Young Scientists Summer Program

Methane emissions from global Abandoned Oil and Gas wells

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It was finished by Tianyang LEI and has not been altered or revised since.

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Abstract

Abandoned oil and gas wells are both potential crucial sources of methane emissions and capacity for carbon storage. Numerous and continuously growing numbers of global abandoned oil and gas wells can be a key obstacle in delivering the Paris Agreement goals of keeping global warming below 1.5ºC. Abandoned oil and gas wells worldwide will continue releasing methane into the atmosphere without effective cleaning-up strategies, but the actual numbers, methane flux, and geology-related details of them remain poorly understood. Here, we developed a resource-type-specific and complete emission inventory for global abandoned oil and gas wells at the well/state/territorial/country levels, covering 4.5 million abandoned wells worldwide by 2020, 9% of which are identified individually in terms of emissions and well-level details. According to our estimate, annual methane leakage of global abandoned oil and gas wells is about 0.4 million tons in 2022, which is 1% of total global oil and gas sector methane emissions, 70% of which come from abandoned wells in the United States. There are strong characteristic heterogeneities among abandoned oil and gas wells in terms of terrain, resource type, plugging status, geographical location and so on. Timely plugging of those abandoned wells is critical for eliminating methane leakage from abandoned wells, particularly from historically major oil and gas producers, which could potentially reduce global cumulative emissions from this source by 31% during 2022 to 2050.

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Tianyang Lei is a Ph.D. candidate in the Department of Earth System Science at Tsinghua University. Her current research focuses on the development of global key infrastructure greenhouses gas emissions datasets, such as oil and gas facilities, iron and steel plants, and so on. (Contact: leity19@mails.tsinghua.edu.cn)

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Introduction

Net-zero greenhouse gas emissions is the central focal point in curbing climate change today, both in the scientific and political discussion[1-3]. Many countries have set climate neutrality targets for the purpose of limiting global temperature increase well below 2°C and pursuing efforts to avoid a 1.5°C increase, as required by *the Paris Climate Agreement*[4-6], entailing a transition to net-zero carbon emission systems in every sector in the second half of the 21st century[5,7]. Thus, it is an urgent need of accelerating the energy transition and reducing greenhouse gas (GHG) emissions.

Methane is the second-most important anthropogenic greenhouse gas behind CO_2, but its warming impact over a 20-year period is 84 times greater than that of CO_2[8,9], making it a crucial target for emission reductions in the next two decades. According to the IPCC's global warming report of 1.5°C[6], reducing methane immediately along with other climate forcing gases are necessary to achieve the Paris Agreement.

Abandoned oil and gas (AOG) wells are potential crucial sources of methane emissions, however, with large uncertainty[10] and significant surface mitigation potential[11]. An abandoned well[12], even plugged appropriately, may still permanently leak methane[13]. Not to mention that millions of inactive wells worldwide are abandoned without enough clear measures. Methane emissions from the AOG wells at state-level[10-12,14,15], territorial-level[16,17], and country-level[18] have been assessed previously, and the methane leakage from the AOG wells have been included in national greenhouse gas inventories of United States[19] and Canada[20], but still largely overlooked in global emission reports. Although the latest report from IPCC AR6[21] mentioned the methane leakage from the AOG wells, it fails to give an estimate of AOG wells worldwide and the associated methane emissions. Considering the various oil and gas reserves[22], drilling history, and the environmental policies[16], most previous studies are limited to a certain region, which makes it difficult to use them as basis for generalized conclusions about methane mitigation of global AOG wells as they cannot be translated into effective mitigation action of high-emitters at the well-level.

A publicly available, harmonized and comprehensive dataset for measuring methane emissions is crucial for evaluating and decarbonizing the methane leakage of global AOG wells at all kinds of scales, such as well level, state-level, country level and global level. Here, we firstly developed a national methane inventory for global abandoned oil and gas wells, covering 4.5 million oil and gas wells in 127 countries. Details of the methods and data used to construct the inventory are shown in the ***Materials and Method Section***. This sheds light on the current methane leakage of closed oil and gas activities controlled by targeted contributors and supports the process to reduce methane emissions in view of global climate targets.

Results

Number of AOG wells worldwide

The total number of AOG wells worldwide are estimated at 4,493,000 of which (3,557,000 wells) are in the United States (**Figure 1**) according to our collected and compiled well/state/territorial datasets, research articles, national reports.

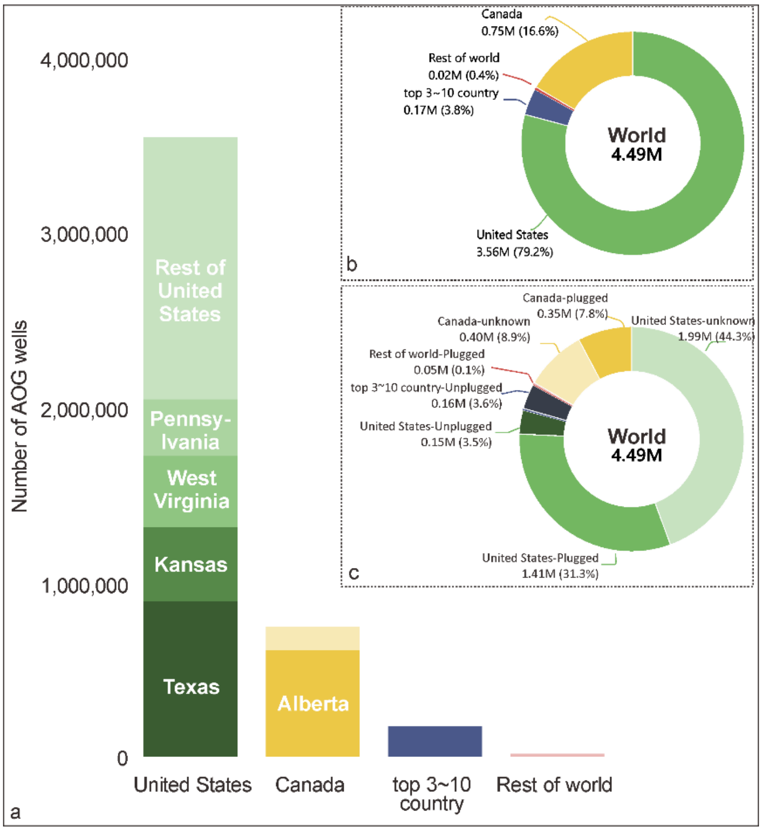

Figure 1 Number and distribution of AOG wells worldwide. a, *Number of the AOG wells by state/country/region;* ***b,*** *proportion of the AOG wells by main regions;* ***c,*** *proportion of the AOG wells by plugging-status at the region-level. top 3~10 country is classified by the number of national AOG wells: Romania, Argentina, Russia, Australia, United Kingdom, Brazil, Norway, and Mexico. Labels in the column represent the names of the state.*

Globally, **abandoned oil and gas wells are highly concentrated in a few countries** due to the oil and gas reserves and production history[22]. We find that up to 99.6% (4476.1 thousands) of the total number of AOG wells worldwide in 2022 are located in a mere ten countries (**Figure 1**).

Specifically, United States owns more than 79.2% of global AOG wells, mainly located in Texas, Kansas, West Virginia, and Pennsylvania, with century-and-a-half-long crude oil and gas production history[14], accounting for 25.1%, 12.0%, 11.6%, 9.1% of the national total, respectively (**Figure 1**a). Canada is the second-largest controller of AOG wells worldwide, owning 746.9 thousand AOG wells, of which 81.7% locate in Alberta. The high spatial concentration of AOG wells indicates that the management of abandoned oil and gas wells in these states is critical to the methane emissions from inactive oil and gas operations, not only for their own country but also globally. This has forced these state governments to investigate and obtain clear statistics on AOG wells: accurate number, location, and management policies, to reduce the uncertainty of AOG wells (lasting methane leakage, risks from sink), which may also benefit the applications for the storage potential of these inactive bore holes in the future. Moreover, the importance of Romania, one of the largest and oldest producers of oil and gas in Europe[23] cannot be ignored, having about 60 thousand AOG wells, most of which were drilled without modern environmental standards, making them not only a significant source of methane leakage but may also be very dangerous. Thus, it is an urgent need for Romania government companies to tackle action on the management of AOG wells.

Figure 1c shows the plugging status of the recorded global AOG wells by region. Obviously, **the proportion of plugged wells of the currently known AOG wells in the United States is higher than in the other region** (90% of total domestic known 1.6 million AOG wells), reflecting the strict management of discovered AOG Wells in the United States. A high proportion of plugged wells to the domestic total also shows in Canada, with 46.7% of its AOG wells have been plugged. Conversely, the general plugging rate in the other countries is lower than 30%, with 6.5% for the top 3~10 countries, and 27.1% for the rest of the world, calling for an urgent investigation and clearance of those abandoned oil and gas wells in the future.

Despite the higher plugging rate, **a vast amount of AOG wells remain unknown in the United States and Canada, which may be left from the oil drilling rush between 1859 and the mid-1870s**[24]. This number is even more than 12 times the total AOG wells in the rest of the world, urging these two countries to target these historically left orphaned oil and gas wells to reduce methane leakage and the associated high uncertainties.

Distribution patterns of abandoned oil and gas well methane leakage

Figure 2 presents methane emission and average emission intensity (annual methane emissions per well) by country; and the geographical location, current plugging status of 419,047 AOG wells across two different assumptions of unknown plugging status scenarios. As depicted in the Global AOG wells methane emission inventory, the total methane emissions of global AOG wells is 380.0 thousand tons (kt) in 2022 in the baseline scenario. The United States is the leading emitter of methane from abandoned oil and gas wells, contributing about 69.6% of the global total. Followed by Canada, contributing 10.8% of the global methane leakage from AOG wells. Romania, Norway, the United Kingdom, and Brazil are also critical to the methane leakage from their domestic AOG wells, contributing 5.2%, 3.9%, 3.0%, and 1.8%, respectively.

The importance of investigation and plugging of those unknown orphaned AOG wells in the United States and Canada is illustrated by **Figure 2**a, 2b, which show the methane emission under the baseline scenario and the unknown-plugged scenario, respectively. If all the currently unknown AOG wells are found and plugged, the methane emissions could be reduced by 55.3%. **Figure 2**c, 2d further emphasizes the importance of plugging these orphaned unknown wells in reducing methane leakage and supporting the net-zero carbon target, the average methane emission intensity of global AOG wells will diminish by 50% in the unknown-plugged scenario,

Figure 2a, **2c** illustrate a completely different global distribution pattern of total methane emission and average emissions intensity from AOG wells worldwide. In the baseline scenario, the methane emission intensity of the United States and Canada is lower than the global average, only 0.07 t/well/yr and 0.05 t/well/yr, respectively. Quite conversely, African countries alongside the coast, such as South Africa (13.8 t/yr), Republic of Congo (12.2 t/yr), Benin (30.6 t/yr), with very small emission amount but high emission intensity (higher than 1.4 t/well/yr). Given the terrain and plugging status of AOG wells shown in **Figure 2**, it is likely that **the high emission intensity in these countries is caused by the aggregation of unplugged AOG gas wells offshore**. Furthermore, despite the high rate of plugging AOG wells, the emission intensity of abandoned wells in Norway and the UK was 2.7 t/well/year and 0.9 t/well/year, respectively, much higher than Brazil (0.7 t/well/year), which also has a large number of abandoned offshore wells. This may be explained by the different resource types of abandoned well in these countries, as Norway and the United Kingdom are dominated by gas wells in the North Sea Shelf, while the majority of Brazil's offshore wells are oil/oil + gas mix, illustrating **the abandoned gas wells may be a key driver for methane leakage.** Thus, the **review, removal and monitoring of offshore abandoned gas wells** are critical in diminishing the methane leakage from inactive oil and gas operations and achieving climate targets worldwide.

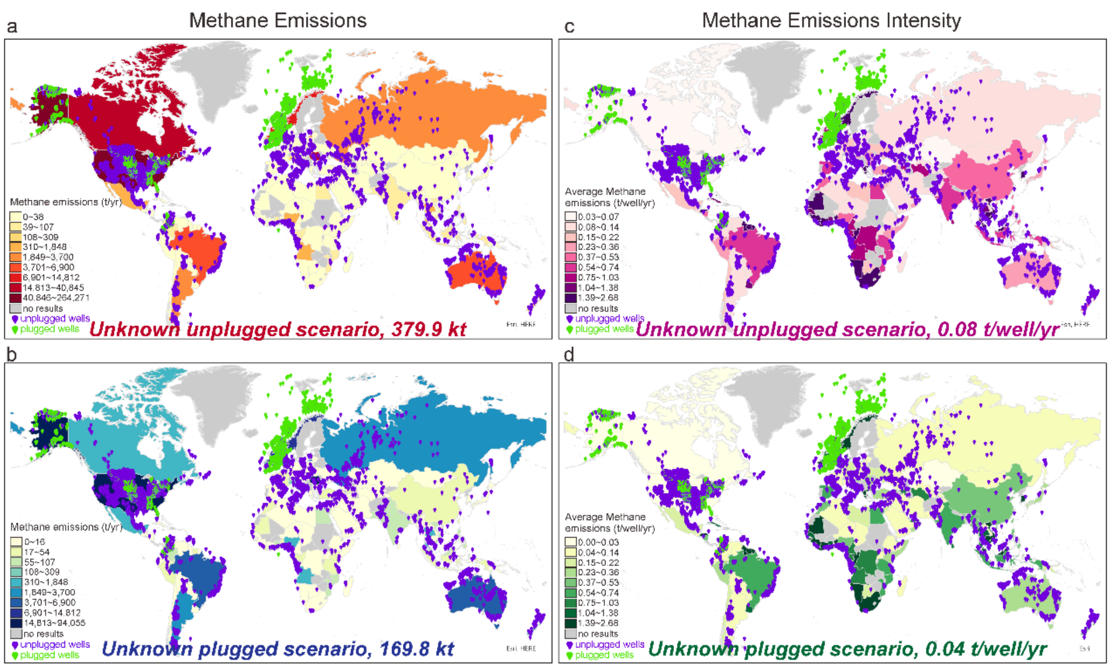

Figure 2 Map of methane leakage and emission intensity of AOG wells by country in different plugged policies scenarios. *Maps (**a-b**) show methane emissions under all the unknown plugging status wells unplugged scenarios (named as **baseline scenario**), all the unknown plugging status wells pluged scenarios. Maps (**c-d**) show the average emission intensity (methane emissions per well per year) in the unknown-unplugged scenario and*

unknown-plugged scenario. Points in each map show the location of currently known abandoned wells (purple for unplugged wells, green for plugged wells). Numbers at the bottom of each map indicate the global annual methane emissions (a-b) and global average emission intensity (c-d) for each scenario; shading denotes the regional distributions of these emissions and emission intensity.

Emission reduction potential of existing AOG wells

Considering the importance of plugging the AOG wells in controlling methane leakage and the dominance of the top 10 countries in the current AOG methane leakage, we have comprehensively analyzed the methane emissions mitigation pathway at the country level by assuming the plugging process. We suppose an annual growth rate of 5% for the number of country-/terrain-/resource-type-specific plugged AOG wells in the current major AOG wells methane leakage countries. We further analyze the potential methane emissions under the current baseline scenario and all-unknown-plugged scenarios in 2030, 2040, and 2050.

Figure 3 summarizes the potential methane emissions mitigation from AOG wells in 2030, 2040, and 2050 compared to the current methane leakage under the baseline and all-unknown-plugged scenarios. Overall, plugging the abandoned wells in the major countries can promote large-scale emission reduction from global AOG wells. In the baseline scenario, with the plugging process, the total methane leakage from AOG wells worldwide could be reduced by 50% to 199.4kt in 2050, while it can be 35.1% smaller (129.3kt) in the all-unknown plugged scenario. However, it will still not meet the net-zero carbon emissions under the Paris agreement of 1.5°C. We estimate the minimized methane leakage of the currently 4.5 million AOG wells worldwide by assuming the full plugging of all AOG wells under the current technology. The annual methane leakage could be reduced to a mere 96.5kt, still far from zero-emission, suggesting a deeper clearance and ongoing monitoring of those plugging AOG wells is needed to achieve truly net-zero carbon emissions in the future.

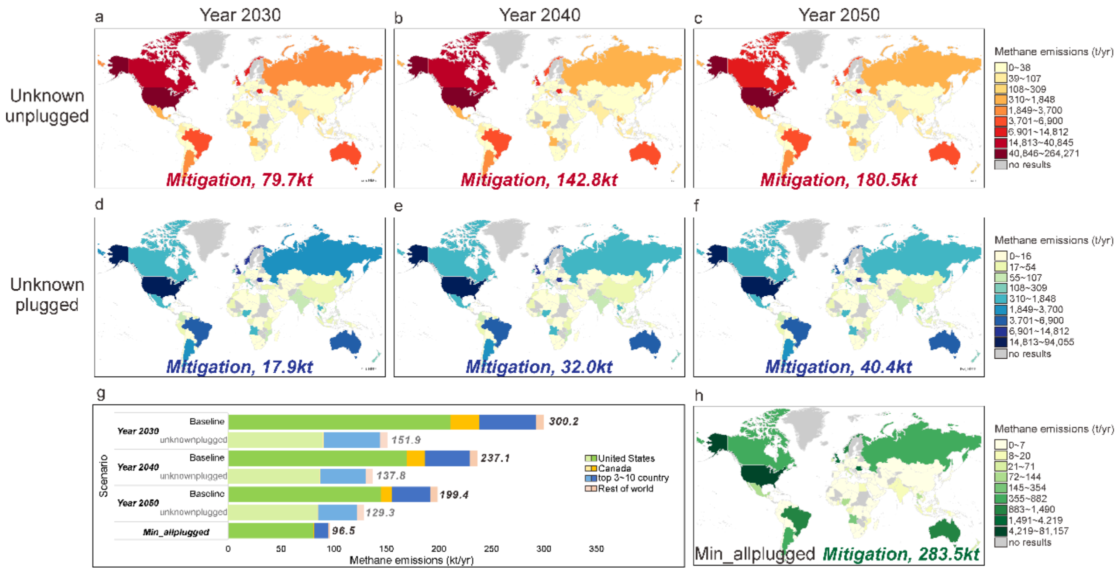

Figure 3 Potential methane emissions from global AOG wells assuming different plugging strategies in 2030, 2040, 2050. *Maps (a-f) show results by time point (column of panels) for 2 plugged strategies scenarios with different assumption of plugging status of currently unknown-plugging-status AOG wells (rows of panels); shading denotes the regional distributions of these emissions in the future. Numbers at the bottom of each map indicate the global methane emissions reductions in 2030, 2040, and 2050 compared to 2022 for each scenario. The bar charts (g) summarize the annual methane emissions in 2030, 2040, and 2050 by major region (color of stacked areas), showing the changes of methane emissions from the AOG wells under different plugging strategies (bar of column). Maps (h) show the minimum methane emissions if all currently recorded AOG wells were plugged with the current technology of AOG wells clearance.*

Discussions and Conclusions

Abandoned oil and gas wells are potentially a significant source of methane emissions. This study provides a detailed picture of the number of abandoned oil and gas wells, and associated methane leakage emissions, worldwide. This in turn offers a comprehensive understanding of methane emission patterns associated with well-type, plugging status of abandoned oil and gas wells. By evaluating the effect of plugging strategies of the abandoned oil and gas wells in the future, this study sheds light on the reduction of the inactive oil and gas activities to the net-zero emissions target required by the Paris Agreement. For example, timely plugging of abandoned oil and gas wells is critical to reducing leaking methane emissions and meeting global emissions reduction targets. In particular, the complete plugging of abandoned wells in major countries could reduce global emissions from abandoned wells by almost 4 times. Furthermore, we highlight that the spatial concentration of methane emissions from abandoned and active wells is entirely reversed and that developing regions have high methane emissions from active fields but low methane emissions from abandoned fields. Given the increasing number of oil and gas well shutdowns that the future energy transition may trigger, accurate information on the number of oil and gas wells in operation and proposals for drilling and exploration and ways to reduce leakage from abandoned oil and gas wells in both developed and developing regions will be critical to achieving future climate goals.

Materials and Method

Global Abandoned Oil and Gas wells Methane Emissions Database

The Global Abandoned Oil and Gas wells Methane Emissions Inventory developed in this study encompasses 4,492,748 oil and gas wells in 127 countries; 9.3% of which (419,047 wells) with well-level details (name, geo-locations, status, terrain, start and end date of production), 84.8% of which (3,811,462 wells) with state-level information, and the remaining 1.9% (85,772 wells) only known the country they located.

We started with associated information collection (number, plugged status) of abandoned oil and gas wells from the state (Pennsylvania[25], Oklahoma[26], etc.), territorial (North Sea Transition Authority[27], etc.), country (Nederlandse Olie-en Gasportaal[28], etc.) databases, emission reports[29], related news[30,31], and the research articles[10,13,14,18]. For the countries with historical oil and gas production but unknown records of abandoned oil and gas wells, we use the GlobalData oil and gas wells database[32] to compile well-level information on abandoned wells (for example, country/district, terrain, well type, well status, start and stop year of spud). We also try to find out the associated management policies of abandoned oil and gas wells once controlled by the critical oil and gas producing countries (Nigeria[33], Angola[34], Colombia[35]) from the annual reports or commitments of major oil and gas companies, such as Shell.

Well-based Methane emission estimation

We estimate the country-level annual methane emissions of the abandoned wells according to the well-based accounting methodology as detailed in the previous studies[14], using the following equation:

$$E_{c,t} = \sum_{i=1}^{N} EF_{i,j,t}$$

where *c, i, t, j*, represent the region, wells, year, and district (state), respectively. *E* represents country-level emissions (t), *N* represents the numbers of abandoned wells in each country (t); EF represents the emission factors (t methane per abandoned wells). The emission factors differ depending on whether wells are plugged or unplugged, oil + gas mix or gas, onshore or offshore and their locations.

Numbers of abandoned oil and gas wells

The abandoned oil and gas wells defined in this study as inactive wells with no production, following the definitions in the previous studies[10] and the national related dataset[19,25,27,28], including terms: inactive, suspended, abandoned, orphaned, plugged, plugged back and sidetracked, junked, etc. The abandoned oil and gas wells worldwide are classified by terrain (onshore/offshore), resource type (oil, gas, oil + gas mix), and plugging status (unplugged, plugged, plugged with control) according to previous studies and published datasets. We use three main type of sources (datasets by official institutions, research articles, and relevant news items) to determine the number of abandoned oil and gas wells at the well/state/country level.

We start from the published open-source datasets from the state/territorial/national agencies of abandoned wells in the United States[19,25], Canada[20], Netherlands[28], United Kingdom[27], and Norway[36]. Considering the domination and high number of abandoned wells in the United States and Canada, we then crossed check the state-/plugged status-/ terrain-/resource-type-specific number of abandoned oil and gas wells with the previous studies[10,11,14]. There are about 3.6 million and 0.8 million AOG wells in the United States and Canada by 2022, respectively, 44% of which are currently known (with recorded well details), the remaining 56% are additional unknown orphaned AOG wells only estimated by the state agencies. Next, we used the GlobalData oil and gas wells database[32] to compile the abandoned wells in other countries. As the GlobalData well information dataset did not provide the detailed plugging status of the abandoned wells, for the main oil and gas producing countries, we searched and used the related news or reported quotes from the government to determine the plugged status- a specific number of abandoned oil and gas wells in Russia[30], Kazakhstan[31], and Romania[37]. We also used the related reports and news to determine the management of abandoned wells in Nigeria[33], Angola[34], and Colombia[35].

Methane emission factor

Methane emissions from AOG wells vary with location, terrain, resource-type, plugging status and so on[14]. Historic data of methane emissions has been estimated in several regions, but we found no comprehensive record for the AOG wells worldwide. We collected and compiled the existing methane emission factors generated from measurements of abandoned wells in previous studies (e.g., Kang et al. 2014[11], 2016[14]; Williams et al. 2021[10], Netherlands[13] and UK[18] studies). According to the classification of emission factors, we categorized the wells by region, terrain, resource type, and plugging status in the ***Global Abandoned Oil and Gas wells Methane Emissions Inventory***, and selected the corresponding emission factors to estimate their methane emissions. Details of terrain-/resource-type-/district-/technology-specific methane emission factor inventories for abandoned oil and gas wells worldwide are shown in Table 1. For AOG wells in countries without published measured emission factors, we use the global average value generated by the currently known emission factors classified according to terrain, resource type, and plugging status as the default emission factor.

Table 1 Methane Emission Factor of abandoned oil and gas wells worldwide

Country	Constituent Entity	District	Oil/Mix unplugged (g/h)	Gas unplugged (g/h)	all unplugged (g/h)	Oil/Mix plugged (g/h)	Gas plugged (g/h)	all plugged (g/h)
Canada	Canada	WHOL	12	22	10	0.046	4.8	1.5
	Alberta	West	14	15	12	0.051	4.8	0.0018
	British Columbia	British Columbia	12	22	0.15	0.046	4.8	1.5
	Manitoba	East	12	28	9.6	0.12	18	2.5
	Newfoundland and Labrador	East	12	28	9.6	0.12	18	2.5
	Northwest Territories	West	14	15	12	0.051	4.8	0.0018
	Nova Scotia	East	12	28	9.6	0.12	18	2.5
	Saskatchewan	West	14	15	12	0.051	4.8	0.0018
	Unknown	Remainder	12	22	10	0.046	4.8	1.5
United States	Pennsylvania	Pennsylvania	12	60	22	0.33	24	15
	Alabama	East	14	28	9.6	0.13	18	2.8
	Alaska	West	13	17	15	0.051	4.8	0.0018
	Arkansas	East	14	28	9.6	0.13	18	2.8
	California	West	13	17	15	0.051	4.8	0.0018
	Central Planning Area	Remainder	13	23	11	0.51	4.8	1.6
	Colorado	Colorado	13	23	11	0.51	4.8	1.6
	Eastern Planning Area	East	14	28	9.6	0.13	18	2.8
	Florida	East	14	28	9.6	0.13	18	2.8
	Illinois	East	14	28	9.6	0.13	18	2.8
	Indiana	East	14	28	9.6	0.13	18	2.8
	Kansas	West	13	17	15	0.051	4.8	0.0018
	Kentucky	East	14	28	9.6	0.13	18	2.8
	Louisiana	East	14	28	9.6	0.13	18	2.8

	Michigan	East	14	28	9.6	0.13	18	2.8
	Mississippi	East	14	28	9.6	0.13	18	2.8
	Montana	West	13	17	15	0.051	4.8	0.0018
	Nevada	West	13	17	15	0.051	4.8	0.0018
	New Mexico	West	13	17	15	0.051	4.8	0.0018
	New York	East	14	28	9.6	0.13	18	2.8
	North Dakota	West	13	17	15	0.051	4.8	0.0018
	Ohio	East	14	28	9.6	0.13	18	2.8
	Oklahoma	Oklahoma	14	22	17	0.51	4.8	1.6
	Pacific Outer Continental Shelf	Remainder	13	23	11	0.51	4.8	1.6
	Tennessee	East	14	28	9.6	0.13	18	2.8
	Texas	Andarko	13	22	16	0.51	4.8	1.6
	Unknown	Remainder	13	23	11	0.51	4.8	1.6
	Utah	Utah	13	23	11	0.51	0.041	0.024
	Virginia	East	14	28	9.6	0.13	18	2.8
	West Virginia	West Virginia	13	23	3.2	0.51	4.8	0.1
	Western Planning Area	West	13	17	15	0.051	4.8	0.0018
	Wyoming	West	13	17	15	0.051	4.8	0.0018
	United States	WHOL	1.38	1.38	1.38	1.38	1.38	1.38
	West	West	1.71	1.71	1.71	0.002	0.002	0.002
	East	East	28.01	28.01	28.01	0	0	0
United Kingdom	Onshore	WHOL	1.6621	1.6621	1.6621	1.6621	1.6621	1.6621
Netherlands	Netherlands	WHOL	443	443	443	0	0	0
Rest of World	AVERAGE	WHOL	12.78422	23.58	11.54778	0.1976	10.11162	1.931724
North Sea	AVERAGE	WHOL			174.4865			30.79174
United Kingdom	OFFSHORE_AVERAGE				267.5514			44.59189

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