop geothermal systems, the cost of drilling an EGS well is extremely high, averaging at around $10 million per well (Lu, 2018; Santos *et al.*, 2022). A feasibility study in West Virginia found that converting abandoned oil and gas wells to EGS would not be competitive with current U.S. electricity prices (Anderson, 2015). To be competitive, the abandoned and orphaned wells would need to be close to energy demand and involve reliable and productive reservoirs (Westphal and Weijermars, 2018). The potential for EGS has been evaluated at various oil and gas basins and regions, such as in Texas (Erdlac *et al.*, 2007), the Illinois and Michigan basins (Gosnold and Crowell, 2014), and the Bohai Bay basin and Daqing field in China (Wang *et al.*, 2016). However, more feasibility studies and pilot projects are needed to assess the potential for EGS using repurposed abandoned and orphaned wells.

The potential for converting abandoned and orphaned wells for geothermal energy production depends on various factors, such as well depth, cement quality, and proximity to end users. The location of the well is critical. For example, abandoned and orphaned wells located far from areas of high energy demand, such as in rural areas, may increase the cost and complexity of the project (Nordquist and Johnson 2012; Wang *et al.*, 2018). Each abandoned and orphaned well is unique and contain its own set of challenges. Therefore, data on abandoned and orphaned wells is crucial in determining the well-specific potential for geothermal energy production. However, data remains scarce or incomplete for many abandoned and orphaned wells, especially older wells. For example, well data might only be available in unscanned records or records may be incomplete due to discrepancies in data reporting standards. Therefore, data gaps and unknown well conditions can lead to uncertainty during repurposing operations (Osundare, 2018).

When the integrity of an abandoned oil and gas well is comprised, repurposing the well for geothermal energy production might require expensive and time-consuming repairs. Well integrity failures are common in oil and gas wells and commonly occur during drilling or completion operations. As such, converting properly maintained abandoned and orphaned wells for geothermal energy production would avoid well integrity issues faced during well drilling (Teodoriu *et al.*, 2013; Shadravan *et al.*, 2015; Allahvirdizadeh, 2020). However, if well integrity issues are not addressed during the retrofit, they may significantly reduce the efficiency of the geothermal well by reducing its heat extraction capacity (Philippacopoulos, 2001). Furthermore, the leakage of geothermal fluids from the well might contaminate nearby aquifers. Therefore, there is a need for policies and regulations to address monitoring and repair of well integrity issues during and after the conversion of abandoned and orphaned wells for geothermal energy production.

Converting abandoned and orphaned wells for geothermal energy production is a relatively new concept. Therefore, to date, there are no standards or regulations specific to the conversion of abandoned and orphaned wells to geothermal energy wells. Regulations for geothermal wells vary depending on the state, province, territory, and country. Some geothermal wells are regulated by mining authorities, while others fall under existing legislation and regulatory frameworks for natural resources, hydrocarbons, geology, or groundwater (Goodman *et al.*, 2010). Therefore, there is a need for policies and regulations to integrate guidelines for the conversion of abandoned and orphaned wells to geothermal energy production.

2.4.2. Wind and solar energy

Most of the research on repurposing abandoned wells for renewable energy production has been focused on geothermal energy. A high level assessment of the potential for renewable energy production for a subset of 81,857 documented orphaned wells in the U.S. (2% of all abandoned wells in the U.S.) indicate high potential for wind and solar development (Kang *et al.*, 2023). However, to our knowledge, there are no pilot projects restoring abandoned and orphaned wells for wind energy production. Only one project in southern Alberta is currently converting abandoned and orphaned well sites for solar energy production by repurposing disturbed land and existing infrastructures, such as access roads, well pads and electrical infrastructures, without impacting nearby agricultural lands (Hirsche and Stendie, 2020). Another study has proposed storing wind and solar energy in retrofitted abandoned and orphaned wells by underground compressed air energy storage (Qin and Loth, 2021).

While the literature on repurposing abandoned and orphaned well sites for solar and wind energy is sparse, there are several successful pilot projects that have remediated and converted contaminated lands, landfills, and mine sites for wind and solar energy under the E-Powering America's Land Initiative (United States Environmental Protection Agency, 2023). Launched in 2008 by the U.S. Environmental Protection Agency (EPA), the program has since reused abandoned industrial sites and landfills for wind farms and solar arrays. Similar to repurposing abandoned and orphaned well sites, converting these contaminated sites can offer significant advantages, such as repurposing existing infrastructure, shortening development timeframe, reducing land costs, incentivizing remediation, protecting open spaces that may have otherwise been used for renewable energy development, and creating jobs. Among the successful pilot projects, a combined solar and wind system was installed on a former chemicals and explosives manufacturing site in Arizona. The renewable energy project reduced the 30-year clean-up cost from $25 million to approximately $2.5 million (United States Environmental Protection Agency, 2009). Furthermore, a former solid waste landfill was converted to a solar PV system in a small town in Massachusetts using only local labor. The town leased the property to a renewable energy developer and the project now provides the town with 100% of its municipal power needs (United States Environmental Protection Agency, 2014). Therefore, existing pilot projects that have repurposed contaminated sites can help guide future efforts for the conversion of abandoned and orphaned well sites to wind and solar energy production.

Studies agree that determining the wind density and solar irradiation of a location is the first step towards selecting a site for wind and/or solar energy development since they affect the economic feasibility of a project (Al Garni and Awasthi, 2018; Rehman *et al.*, 2019; Rediske *et al.*, 2019; Wu *et al.*, 2020). One of the greatest challenges for wind and solar energy development is site selection. Ideally, wind turbines and solar panels should not interfere with current land use. Converting abandoned and orphaned well sites for wind and/or solar development can take advantage of existing energy infrastructures and sites, while preserving undeveloped lands that would have otherwise been used for renewable energy development. Typically, the optimal location for wind and solar projects are areas of open land with minimal vegetation (Villacreses *et al.*, 2017), such as agricultural lands. Agricultural areas are typically favored since they allow the continuation of farming operations and the income generated from the land lease is typically greater than the loss in crop production (McKeown *et al.*, 2011). In wind projects, only 5 - 10% of the total acreage of the land is typically used for infrastructures, access roads, and turbines while the rest of the land can maintain its former use (Bureau of Land Management, 2005). For solar energy, the average land use for a small PV system of 1 MW is 4 - 6 acres, which includes the solar PV array, access roads, and other associated infrastructures (Perpiña Castillo *et al.*, 2016). A study in Alberta found that abandoned and orphaned well sites range in size from 2 to 5 acres, which is ideally sized for solar PV installations with capacity up to 1 MW (Hirsche & Stendie, 2020). In addition, solar PV modules have the advantage of being flexible in their placement and may require less surface area compared to wind turbines. To address land restrictions, solar PV systems can be arranged in square or rectangular arrays or installed on rooftops. As the efficiency of solar PV modules continues to increase, less surface area will be required. In fact, the amount of land used by solar PV arrays has declined by 62% between 2010 and 2021 (International Renewable Energy Agency, 2022). Local zoning laws are also a key factor in determining the location of wind and solar energy projects (McKeown *et al.*, 2011). Zoning controls land-use actions in certain areas, such as whether a wind turbine or solar panel can be installed in a particular location. Jurisdictions can also define specific zones that limit wind and solar energy development to certain parts of the town/county or can set uniform rules across the jurisdiction.

Another challenge for wind and solar energy development is the high initial capital investment. For example, the major cost component for wind energy development is the wind turbines, which can represent 68 - 84% of the total project cost (European Wind Energy Association, 2009). Solar panels are also expensive, but costs have significantly decreased in the past decade, with solar panel prices decreasing by 93% between 2010 and 2020 (International Renewable Energy Agency, 2023). Other cost components associated with solar and wind energy development include access roads, foundations, and transmission lines. However, these costs can potentially be avoided by repurposing existing infrastructures at abandoned and orphaned well locations. As the value of open landscapes increase, leasing or purchasing abandoned and orphaned well sites could represent significant cost savings. For example, converting an abandoned or orphaned well site for solar energy development could involve cost savings up to 25% for the installation of solar PV panels and cost savings up to 40% for the reclamation and mitigation of the abandoned and orphaned well site (Bruce, 2020).

The main challenge for wind and solar energy development is public opposition (Rediske *et al.*, 2021). For example, wind turbines are typically far from urban centers due to their height. Depending on the local landscape, wind turbines may be the tallest structure in the skyline. In 2021, the average wind turbine hub height was nearly 100 m (U.S. Department of Energy, 2023). Wind turbines have been found to be visually intrusive and cause noise disturbances. In a survey conducted in North Carolina, 44% of the respondents found that the "pollution" of the visual landscape caused by wind turbines was their biggest issue with wind energy (Grady and Inn, 2002). However, other studies suggest that public response towards wind power is more positive in areas with prior experience with wind energy development (Kaldellis, 2005; Eltham *et al.*, 2008). In other words, public acceptance increases with increasing level of information and experience with wind energy. Public opposition due to noise disturbances can also be a challenge, especially in urban areas (Kazak *et al.*, 2017). However, noise levels must meet the norms and standards established by local legislation. Typically, wind turbines are kept more than 500 m away from houses (Howe *et al.*, 2007; Aydin *et al.*, 2010). Solar energy development can also face public opposition, mostly in urban areas. Solar arrays located in cities often face "Not in My Back Yard" (NIMBY) opposition (Janke, 2010; Uyan, 2013; Sanchez-Lozano *et al.*, 2014). This opposition is generally caused by perceived negative changes to the landscape, damage to the environments, or other detrimental impacts to the local area. Overall, abandoned and orphaned well locations in agriculture and rural areas may be ideal candidates for wind and solar energy development, but may face public opposition due to visual disturbances to the landscape.

Bridging Text

In the following chapter, we estimate the number of documented orphaned wells in the United States over time and evaluate their attributes to identify and characterize the full set of wells eligible to be plugged and remediated via federal funding from the Bipartisan Infrastructure Law (or Infrastructure Investment and Jobs Act). Based on oil and gas well data from state agencies, we provide geospatial datasets of documented orphaned wells and potentially documented orphaned wells and analyze their numbers, geographical distribution, and attributes.

This study corresponds to the paper: "Documented orphaned oil and gas wells across the United States", which was published in *Environmental Science and Technology* in September 2022. It is co-authored by Adam S. Peltz and Renee McVay from the Environmental Defense Fund (EDF) and my supervisor, Prof. Mary Kang, from the Department of Civil Engineering at McGill University. Reprinted with permission from Environ. Sci. Technol. 2022, 56, 14228−14236. Copyright 2022 American Chemical Society. https://doi.org/10.1021/acs.est.2c03268.

3. Documented orphaned oil and gas wells across the United States

3.1. 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 3.1). 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 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]

Table 3.1.: Summary of orphaned and abandoned oil and gas well definitions.

Well Status	Production	Plugging Status	Legal responsible operator	Financial responsibility	Example of other terms used by States
Abandoned	Non-producing 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	Non-producing 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*

*The terms are based on documented orphaned well data compiled as of January to April 2022. State-specific terms can be found in the Supporting Information (Table S4).

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.

3.2. 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 "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 "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 considered 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]

3.3. Results

3.3.1. 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 3.1). 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.

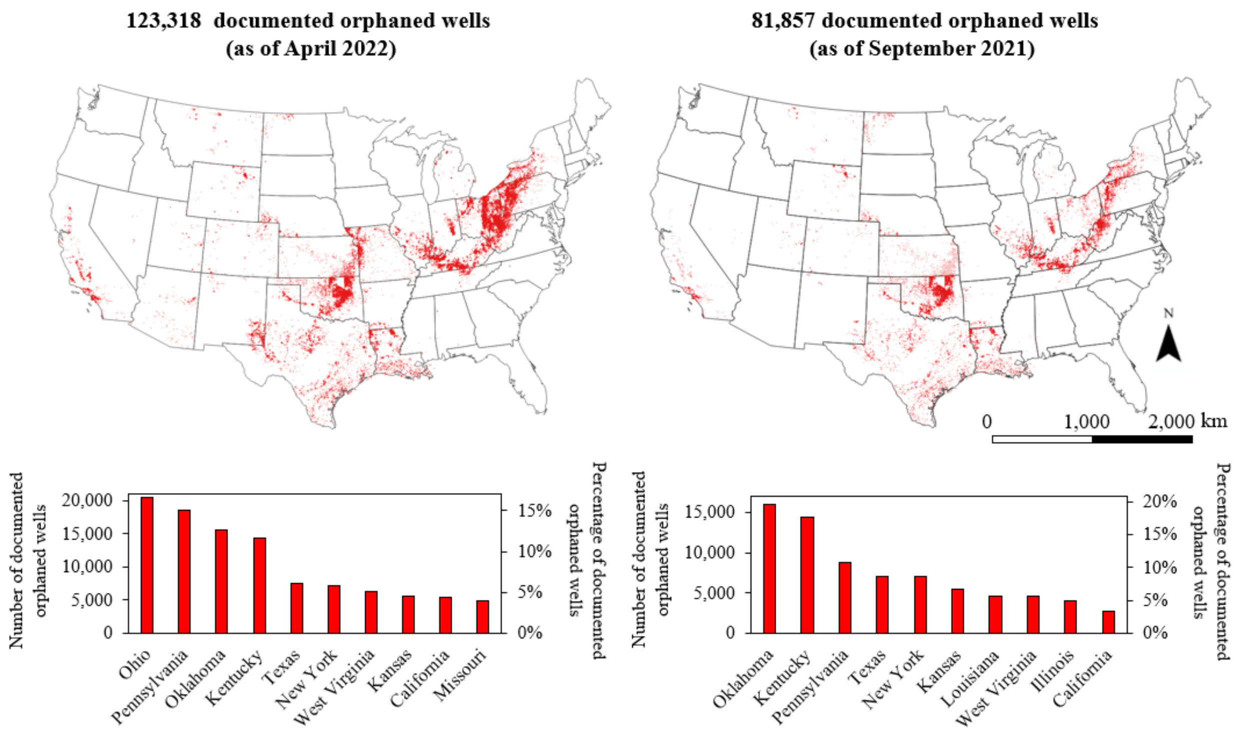


Figure 3.1. Distribution of documented orphaned oil and gas wells across the U.S. based on state databases as of April 2022 (left) and September 2021 (right). Parts of this figure are reproduced in the Table of Contents graphic.

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 3.1). 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.

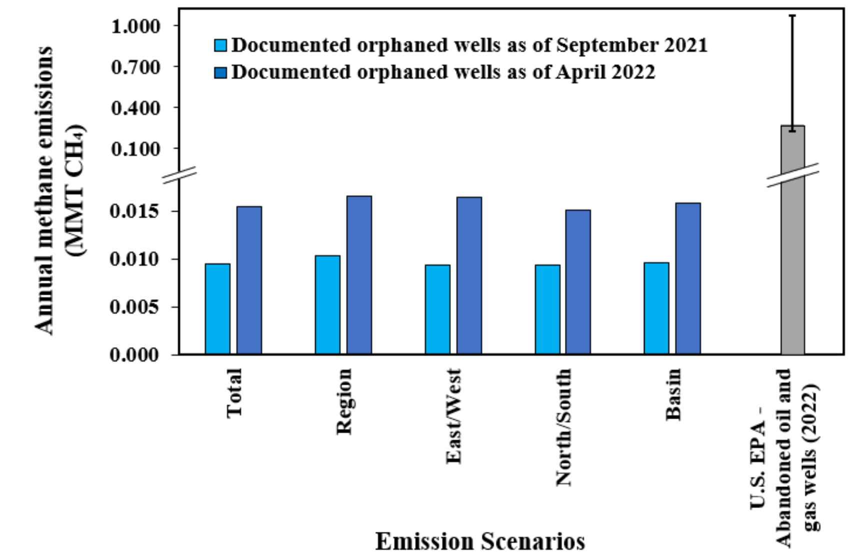
As such, we identify documented orphaned wells across 28 states as of September 2021 and across 30 states as of April 2022.

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.

3.3.2. 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 3.2 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 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.



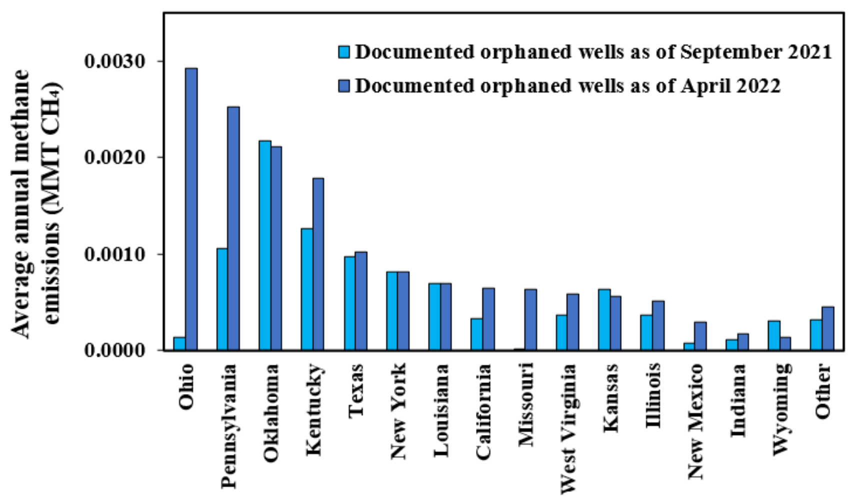


Figure 3.2. Total annual methane emissions by scenarios developed in Williams *et al.* (2021)[6] with methane emissions and emissions uncertainty for abandoned wells by the U.S. EPA[9] (top) and distribution of annual methane emissions by state for the average of all five scenarios (bottom). All emission scenarios are described in the Supporting Information (Table S8).

3.3.3. 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 3.3 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.

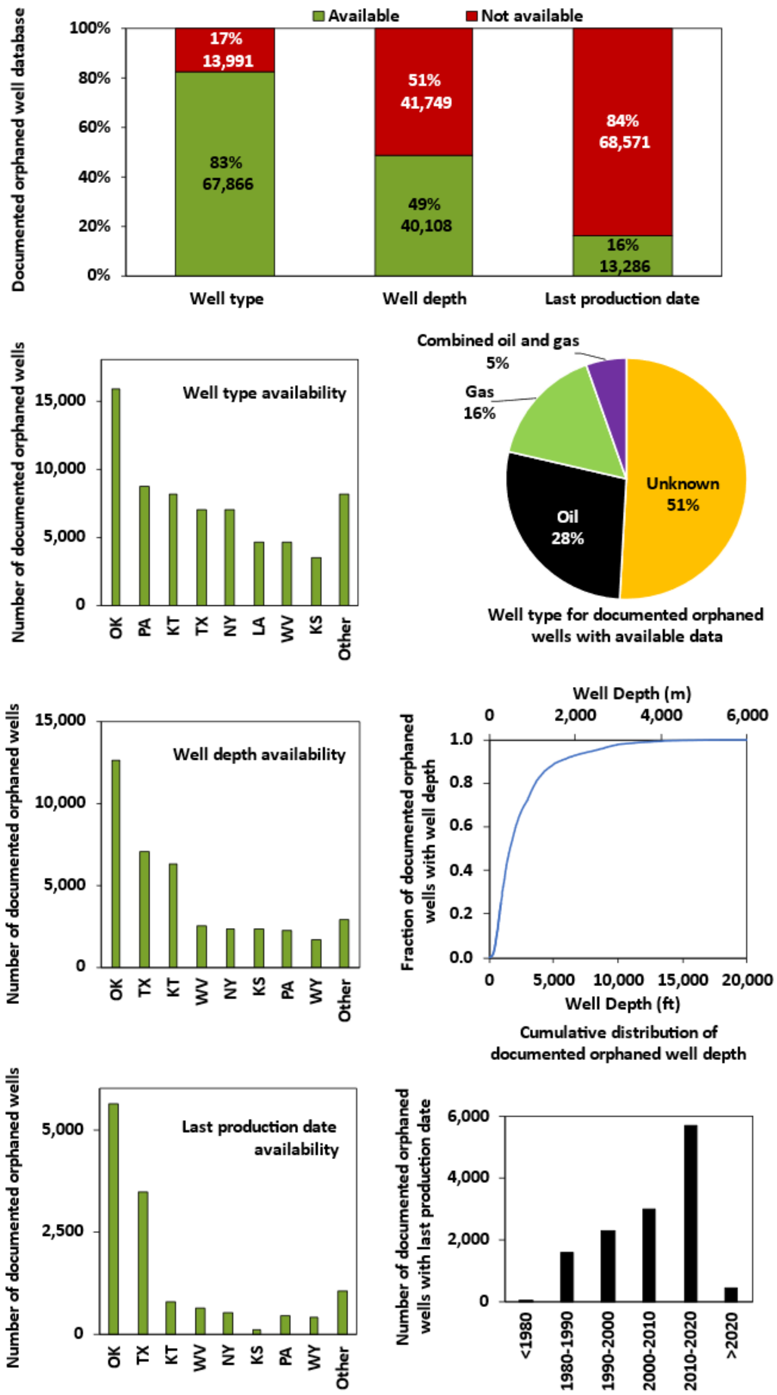


Figure 3.3. Well attribute availability for the 81,857 documented orphaned oil and gas wells as of September 2021 (top left), availability of well type, well depth, and last production date per state left column), pie chart of well type distribution (top right column), cumulative distribution of well depth (middle right column), and histogram of last production date (bottom right column).

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 3.4). 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.

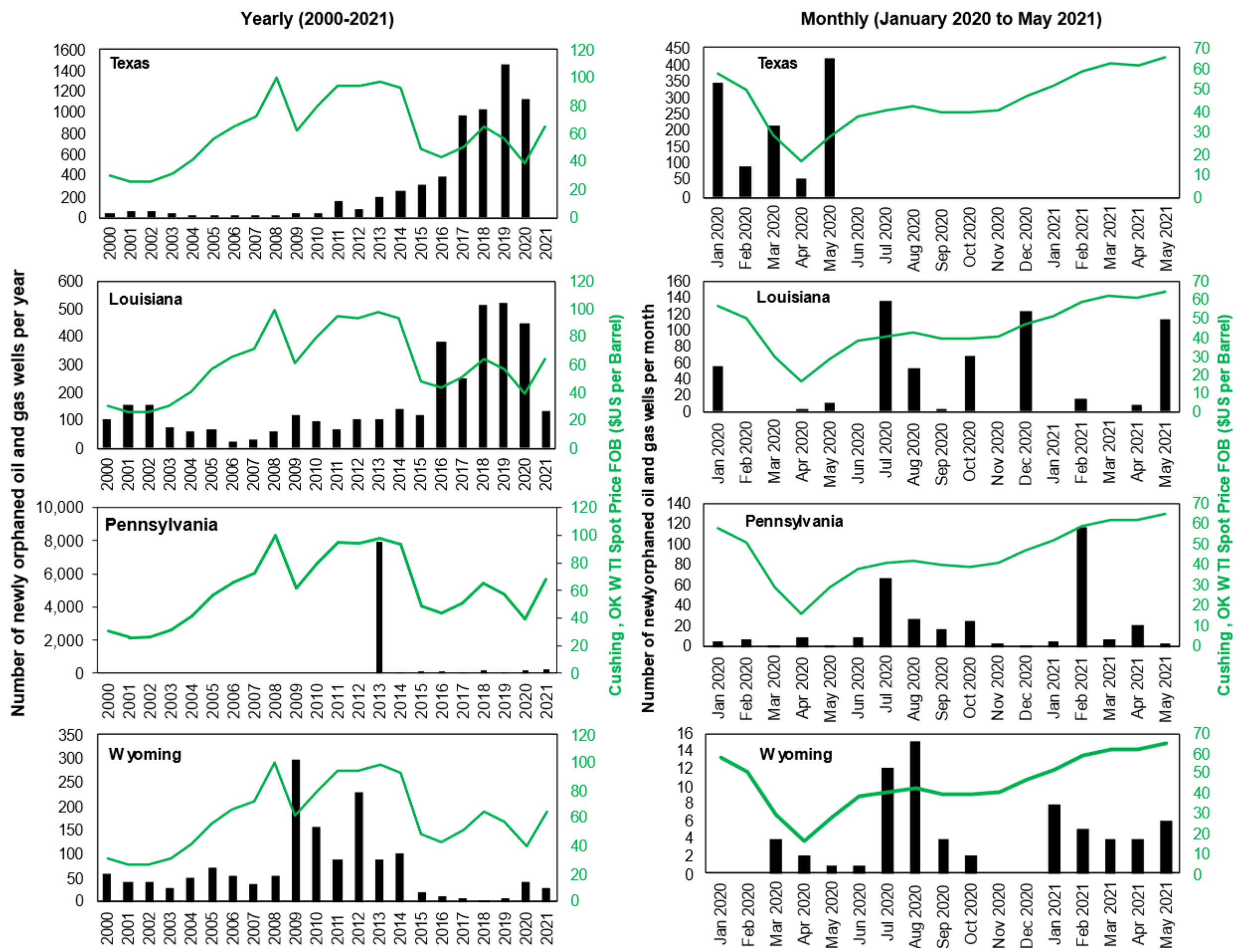


Figure 3.4. Orphaned dates by year (left column) and month (right column) for documented orphaned oil and gas wells in Texas, Louisiana, Pennsylvania, and Wyoming with available orphaned date information as of September 2021.

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 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]

3.4. 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 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.

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

Acknowledgments

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Bridging Text

The previous chapter discussed the methodology for compiling an inventory of documented orphaned wells and analyzed the location, depth, last production date, and well type of documented orphaned wells across the U.S. This work can be used to inform federal funding for plugging and remediating documented orphaned wells under the Infrastructure and Investment Jobs Act (or Bipartisan Infrastructure Law). Importantly, mitigating abandoned and orphaned wells may provide significant environmental benefits and stimulate the economy, but can be expansive. Therefore, converting abandoned and orphaned wells to solar, wind, or geothermal energy production can provide a funding stream for mitigation, while helping fulfill national energy transition goals and emission reduction targets across Canada and the U.S. In the following chapter, we estimate the total number of abandoned and orphaned wells in Canada and the U.S. and estimate their potential for renewable energy production.

The following chapter, named "Converting abandoned and orphaned oil and gas wells for renewable energy production in Canada and the United States", is in preparation for submission to a peer-reviewed scientific journal. This work is co-authored by my supervisor, Prof. Mary Kang, from the Department of Civil Engineering at McGill University.

4. Converting abandoned and orphaned oil and gas wells for renewable energy production in Canada and the United States

4.1. Introduction

There are millions of abandoned and orphaned oil and gas wells in Canada and the United States (U.S.) that are placing a burden on the environment, climate, society, and the economy[1,2]. Abandoned wells no longer produce oil and/or gas, and thus, in general, operators are not financially incentivized to plug and clean up abandoned wells and associated sites. As a result, there are many orphaned wells, which are a subset of abandoned wells that lack a financial responsible party other than government agencies and taxpayers[1,3]. As society transitions away from fossil fuel and towards renewable energy[4,5], converting abandoned and orphaned wells to solar, wind, or geothermal energy production can provide an additional funding stream for mitigating abandoned and orphaned wells. Funding is needed to repurpose the land, remove and restore existing infrastructures (e.g., access roads, transmission lines), and plug the wells, all of which provide environmental benefits, stimulate the economy, and incentivize plugging and remediation[6-8]. A high level assessment of the potential for renewable energy production for a subset of 81,857 documented orphaned wells in the U.S.[9] (2% of all abandoned wells in the U.S.) indicate that wind and solar development potential may be substantial, but emphasized the need to consider other factors such as land cover[2]. Importantly, there are no assessments of renewable energy conversion potential for the millions of abandoned wells in the U.S. and elsewhere.

One reason for this gap is that there are, to our knowledge, no published databases of abandoned and orphaned well locations and attributes across Canada and the U.S. Determining the number and location of abandoned and orphaned wells is crucial in informing and providing frameworks for federal funding, such as programs addressing the mitigation of inactive wells in Canada[10] and the plugging and remediation of orphaned wells in the U.S.[11]. In addition, abandoned and orphaned wells can emit methane, a potent greenhouse gas[12-15]. As such, converting abandoned and orphaned wells and sites for renewable energy production can help meet national emission reduction targets and net-zero emission goals for both Canada and the

U.S.[16,17]. However, spatial continental-scale analysis on their renewable energy potential (solar, wind, and geothermal) and depth (critical to assess geothermal energy potential) has not been previously performed.

The objectives of this paper are to: (1) map the locations of abandoned and orphaned wells across Canada and the U.S., (2) determine the land cover type at abandoned and orphaned well sites, (3) analyze spatial patterns of abandoned and orphaned well depths to inform geothermal potential and (4) assess the potential for wind, solar, and geothermal energy production at abandoned and orphaned well sites. To meet our objectives, we develop a previously-unavailable database of abandoned and orphaned oil and gas wells from public databases across 32 U.S. states and 13 Canadian provinces/territories. We then juxtapose national land cover maps with abandoned and orphaned well locations to identify land cover types, necessary for assessing solar and wind installation potential. To evaluate geothermal energy potential, we analyze how well depths vary across the two countries. Finally, we compare locations of abandoned and orphaned wells with maps of renewable energy potential (wind, solar, and geothermal). Importantly, we assess how our findings differ for orphaned and abandoned wells, which has important implications for regulations, policies, and funding. Assessing the nation-wide potential for wind, solar, and geothermal energy production at abandoned and orphaned well locations will help fulfil the U.S. and Canada's energy transition goals – shifting away from polluting fossil fuel resources and providing funding for managing the legacy of the millions of non-producing wells across the two nations and the world.

4.2. Results

4.2.1. <u>Abandoned and orphaned oil and gas wells in the United States follow different spatial patterns and land cover distribution</u>

To determine the number and spatial distribution of abandoned and documented orphaned wells across Canada and the U.S., we analyze public oil and gas well data from regulatory oil and gas agencies in 32 U.S. states and 13 Canadian provinces/territories (Supplementary Table 2-5). Documented orphaned wells, hereafter referred to as "orphaned wells", are wells documented in governmental databases and which have gone through the state, province, or territory's internal verification process to determine the well as being orphaned[18-20] (Supplementary Table 1). We note that there may be up to a million undocumented orphaned wells in the U.S. and tens to hundreds of thousands of undocumented orphaned wells in Canada[3,15,21].

We find the total number of documented abandoned and orphaned wells in Canada and the U.S. to be 3,746,078 (Supplementary Note 1). The total population of abandoned and orphaned wells is seven times greater in the United States (3,320,246 wells) than in Canada (425,832 wells). We normalize the total number of abandoned and orphaned wells based on GDP, oil production, gas production, and population (Supplementary Note 4). Compared to Canada, we find that the U.S. has twice as more abandoned and orphaned wells per oil produced (170 wells/thousand barrels of oil per day in the U.S. and 76 wells/thousand barrels of oil per day in Canada) but about 50% more abandoned and orphaned wells per gas produced than in Canada (Supplementary Figure 4 and Table 7). With respect to GDP, Canada (0.2 wells per GDP) has twice as more abandoned and orphaned wells relative to the national GDP than the U.S. (0.1 wells per GDP) The proportion of abandoned and orphaned wells per population is identical in Canada and the U.S. at 0.01 wells per person.

Orphaned wells, which are the financial responsibility of governments and taxpayers, represent only 3% (128,047 wells) of the combined population of abandoned and orphaned wells in both countries. However, the percentage of orphaned wells is larger in the US at 4% (123,318 orphaned wells), compared to Canada at 1% (4,729 orphaned wells), and can be as high as 52% at the state/province/territory level (Supplementary Figure 2 and Table 6).

We mapped abandoned and orphaned well locations (available for 91% of the wells) to analyze spatial patterns across Canada and the U.S. (Fig. 1). Most abandoned and orphaned wells are distributed across oil and gas basins, such as the Western Canadian Sedimentary Basin, Appalachian Basin, and Permian Basin (Supplementary Figure 3). As such, we identify five main regions of abandoned and orphaned wells (Eastern U.S., U.S. Coastal Plains, U.S. Mid-Continent, U.S. Northern Great Plains, and Western Canadian Sedimentary Basin) based on oil and gas field/basin regions by the Homeland Infrastructure Foundation-Level Database (HIFLD)[22]. Most abandoned (72% or 303,994 wells) and orphaned (49% or 2,324 wells) wells in Canada are in Alberta, which is the largest oil and gas producing province in the country[23,24]. In the U.S., we find that 31% of abandoned wells (1,000,588 wells) are in Texas, which is the largest oil and gas producing state[25], but 56% of orphaned wells (68,977 wells) in the U.S. are located across 4 states (Ohio, Pennsylvania, Oklahoma, and Kentucky)[18], indicating a mismatch in spatial distributions of abandoned and orphaned wells in the U.S. (Supplementary Figure 1).

Wind turbines and solar panels are surface installations and are easier to install in open areas, such as agriculture, shrubland, or grassland zones. Therefore, we determine the land cover type at abandoned and orphaned well sites based on national land cover maps[26-28] (Supplementary Table 8 and Figure 5). We find that most orphaned wells across Canada and the U.S. are in forests (37% or 47,637 wells), while the rest are in agriculture (24% or 30,385 wells), developed areas (21% or 26,644 wells) and shrubland/grasslands (12% or 15,072 wells) (Supplementary Table 9). In contrast, most abandoned wells are in shrubland/grasslands (30% or 1,097,974 wells) and agricultural zones (27% or 971,317 wells), while the rest are in developed zones (15% or 543,623 wells) and forests (13% or 478,203 wells) (Supplementary Table 10).

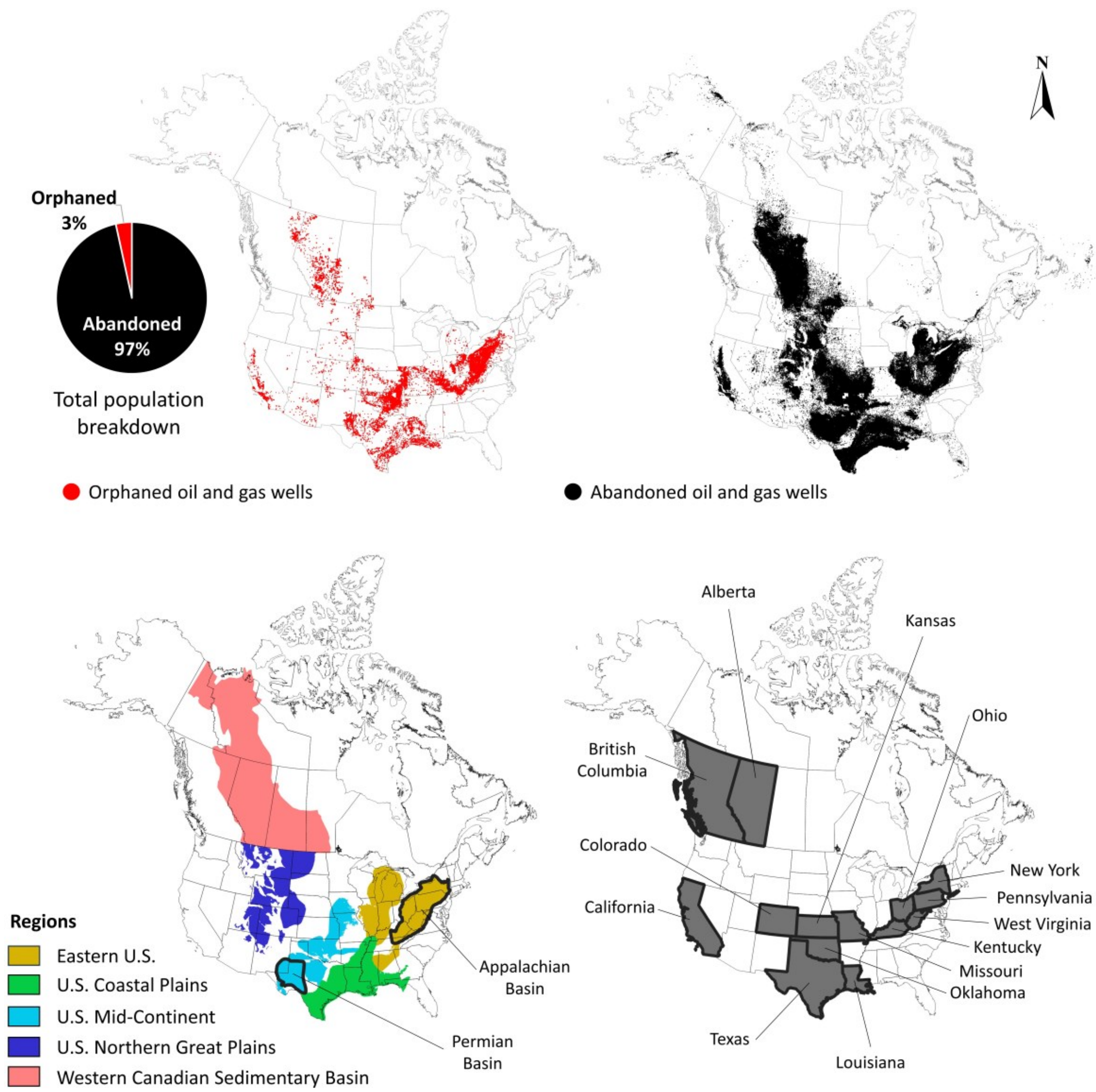

Fig. 4.1: Spatial distribution of orphaned and abandoned oil and gas wells across Canada and the United States. The “abandoned well” category in this figure does not include orphaned wells. The pie chart (top left) offers a breakdown of the total population of abandoned and orphaned wells across Canada and the United States. Refer to the Methods and Supplementary Information for more details on the data compilation and quality control steps. Regions based on oil and gas fields and basins (bottom left) are provided by the Homeland Infrastructure Foundation-Level Database (HIFLD)[22]. Provinces and states in Canada and the United States mentioned in the text are identified (bottom right).

4.2.2. Large wind energy potential (>400 W/m²) at more than 1 million abandoned and orphaned well sites

Instead of restoring the land of abandoned and orphaned wells, the sites may be repurposed for wind energy production. To assess the potential for wind energy production, we consider wind power density (a function of wind speed and air density) as a proxy for wind potential. Maps of wind power density for Canada and the U.S. were obtained from the Global Wind Atlas, which accounts for surface elevation, land use, and surface roughness[29]. We do not explicitly consider other factors, such as land ownership or access to infrastructure.

We find high wind potential (>400 W/m²) across four of the main identified regions of abandoned and orphaned wells (Eastern U.S., U.S. Mid-Continent, U.S. Northern Great Plains, and Western Canadian Sedimentary Basin) (Fig. 2). High wind potential (>400 W/m²) is available for more than a million abandoned and orphaned wells (1,247,340 abandoned and 39,397 orphaned wells). For orphaned wells, the highest wind potential (>400 W/m²) is in Oklahoma (13,982 wells or 90% of orphaned wells in the state), Kansas (5,293 wells or 99% of orphaned wells in the state), and Ohio (4,897 wells or 24% of orphaned wells in the state), which are some of the states with the largest number of orphaned wells (Supplementary Table 11). More than half of orphaned wells with high wind potential (>400 W/m²) are in areas of agriculture (37% or 14,549 wells) and shrubland/grasslands (20% or 7,934 wells) (Supplementary Table 12). Abandoned wells with the highest wind power density (>400 W/m²) are in Texas (309,138 wells or 31% of abandoned wells in the state), Kansas (296,681 wells or 98% of abandoned wells in the state), and Oklahoma (251,393 wells or 53% of abandoned wells in the state), which are the states with the largest number of abandoned wells (Supplementary Table 13). The majority of abandoned wells with high wind power density (>400 W/m²) are in agriculture (35% or 430,867 wells) and shrubland/grassland areas (44% or 550,750 wells) (Supplementary Table 14).

4.2.3. Abandoned wells are twice as more likely to have high solar energy potential (>1,600 kWh/kWp) compared to orphaned wells

Abandoned and orphaned well lands may also be redeveloped to harness solar energy by installing solar photovoltaic (PV) panels, concentrated solar power systems, or other types of solar energy systems. To assess the potential for solar energy production, we consider the PV power potential of a typical utility-scale photovoltaic (PV) system at peak performance as a proxy for solar potential. The values of PV power potential for Canada and the U.S., obtained from the Global Solar Atlas[30], are calculated based on several factors including location specific data (e.g., solar radiation, air temperature, elevation) and assumptions for a typical PV system (e.g., type, capacity, tilt, losses).

Solar potential is high across the U.S. Northern Great Plains and Mid-Continent (Fig. 2). Orphaned wells with the highest solar potential (>1,600 kWh/kWp) are across California (5,100 or 95% of orphaned wells in the state), Texas (3,775 or 51% of orphaned wells in the state), and Oklahoma (3,056 or 20% of orphaned wells in the state) (Supplementary Table 15). Nearly half (47% or 8,224 wells) of the orphaned wells with high solar potential (>1,600 kWh/kWp) are in zones of shrubland/grassland while more than a third (35% or 6,150 wells) are in developed zones (Supplementary Table 16). The proportion of abandoned well sites (37% or 1,323,828 wells) with high solar energy potential (>1,600 kWh/kWp) is more than two times higher than that of orphaned wells (14% or 17,409 wells). Abandoned wells with the highest solar potential (>1,600 kWh/kWp) are located in states with the highest wind potential, which are Texas (573,022 or 57% of abandoned wells in the state), Kansas (187,083 or 62% of abandoned wells in the state), and Oklahoma (167,609 or 35% of abandoned wells in the state) (Supplementary Table 17). Almost all abandoned (165,416 or 99.9%) and orphaned (5,100 or 95%) wells in California have solar potential greater than 1,600 kWh/kWp. Moreover, the majority of abandoned wells (56% or 741,072 wells) with high solar potential (>1,600 kWh/kWp) are in zones of shrubland/grassland while the rest are mostly in agricultural areas (19% or 254,467 wells) (Supplementary Table 18). Solar potential is low across Canada and tends to decrease with higher latitudes. Nearly half of the orphaned (46% or 2,137 wells) and abandoned (54% or 224,785 wells) wells in Canada have solar potential less than 1500 kWh/kWp.

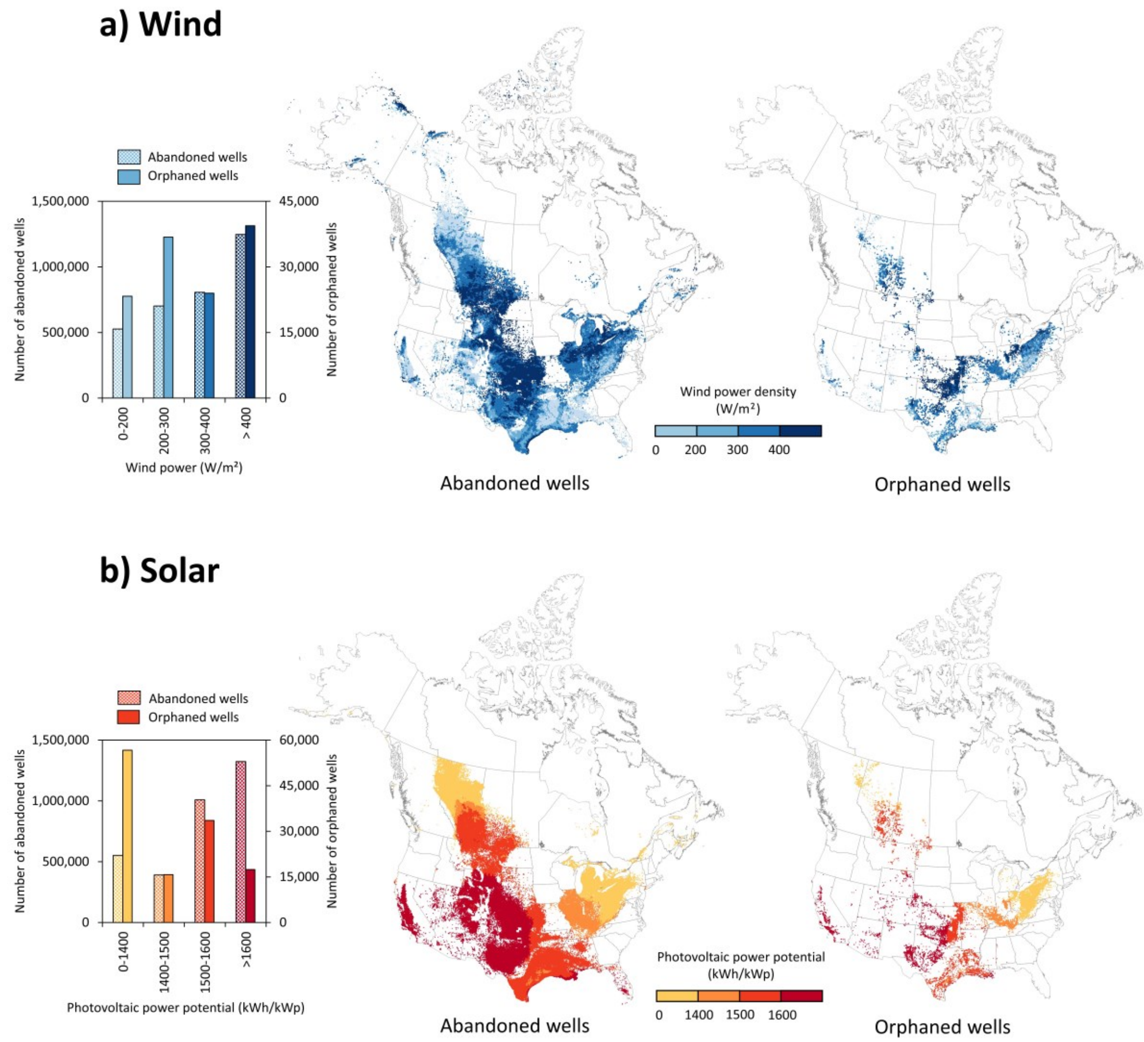

Fig. 4.2: Wind and solar potential at orphaned and abandoned oil and gas well locations across Canada and the United States. The "abandoned well" category in this figure does not include orphaned wells. The bar charts and maps offer the distribution of wind (a) and solar (b) energy potential throughout Canada and the United States.

4.2.4. <u>>90% of abandoned and orphaned wells are better suited for hydrothermal systems, yet enhanced geothermal possible at up to 10% of wells</u>

Well depth is critical in assessing geothermal potential. Natural geothermal wells (or hydrothermal systems) are typically less than 3 km deep and involve the capture of underground heat through the circulation of fluids. Geothermal wells with depths between 3-10 km are often employed for enhanced geothermal systems (EGS) because their natural permeability is often insufficient. As such, for EGS, permeability is increased by injecting fluid into the subsurface, which allows for the circulation of fluids and transportation of heat to the surface. Therefore, we compiled available abandoned and orphaned well depth data from public oil and gas well databases to analyze spatial patterns in well depth.

Abandoned wells tend to be deeper than orphaned wells, based on available data from 42% of orphaned and 50% of abandoned wells. Deeper abandoned and orphaned wells (3-10 km) suited for EGS are spread across the U.S. Coastal Plains, while most shallow orphaned and abandoned wells (<3 km deep) are spread across the Eastern U.S. (Fig. 3). Orphaned well depths average at 753 m, with a median depth of 500 m and a 5th to 95th percentile range of 99 to 2,552 m (Supplementary Table 19). On the other hand, abandoned wells have a deeper average depth of 1,427 m with a median depth of 1,081 m and a 5th to 95th percentile range of 152 to 3,638 m (Supplementary Table 20). Orphaned wells are 70% more likely to have been drilled to depths shallower than 1 km, compared to abandoned wells. Considering depths up to 3 km, which are more suitable for hydrothermal geothermal systems than EGS, 97% of orphaned wells with available depth data are suitable, while 90% of abandoned wells are suitable. This leaves only 3% of orphaned wells with available depth data as potential EGS wells and 10% of abandoned wells as potential EGS wells. Looking at well counts, this difference is even more substantial with only 1,637 orphaned wells and 186,753 abandoned wells as potential EGS wells.

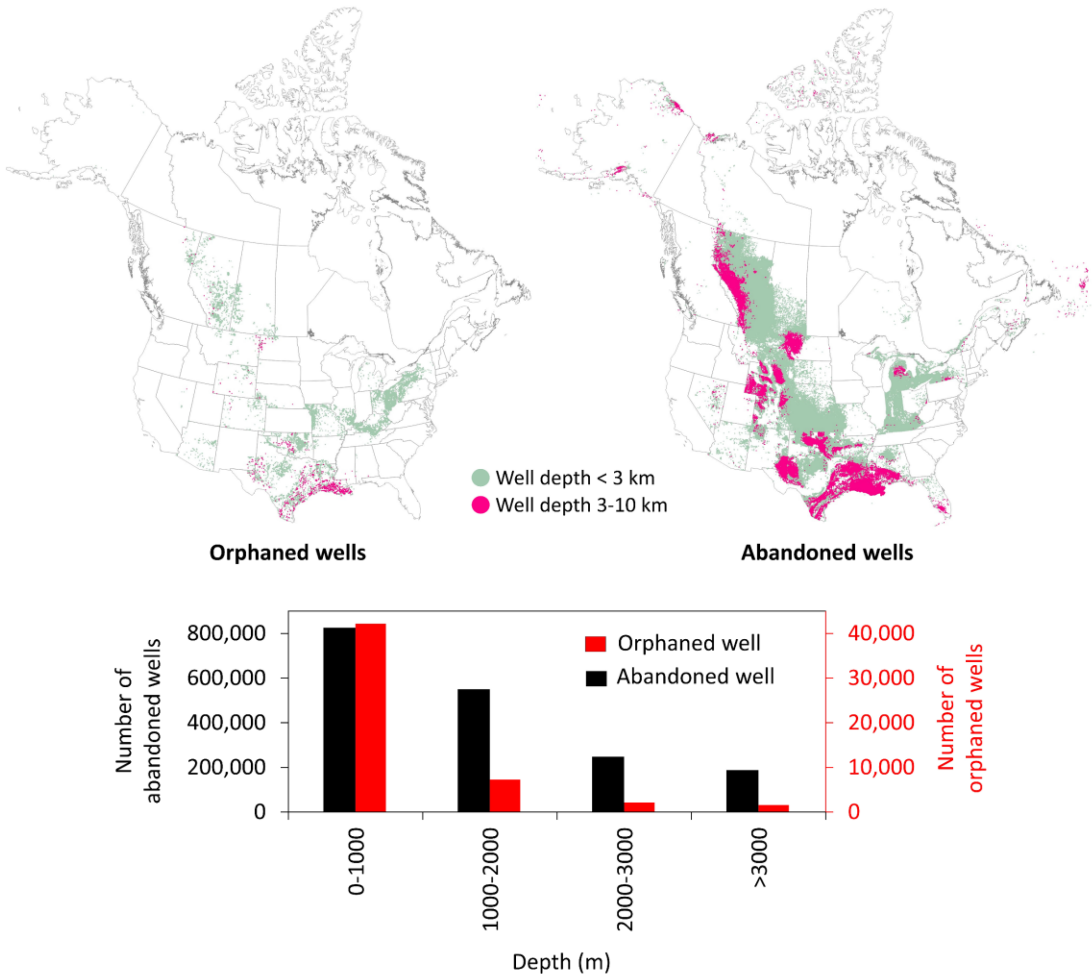

Fig. 4.3: Available orphaned and abandoned oil and gas well depth across Canada and the United States. The "abandoned well" category in this figure does not include orphaned wells. The bar chart (bottom) offers the distribution of well depth, while the maps (top) show the spatial distribution of well depths suited for hydrothermal geothermal wells (< 3km deep) and enhanced geothermal systems (3-10 km deep).

To evaluate the potential for geothermal energy across Canada and the U.S., we analyzed maps of heat flow and technical enhanced geothermal system (EGS) potential from the International Renewable Agency (IRENA) (Fig. 4). Heat flow, which represents the amount of thermal energy at the well site, was used as a proxy for hydrothermal and EGS geothermal potential. To evaluate the potential for EGS specifically, we analyzed EGS power density values, which are derived from geology and temperature data.

Based on heat flow only, orphaned wells with the highest hydrothermal and EGS geothermal potential (>60 mW/m^2) are in Pennsylvania (18,513 wells or 47% of orphaned wells in the state), Oklahoma (6,226 wells or 40% of orphaned wells in the state), and California (4,274 wells or 80% of orphaned wells in the state) (Supplementary Table 21). The majority of orphaned wells (52%) with the highest EGS potential (>0.2 MWe/km^2) are in California (2,402 wells or 23% of orphaned wells in the state) (Supplementary Table 23). The rest (21%) of the orphaned wells with the highest EGS potential are located in British Columbia (268 wells or 32% of orphaned wells in the province) and Colorado (239 wells or 52% of orphaned wells in the state). Most (51%) abandoned wells with the highest geothermal potential (>60 mW/m^2) based only on heat flow are located in Texas (229,393 wells or 23% of abandoned wells in the state), Kansas (129,445 wells or 43% of abandoned wells in the state), and California (125,728 wells or 76% of abandoned wells in the state) (Supplementary Table 22). The majority (80%) of abandoned wells with high EGS potential (>0.2 MWe/km^2) are in California (58,270 wells or 35% of abandoned wells in the state), Colorado (38,371 wells or 67% of abandoned wells in the state), and Texas (38,084 wells or 4% of abandoned wells in the state) (Supplementary Table 24).

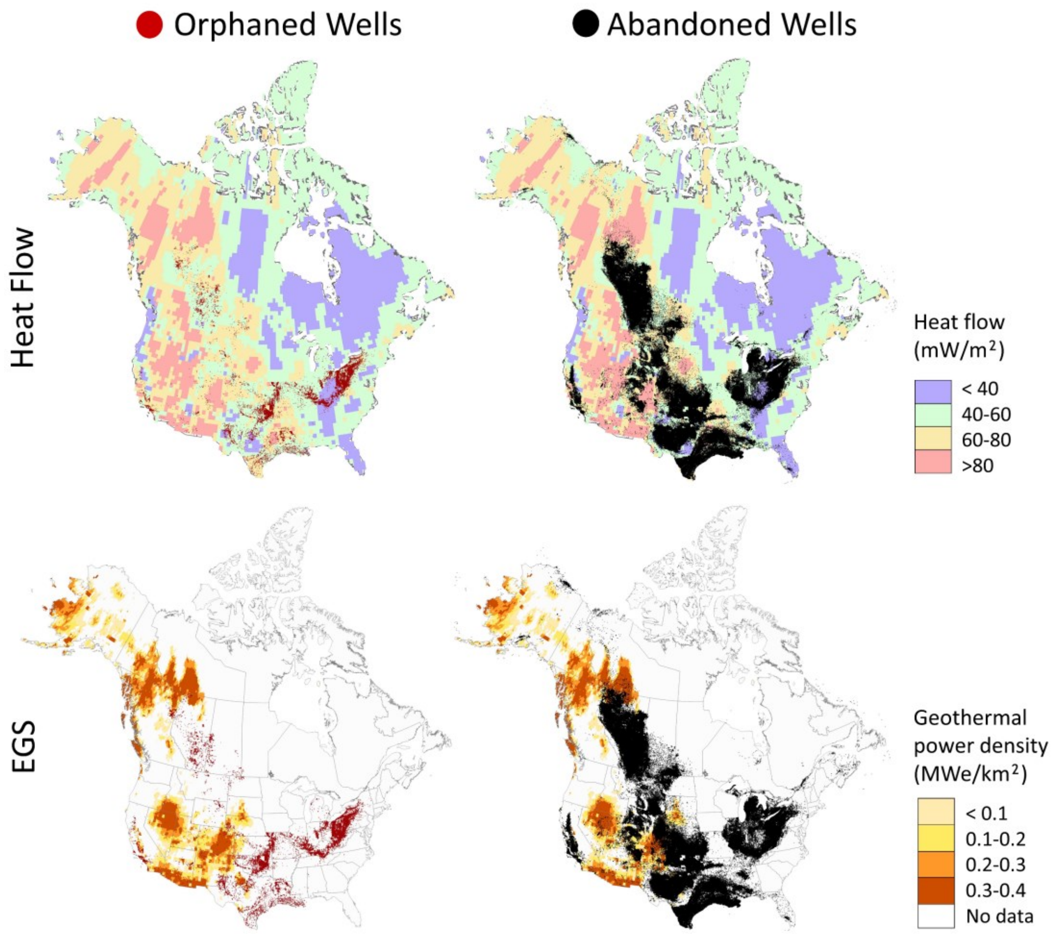

Fig. 4.4: Geothermal potential across Canada and the United States. The "abandoned well" category in this figure does not include orphaned wells. Geothermal potential is assessed via maps of heat flow (top) and potential for enhanced geothermal systems (bottom).

4.3. Discussion

In this study, we provide the first nation-wide assessment of wind, solar, and geothermal energy potential at abandoned and orphaned well sites across Canada and the U.S. Redeveloping these non-producing infrastructure and sites can bring many benefits, including reducing costs of renewable energy deployment (especially cost associated with site acquisition), preserving undeveloped lands that would have otherwise been used for renewable energy development, accelerating and incentivizing well plugging and remediation, creating jobs and stimulating the economy, and limiting climate change.

There are large variations in regulations for plugging and remediating abandoned and orphaned wells and restoring land surfaces and cover among states, provinces, and territories[31-33]. Ideally, the well is plugged, surface equipment is removed from the site, and the land is remediated and restored. However, depending on regulations, only a simple clean-up and surface equipment removal may be necessary with no requirements to restore the land to its original condition. Well site remediation and surface restoration can be especially expensive and can represent more than double the cost of plugging alone[33]. Certain regulatory bodies require operators to pay bonds, but they are often not sufficient to cover the full cost of plugging and restoration. Redeveloping abandoned and orphaned wells for renewable energy production may address this funding gap while providing a financial incentive for mitigation, increasing the land value, and creating jobs.

Several studies have detailed the opportunities and challenges of converting abandoned and orphaned wells to renewable energy production[6-8,34], while others have proposed prototype designs and analytical models[35-40]. Most of this research has been focused on retrofitting abandoned wells for geothermal energy; the potential for wind/solar redevelopments remains underexplored with only one solar project development to our knowledge[41]. There have not been any geospatial assessment studies conducted at the national/continental scale and very few have conducted pilot projects outside of the lab or numerical simulations[41-43].

To meet global commitments to net-zero emissions by 2050, the federal governments of Canada and the U.S. have released emission reduction targets for the oil and gas sector[16-17] and are investing in clean energy infrastructure, such as wind, solar, and geothermal[44-45]. Our database of abandoned and orphaned wells may be useful in developing individual projects. Furthermore, we show nation-wide potential for wind, solar, and geothermal energy production at abandoned and orphaned well locations, which could be useful in fulfilling and financing the U.S. and Canada's energy transition goals and emission reduction targets.

4.4. Methods

4.4.1. Compilation of abandoned and orphaned wells

To compile the number, location, and depth of abandoned and orphaned wells, we analyzed public oil and gas well databases provided by state, provincial, and territorial oil and gas regulatory agencies. When locations, definitions, or statuses of abandoned or orphaned wells were not available from public databases, we contacted the corresponding oil and gas agency to obtain the required information.

We use the abandoned well definition from the U.S. Environmental Protection Agency (2023)[9], which defines abandoned wells as plugged or unplugged wells with no recent production and with, or without a responsible operator. Depending on regulatory agency definitions, abandoned wells can include wells with a status of “inactive”, “temporarily abandoned”, “idle”, or “abandoned”. Orphaned wells are considered to be a subcategory of abandoned wells. Here, we separately compile abandoned and orphaned wells and do not include orphaned wells in our abandoned well compilation. We define orphaned wells as “unplugged non-producing 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”[18]. Depending on state/provincial/territorial definitions and statuses, orphaned wells can include wells with a status of “abandoned”, “revoked”, “unknown”, “shut-in”, or “forfeited”. In this study, the dataset of orphaned wells in the United States (as of April 2022) is obtained from Boutot *et al.* (2022) [18].

We quality controlled our dataset of abandoned and orphaned wells by (1) removing non-oil or gas wells (for example, salt solution mining wells) (2) removing duplicate records (including duplicate well events), (3) separating orphaned wells from our abandoned well dataset, and (4) removing unrealistic locations and depths.

We removed duplicate well records by excluding wells with rows containing identical entries in every column of the original state/provincial/territorial dataset. To remove duplicate well events, we used available unique oil and gas well numbers, which are API (American

Petroleum Institute) numbers for the U.S and UWI (Unique Well Identifier) numbers in Canada. Although unique well numbers were not available for all wells, API numbers were used by all U.S. states included in this study except for Indiana and UWI numbers in Canada were used only by Alberta, British Columbia, Manitoba, Newfoundland and Labrador, Northwest Territories, Nunavut, Saskatchewan, and Yukon. The other provinces in Canada (Quebec, Ontario, New Brunswick, Nova Scotia, and Prince Edward Island) use different well identification numbers specific to the province, such as well license numbers. Typically, the last two digits of a unique well number represent the well event code (for example, 13-14th digits of an API number), which are chronologically sequenced in order of well re-entry operations (for example, drilling and/or completion) and can occur even after the well has been plugged and abandoned. However, most unique well numbers in our dataset did not have a well event code. When a well event code was available, we removed wells with identical unique well numbers and different well event codes, and retained the well entry with the most recent well event code. Lastly, we separated orphaned wells from our abandoned well dataset based on matching API10 numbers for the U.S. and UWI numbers for Canada.

The abandoned and orphaned well locations were quality controlled in *ArcGIS* using the same methodology as in Boutot *et al.* (2022)[18]. We used the "Near" tool in *ArcGIS* to determine if the well locations were within 2 km of the corresponding state border or within federal waters. For Kansas, the orphaned 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.

Combining multiple public oil and gas well datasets introduces uncertainties, which can only be measured qualitatively (Supplementary Notes 1-3). We note that our dataset only includes wells documented in public databases. As such, it does not include undocumented wells or wells sourced from proprietary databases. We find that location and depth information is missing for many wells, mainly due to lack of recordkeeping and nondigitized records, especially for older wells. As such, there are likely many more abandoned and orphaned wells that are not documented in public databases or with incomplete records. As such, our study only reflects the state of current public knowledge on abandoned and orphaned wells. Nonetheless, our dataset and associated results can support national and continental analysis and help inform policies and regulations.

4.4.2. Compilation of abandoned and orphaned well depths

We compiled available well depth data from public oil and gas well databases across Canada and the U.S. as described above. For abandoned and orphaned wells in the United States, we converted depth values from feet to meters. We quality controlled the depth values by removing any unrealistic depths or likely placeholder values such as “-999”, “0”, or “NaN’’.

4.4.3. Estimating wind energy potential

Wind power density, a function of wind speed and air density, was used as a proxy to determine wind energy potential at abandoned and orphaned well sites. It represents the mean annual power available per square meter of a turbine’s swept area. To determine wind potential at abandoned and orphaned well sites, we acquired a 250-m resolution map of mean wind power density at a 100 m height from the Global Wind Atlas[29] for Canada and the U.S. Based on validation results conducted at 35 sites in 6 different countries, the authors of the Global Wind Atlas estimate a mean absolute bias of 14% between modeled and field-measured wind speeds. We sampled values of wind power density from the Global Wind Atlas raster at abandoned and orphaned well locations using *ArcGIS*.

4.4.4. Estimating solar energy potential

To identify solar energy potential at abandoned and orphaned well sites, we determined values of photovoltaic (PV) power potential. PV power potential represents the amount of achievable solar power generated per unit of installed PV capacity, assuming a typical utility-scale PV system. This metric considers other factors such as global horizontal irradiation, air temperature, system configuration, shading, and topography.

We acquired a map of PV power potential across Canada and the U.S. from the Global Solar Atlas[30]. In *ArcGIS*, we sampled values from the Global Solar Atlas raster at abandoned and orphaned well locations. The Global Solar Atlas was developed and operated by the company

Solargis, on behalf of the World Bank Group and utilizes data from the *Solargis* model. The *Solargis* model has been validated at 228 sites around the world and the biases average at +0.3% for global horizontal irradiance (GHI) and +2.2% for direct normal irradiance (DNI)[46]. More details on the methodology can be obtained from the Global Solar Atlas website or the *Solargis* technical report[46].

4.4.5. <u>Determining land cover type</u>

We determine the land cover type at abandoned and orphaned well sites to infer the potential for wind and solar energy development. To create a land cover map for Canada and the U.S., we retrieved the "National Land Cover Database 2019 - CONUS" [26] and "National Land Cover Database 2016 – Alaska"[27] from the U.S. Geological Survey (USGS) and the "2020 Land Cover of Canada" from Natural Resources Canada[28]. The land cover maps for Canada and the U.S. are based on 30-meter resolution Landsat satellite imagery.

The land cover dataset for Canada is produced using observation from the Operational Land Imager (OLI) Landsat sensor. Natural Resources Canada conducted an accuracy assessment based on 832 randomly distributed samples and found the land cover map to be accurate at 86.9%[28]. The U.S. Geological Survey conducted a similar analysis based on stratified random samples and estimated an accuracy of 77.5%[47]. Similar to the land cover analysis in Kang *et al.* (2023)[2], we merged the 20 land cover classifications for the U.S. and 15 land cover classifications for Canada to obtain a simplified classification with six land cover categories: "Agriculture", "Developed", "Forest", "Shrubland/Grassland", "Wetland", and "Other".

4.4.6. <u>Estimating geothermal energy potential</u>

We evaluate the potential for EGS and hydrothermal geothermal systems at abandoned and orphaned well locations by acquiring maps of heat flow and EGS technical potential from the Global Atlas for Renewable Energy maintained by the International Renewable Energy Agency (IRENA)[48].

Heat flow represents the amount of energy moving from the earth towards the surface and is a function of rock thermal conductivity and temperature gradient. The IRENA heat flow map has a 70 km resolution and was developed by the Royal Melbourne Institute of Technology (RMIT) from the Global Heat Flow Database maintained by the International Heat Flow Commission (IHFC). The heat flow data points in the Global Heat Flow Database are sourced from heat flow measurements in peer-reviewed publications and public databases.

The map of EGS potential represents the theoretical EGS potential that might be extracted after considering land access, heat flow, recoverability factor, and temperature drawdown factor. It is assumed that the wells have a depth between 3-10 km and a recovery factor of 14%. The map of EGS potential has a 18 km resolution and is based on the peer-reviewed protocol by Beardsmore *et al.* (2011)[49] to estimate and map global EGS potential.

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5. General Discussion

5.1. Policy implications for orphaned wells

In this thesis, we highlight the importance of analyzing data on orphaned oil and gas wells to inform policies and regulations. In Chapter 3, we specifically focus on identifying and characterizing documented orphaned wells, which are wells eligible to be plugged and remediated in the U.S. with federal funding from the Bipartisan Infrastructure Law (BIL or Infrastructure and Investment Jobs Act). In the following section, we provide updated definitions of “documented orphaned wells” from the BIL guidelines and review state plugging prioritization systems. Furthermore, we discuss the policy implications of methane emission from orphaned wells and consider alternative end-of-life options. Lastly, we show the need for further research on documented orphaned wells to inform federal spending, policies, and regulations.

5.1.1. Documented orphaned well definitions in the United States

At the time of the publication of Chapter 3, the U.S. Department of the Interior (DOI) had released initial guidance to states on activities permissible to be carried out under the initial grants of the IIJA and recommended practices for plugging and remediating documented orphaned wells (U.S. Department of the Interior, 2022). In Chapter 3, we show that in these initial guidelines, there are no definitions for “documented orphaned wells”, which are wells eligible for funding, and “undocumented orphaned wells”, which are recommended to be identified and characterized by states. A few months later, a revised set of guidelines was published (U.S. Department of the Interior, 2023). In these guidelines, the terms “documented orphaned wells” and “undocumented orphaned wells” are now defined based on the IOGCC definitions (2021). However, contrary to the IOGCC definition, the new DOI definition requires the precise well location (i.e., latitude/longitude) and other well attributes (e.g., type of well, surface ownership, mineral ownership) for the well to be considered “documented orphaned”. If states fail to provide the precise coordinates and other attributes of documented orphaned wells, the grant amount provided to the state will be reduced. This ensures that states have characterized and verified the existence of documented orphaned wells and receive appropriate funding for plugging and remediation. Furthermore, this highlights the growing importance of characterizing documented orphaned wells and establishing consistent definitions for orphaned wells across states, since only "documented orphaned wells" will be eligible for funding through the IIJA.

5.1.2. Plugging prioritization for documented orphaned wells in the United States

In October 2022, the first documented orphaned wells were plugged and remediated in Illinois, Louisiana, and Texas using initial grant funding from the IIJA (Environmental Defense Fund, 2022; U.S. Department of the Interior, 2023). Among the activities eligible for funding, states can prioritize orphaned wells for remediation based on factors such as public health/safety, environmental impacts, and land use priorities. As such, ranking systems may be state-specific to meet the states' particular needs. As highlighted in the most recent guidelines (U.S. Department of the Interior, 2023), states will need to prioritize the highest methane emitters and documented orphaned wells located within 0.5 miles of communities of color, low-income communities, and Tribal and indigenous communities. Texas (Railroad Commission of Texas, 2022), New York (New York Department of Environmental Conservation, 2022), and New Mexico (State of New Mexico Energy, Minerals and Natural Resources Department, 2022) use a scoring rubric to assess the risk to public safety and the environment. For example, once the well is located and inspected by the state, it is scored with numeric values based on various factors (e.g., location, methane emissions) and the component scores are summed to establish a total score. Higher scoring wells represent a greater risk and are therefore given higher priority for plugging. Six states (including California, Mississippi and West Virginia) have committed to measuring methane before and after plugging, while 12 states (including Ohio, Kansas, and New Mexico) have prioritized plugging wells in disadvantaged communities, and several states plan on prioritizing small businesses when issuing plugging contracts (U.S. Department of the Interior, 2023). As more states begin plugging documented orphaned wells and developing their own ranking systems, it will become increasingly important to better characterize documented orphaned wells for cost-effective plugging and remediation operations.

5.1.3. Policy implications of methane emissions from orphaned wells

In this thesis, we estimate that methane emissions from orphaned wells represent a small percentage (5-6%) of total methane emissions estimated for all abandoned wells by the U.S. EPA in their greenhouse gas inventory (2022). However, this estimate remains highly uncertain since it does not rely on emission factors developed specifically for orphaned wells. Instead, we use emission factors based on a small number of direct measurements made at a few abandoned well locations. Furthermore, we use generic emission factors when there was no available well type information (i.e., oil vs gas). Moreover, other than well type and geographic location, we have not considered other factors that may affect emission rates, such as well age or wellbore deviation (El Hachem and Kang, 2023). Although emission factors developed for abandoned wells may include measurements from orphaned wells, studies so far have not differentiated emission factors between orphaned and other abandoned wells. Therefore, to our knowledge, there are currently no emission factors specifically for orphaned wells. Even with the high uncertainties associated with our results, we provide a first nationwide estimate of methane emissions from orphaned wells, which may be useful for policies and mitigation.

There is a need to measure methane emissions at orphaned well locations specifically to better characterize their emissions, develop representative emission factors, and reduce emission uncertainties. Our understanding of methane emissions from the larger population of abandoned wells may not be representative of emissions at orphaned wells and their emission distribution may be different. To our knowledge, only one study has measured methane emissions from orphaned wells (Nivitanont *et al.*, 2023), but the small sample size of 10 orphaned wells is not sufficient to accurately characterize orphaned well emissions nationwide. Therefore, additional measurements and characterization are essential to obtain more representative datasets and emission factors developed specifically for orphaned wells.

Providing a first national estimate of methane emissions from orphaned wells is helpful to determine the magnitude of emissions, inform national greenhouse gas inventories, and develop mitigation strategies. The methodology used in this work could be applied to other countries in their efforts of reducing methane emissions and reporting fugitive emission sources in their national greenhouse gas inventories. In general, national emission inventories use technology- and country-specific emission factors derived from direct measurements. However, when measurements are unavailable, default emission factors derived from measurements made outside of the country can be used. While we found that methane emissions from orphaned wells only represent a small percentage of the total methane emissions from the oil and gas sector in the U.S., this might not be the case for other countries. Importantly, the total number of orphaned wells around the world remains unknown. Therefore, our results might have important implications for emission reporting and mitigation strategies for countries with a long history of oil and gas production. Overall, the methane emission estimate for orphaned wells provided in this work can help improve our understanding of orphaned well emissions and help policy makers develop mitigation strategies at the national and global level.

5.1.4. <u>End-of-life considerations after well abandonment</u>

Many wells drilled today will likely become abandoned or orphaned in a few years or decades. Currently, most regulatory agencies in Canada and the U.S. require bonds to cover plugging and restoration costs. However, bonds almost never meet the full cost of restoration, often forcing taxpayers to cover the clean up costs in the event operators declare bankruptcy or are unable to pay (Ho *et al.*, 2018; Raimi *et al.*, 2021; Kang *et al.*, 2021). To that effect, the U.S. Department of the Interior and the Bureau of Land Management have recently proposed increasing bonding requirements, which have not been raised since 1960 (Department of the Interior and Bureau of Land Management, 2023). The rule proposes to increase the minimum lease bond amount from the existing $10,000 to $150,000 and increase the minimum statewide bond amount, which would cover all leases and operations in a state, from the current $25,000 to $500,000. The proposed rule aims to prevent the financial burden of plugging and restoring orphaned wells from falling on taxpayers. However, we show in this work that repurposing abandoned and orphaned wells to renewable energy could represent significant cost savings by covering some of the costs associated with plugging and remediation. Converting wells to renewable energy at the end of their production life could be included in policies and bonding structures. For example, fees or bonds similar to the ones already in place could be required to ensure oil and gas wells and associated sites are converted to solar, wind, or geothermal energy after abandonment. Furthermore, tax credits or incentives similar to the ones provided by the Inflation Reduction Act for renewable energy projects sitting on brownfield sites (Internal Revenue Service, 2022), could be granted for abandoned and orphaned well sites. Therefore, more research is needed to determine the policy implications and cost savings achieved by including the conversion of abandoned wells to renewable energy in regulations and life-cycle planning of new and active oil and gas wells.

5.2. Global increase in abandoned and orphaned well numbers

As society transitions away from oil and gas and towards cleaner sources of energy, the current fleet of wells that are active today will inevitably become abandoned or orphaned. In 2022, the province of Quebec became the first jurisdiction in the world, and currently the only one in Canada and the U.S., to ban oil and gas exploration and production as well as prohibit its public financing (Government of Quebec, 2022). By passing this legislation, Quebec joined the Beyond Oil and Gas Alliance (BOGA), an international coalition of governments aiming to cease oil and gas production, which is led by Denmark and Costa Rica and with core members consisting of France, Greenland, Ireland, Portugal, Sweden, Tuvalu, Vanuatu, and Wales (BOGA, 2023). However, most of these jurisdictions are not major global oil and gas producers and only intend to ban oil and gas production in the next decades (e.g., by 2050). It is estimated that annual oil and gas production must decline globally by 3% each year until 2050 to keep global temperature rise below 1.5°C (Welsby *et al.*, 2021). In the next decades, as oil and gas production declines around the world, the millions of currently active oil and gas wells will become abandoned or orphaned. Therefore, it is important to develop frameworks to safely manage the millions of wells that are, or will become, abandoned and orphaned and consider how they can be repurposed for renewable energy production.

The total number of abandoned and orphaned oil and gas wells around the world, both onshore and offshore, is still uncertain due to lack of well data (Davies *et al.*, 2014; Agerton *et al.*, 2023). By applying the estimated proportion of abandoned to active wells in Canada and the U.S.

(Kang *et al.*, 2021), there are likely tens of millions of abandoned and orphaned wells globally. Proprietary databases (e.g., Enverus and IHS Markit) may contain worldwide estimates of abandoned and orphaned well numbers, but their sources can be uncertain and their data processing methods can lack transparency. Therefore, geospatial inventories of abandoned and orphaned wells in Canada and the U.S., along with their attributes (e.g., oil and gas production), may be helpful in estimating abandoned and orphaned well numbers in other countries around the world.

Abandoned and orphaned well numbers can change over time due to various factors such as oil and gas prices, bankruptcies of oil and gas companies, improvements in regulatory agencies data management, and introduction of new policies. However, the factors affecting the temporal variations in abandoned and orphaned well numbers remain uncertain. One study found a large spike in orphaned well numbers in Alberta when oil prices dropped in 2016 to 2018 (Kang et al., 2021), but we do not find similar trends in our work. We show that low oil prices do not consistently lead to more wells becoming orphaned in the U.S. at a monthly or annual time scale. However, our data is limited to a few years and does not cover all U.S. states or the larger population of abandoned wells. Apart from oil prices, the effect of other factors on the number of abandoned and orphaned wells have not been studied. As such, we do not yet fully understand when and at what time scale wells become abandoned or orphaned. Additional data compilation and analysis are needed to better understand temporal variations in abandoned and orphaned well numbers and develop appropriate policies to limit the number of wells becoming abandoned and orphaned around the world.

5.3. Other impacts of abandoned and orphaned wells

In this thesis, we mostly focus on methane emissions and land use impacts of abandoned and orphaned wells; however, other impacts, such as water contamination, air pollution, and human health impacts also need to be considered when discussing the risks of abandoned and orphaned wells.

5.3.1. Air pollution

Only a few studies, to our knowledge, have measured non-methane air pollution from abandoned wells, while no studies have focused specifically on orphaned wells. Lebel *et al.* (2020) measured concentrations of benzene, a known human carcinogen, from one unplugged methane-emitting well in California and found benzene concentrations to be nondetectable. Another study measured hydrogen sulfide (H_2S), a highly toxic gas, at two abandoned wells and one potential undocumented well in Ontario (El Hachem and Kang, 2022) and found H_2S-emitting abandoned wells to also be high methane emitters. High methane emissions might be a proxy for estimating emissions of non-methane air pollutants, but remains difficult to determine due to the scarcity of measurements (Kang *et al.*, 2023). A recent study by DiGiulio *et al.* (2023) detected benzene at nearly 70% of measured abandoned wells in Pennsylvania. However, air pollution measurements from only a small subset of abandoned wells are not sufficient to evaluate the full range of impacts on air quality. In addition, no measurements of other air pollutants known to be associated with active oil and gas development, such as particulate matter, nitrogen oxides, or sulfur dioxide, have been conducted at abandoned and orphaned wells. Therefore, additional measurements are needed to better understand the impacts of abandoned and orphaned wells on air quality. In the meantime, plugging abandoned wells might be helpful at reducing not only methane emissions, but also other air pollutants.

5.3.2. Health impacts

To our knowledge, there are no health studies specifically for abandoned or orphaned wells, even though there are at least 4.6 million people living within 1 km of one or more documented orphaned wells in the U.S. (Kang *et al.*, 2023). As mentioned above, abandoned wells have been found to emit highly toxic gas (El Hachem and Kang, 2022) and volatile organic compounds (VOCs) (Lebel *et al.*, 2020; DiGiulio *et al.*, 2023). However, the authors specify that more research is needed to determine whether these emissions from abandoned wells can pose health risks to people living or working near abandoned and orphaned wells. Most health studies have been conducted for active oil and gas development, especially for unconventional operations (HEI Energy, 2023; PSE Healthy Energy, 2023). Some of the observed impacts include adverse birth outcomes, respiratory tract damage, and cancer development, but the pathways that may cause these impacts remain unclear (Deziel *et al.*, 2020; Yadav *et al.*, 2021; Caron-Beaudoin *et al.*, 2021). Studies have also examined the health impacts of oil and gas development on wildlife and domesticated animals, which include respiratory and growth problems (Deziel *et al.*, 2022). Therefore, to prioritize mitigation, further research is needed to better understand how abandoned and orphaned wells impact wildlife and human health.

5.3.3. Water contamination

Abandoned and orphaned wells can provide pathways for the subsurface migration of fluids such as oil, gas, and other pollutants leading to the contamination of groundwater aquifers and surface water (Jackson *et al.*, 2013; Kang *et al.*, 2015). Even if methane emissions are not occurring at the surface, abandoned and orphaned wells can still contaminate water sources (McMahon *et al.*, 2018; Schout *et al.*, 2019). A study reviewing incident reports of groundwater contamination found that 22% of 185 reported incidents in Ohio over a 25 year period (1983-2007) were caused by orphaned well leakage, while 27% of 211 reported incidents in Texas over a 16 year period (1993-2008) were caused by abandoned water disposal sites leaking elevated concentrations of chloride and benzene (Kell, 2011). Additionally in Texas, another study found five orphaned wells releasing large volumes of water, hydrogen sulfide, brine, oil residues, and other hazardous substances (Townsend-Small *et al.*, 2021). Most wells have barriers to prevent leakage, and after abandonment, plugging (often with cement) is required to isolate oil, gas, or water formations. However, well plugging can potentially increase the risks of groundwater contamination, especially if the well is poorly plugged (Jackson *et al.*, 2020). For example, an abandoned gas well in Colorado was found to be contaminating shallow groundwater with methane nearly 30 years after it was plugged (McMahon *et al.*, 2018). To date, only a few case studies have linked groundwater contamination to abandoned and orphaned wells, mainly due to lack of monitoring, scarcity of water quality data, and the complexities of subsurface pathways (Wen *et al.*, 2019; Kang *et al.*, 2023). A recent study by Kang *et al.* (2023) found that 35% of documented orphaned wells in the U.S. are located within 1 km of a domestic groundwater well (Perrone and Jasechko, 2019). To our knowledge, there are no national/regional scale study on surface and subsurface water contamination caused specifically by abandoned and orphaned wells. More research is needed to further characterize the impacts of abandoned and orphaned wells on water quality.

6. General Conclusion

6.1. Summary of results

In this thesis, we compiled inventories of orphaned and abandoned oil and gas wells across Canada and the United States and analyzed their well attributes, spatial distribution, and potential for renewable energy production. We also provided the only temporal analysis of documented orphaned well numbers with oil prices. In addition, we identified data gaps in oil and gas well databases and determined uncertainties in abandoned and orphaned well numbers and attributes.

Based on oil and gas well data from state agencies, we identified and estimated the number of documented orphaned wells in the United States over time and evaluated their attributes. We identified at least 81,857 documented orphaned wells as of September 2021 and 123,318 as of April 2022, representing a 50% increase in the number of documented orphaned well in the span of 6 months. We estimated annual methane emissions to average 0.016 MMt of CH_4 for the 123,318 documented orphaned wells as of April 2022, corresponding to 5% of the total methane emissions estimated by the U.S. EPA for all abandoned wells. We showed that although well type is available for 83% of the 81,857 documented orphaned wells as of September 2021, about half (51%) of available well type are reported as “unknown”, meaning that well type is only known for 41% of the 81,857 documented orphaned wells. Furthermore, 49% and 16% of the documented orphaned wells as of September 2021 have information on depth and last production date, respectively. Overall, we highlighted the need for additional characterization and studies on documented orphaned wells and their attributes to optimize federal spending and mitigation efforts.

Abandoned and orphaned well sites may be repurposed for wind and solar energy, while the wells themselves can be redeveloped for geothermal energy production. Using public well data from state, provincial, and territorial oil and gas regulatory agencies, we compiled the location and depth of all abandoned and orphaned wells across Canada and the United States to estimate their potential for renewable energy production (wind, solar, and geothermal). We estimated the total number of abandoned and orphaned oil and gas wells in Canada and the United States to be 3,746,078, of which 3% are orphaned and in need of government funding. Using national maps of renewable energy potential, we find that abandoned and orphaned wells differ in spatial patterns and renewable energy potential. We show large wind (> 400 W/m^2) and solar (> 1,600 kWh/kWp) energy potential at more than one million abandoned and orphaned well sites. We find that more than 90% of abandoned and orphaned wells with available depth are better suited for hydrothermal systems, yet enhanced geothermal is possible at up to 10% of the wells. Converting abandoned and orphaned wells to renewable energy production can help fulfill and finance the U.S. and Canada's renewable energy transition goals and emission reduction targets.

In this work, we highlight the need for more comprehensive data on abandoned and orphaned wells, particularly from oil and gas regulatory agencies across Canada and the U.S., to identify uncertainties and limitations in abandoned and orphaned well counts and attributes. Importantly, we show how data on abandoned and orphaned wells can inform policies, regulations, and mitigation. Our datasets and related findings can serve as a basis for future research on quantifying the impacts and opportunities of abandoned and orphaned wells across Canada, the United States, and beyond.

6.2. Limitations and recommendations

This work provides previously-unavailable datasets of abandoned and orphaned oil and gas wells and analyzes their attributes and potential for renewable energy production. Therefore, our work is a first steps towards characterizing, mitigating, and repurposing the millions of abandoned and orphaned wells across Canada and the United States. In this section, we provide limitations of our work and propose recommendations for future research efforts.

Our numbers of abandoned and orphaned wells in Canada and the U.S. contain uncertainties and are incomplete. In this thesis, we compile well counts, locations, and other attributes from public databases maintained by regulatory oil and gas agencies. However, due to lack of recordkeeping and undigitized records and the long history of oil and gas development and regulations, many abandoned and orphaned wells and their characteristics are not recorded in public databases. Notably, our compilation does not rely on estimates or assumptions based on expert opinion nor do we attempt to quantify undocumented orphaned or abandoned wells using other soft data. There are likely tens of thousands of undocumented orphaned wells in Canada (El Hachem and Kang, 2022) and up to a million in the U.S. (IOGCC, 2021; Williams *et al.*, 2021), which would significantly increase the number of orphaned wells found in our compilations. Therefore, additional efforts are needed to locate and characterize abandoned and orphaned wells to constrain their uncertainties, inform plugging and remediation efforts, and evaluate their potential for renewable energy.

Large uncertainties remain in abandoned and orphaned well coordinates. Location information from public or proprietary databases may not agree with field inspections (Saint-Vincent *et al.*, 2020a). Well locations from public databases are not often accurate, largely due to differences in spatial localization technologies or improper conversion between coordinate systems (Saint-Vincent *et al.*, 2020b). Overall, our analysis of spatial distribution and renewable energy potential are as precise as the abandoned and orphaned well coordinates from public oil and gas well datasets. Furthermore, the maps of renewable energy potential used in this study contain their own uncertainties. Here, we only quantify renewable energy potential at the national scale and do not attempt to give recommendations for specific sites. Thus, additional studies are needed to verify abandoned and orphaned well locations and develop a framework to quantify renewable energy potential at specific locations.

To determine renewable energy potential, we did not explicitly consider other factors than the ones included in the renewable energy maps. Factors such as regulations, policies, or technical and economic limitations are site specific and are important in determining the feasibility and success of a renewable energy project. For example, important parameters in determining geothermal potential include site geology, reservoir characteristics, and well integrity. For solar and wind development, important site-specific conditions include land size, land value, and distance from power lines. As such, further studies are needed to evaluate the factors that are critical in repurposing abandoned and orphaned wells to wind, solar, and geothermal energy development. Nonetheless, our work can lay the foundation for future studies determining renewable energy potential at abandoned and orphaned well locations in Canada and the United States.

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