October 2017

Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016: Update Under Consideration for Abandoned Wells in Natural Gas and Petroleum Systems

In a previous version of this memo released in June 2017, and during stakeholder webinars and workshops held in April, June, and August 2017, EPA presented preliminary considerations and sought stakeholder feedback on incorporating this emission source in the 2018 Inventory of U.S. Greenhouse Gas Emissions and Sinks (GHGI). This version of the memo is updated to reflect stakeholder feedback. Updates include:

- Refinement of the calculation of total number of abandoned wells (pages 4-5) and an appendix on this calculation (pages 15-18)
- Presentation of options of various levels of disaggregation for emission factors (page 3; page 7-11)
- Additional questions (question 2 and 6) for stakeholder feedback (pages 12-13)

1. Background

Recent studies have investigated methane leakage from abandoned wells in the U.S. The term "abandoned wells" as typically used in published scientific articles and this memo encompasses various types of wells:

- Wells with no recent production, and not plugged. Common terms (such as those used in state databases) might include: inactive, temporarily abandoned, shut-in, dormant, idle.
- Wells with no recent production and no responsible operator. Common terms might include: orphaned, deserted, long-term idle, abandoned.
- Wells that have been plugged to prevent migration of gas or fluids.

Methane emissions from abandoned oil and gas wells are not currently included in the GHGI. Commenters on previous GHGIs supported including this source, but noted that the current data were limited, and suggested reviewing data that will become available in the future. EPA has identified studies with emissions and activity data on abandoned wells (Kang et al. 2014[1], Kang et al. 2016[2], Townsend-Small et al. 2016[3], Brandt et al. 2014[4]) and is considering including an estimate for this source in the 2018 GHGI.

2. Available Emissions Data

EPA is identifying and reviewing available emissions data to characterize methane emissions from abandoned wells, including data from the Kang et al. and Townsend-Small et al. studies.

The Kang et al. 2014 study made direct measurements of methane flow rates from 19 wells in Pennsylvania during 2013 and 2014. The wells were not well-documented in state records, so researchers categorized each studied well as plugged or unplugged based on surface observations. The study did not find significantly different emission rates between the two categories. The Kang et al. 2016 study involved additional measurements to fill data gaps from the earlier study. Kang et al. 2016 measured 88 wells and developed emission factors (EFs) for categories observed to exhibit significantly different emissions levels in that data set: well type (gas versus oil or co-producing), plugging status (plugged versus unplugged), and coal area designation (as Pennsylvania requires wells in regions where mineable coal seams exist to be plugged and vented). Table 1 showing these EFs (in units of

[1] http://www.pnas.org/content/111/51/18173.full
[2] http://www.pnas.org/content/113/48/13636.full, http://www.pnas.org/content/114/29/E6025.full
[3] http://onlinelibrary.wiley.com/doi/10.1002/2015GL067623/full
[4] http://science.sciencemag.org/content/343/6172/733

grams per hour per well, g/h/well) is reproduced from the Kang et al. 2016 study, with minor edits for clarification in the context of this memo.

Table 1. Methane EFs from Kang et al. 2016 Study

Well production type and coal area designation	Number of Measured Wells		Mean (g/h/well)		Standard Error (g/h/well)	
	Unplugged	Plugged	Unplugged	Plugged	Unplugged	Plugged
All production types						
All	53	35	22	15	9.2	10
Coal	17	12	1.2	43	0.99	29
Noncoal	36	23	31	0.45	13	0.28
Oil and combined oil and gas production						
All	34	13	0.19	0.33	0.097	0.26
Coal	13	1	0.000011	0.000012	0.00091	n/a
Noncoal	21	12	0.31	0.36	0.15	0.28
Gas production						
All	19	22	60	24	24	16
Coal	4	11	5.2	47[a]	3.9	32
Noncoal	15	11	75	0.54	29	0.51

a - The measured plugged wells in coal areas are vented as required by regulations.

The Townsend-Small et al. study measured emissions from 138 abandoned wells in the Powder River Basin in Wyoming, Denver-Julesburg Basin in Colorado, Uintah Basin in Utah, and Appalachian Basin in Ohio, during 2015. Townsend-Small et al. developed EFs for categories observed to exhibit significantly different emissions levels: plugged versus unplugged (including inactive, temporarily abandoned, shut in, dormant, orphaned, and abandoned), and eastern versus western U.S. regions. Table 2 showing these EFs is reproduced from the Townsend-Small et al. study.

Table 2. Methane EFs from Townsend-Small et al. Study

Well Category	Number of Measured Wells	Mean (g/h/well)	95% Upper Confidence Limit (g/h/well)
All wells (entire U.S.)	138	1.38	3.17
All wells (eastern U.S.)	12	14.00	32.87
All wells (western U.S.)	126	0.18	0.41
Plugged wells (entire U.S.)	119	0.002	0.005
Unplugged wells (entire U.S.)	19	10.02	22.47
Plugged (eastern U.S.)	6	0	NA
Unplugged (eastern U.S.)	6	28.01	64.00
Plugged (western U.S.)	113	0.002	0.005
Unplugged (western U.S.)	13	1.71	3.83

EPA is considering developing emissions factors based on the available data and is considering several options for stratifying the EFs to reflect differences between populations that were observed in studies. Options include developing separate factors by plugging status, by region, and/or by production type. In addition, EPA is considering whether and how to combine Townsend-Small et al. and Kang et al. data to develop these EFs. Table 3 shows EFs calculated by combining data from Kang et al. 2016 and Townsend-Small 2016 study measurements for the Appalachian basin. While Kang et al. 2014 did not find significant differences between plugged and unplugged well emissions, both Kang et al. 2016 and Townsend-Small et al. 2016 studies did. Limited emissions data are available to support potentially stratifying EFs based on producing formation or production type. Townsend-Small et al. measured wells in both the east (Appalachian Basin) and newer formations in the west, and observed

significantly different emission rates; however, the data available do not include characterization of abandoned wells in other major producing regions such as Texas and California. Kang et al. 2016 observed significantly different emission rates between gas and oil/coproducing wells, and between coal and non-coal areas; however, all such data were collected in Pennsylvania, so they might not represent national emissions.

Table 3. Appalachian Basin Methane EFs Developed from Combining Studies

Data Source	Number of Measured Wells	Mean (g/h/well)
Plugged wells		
Kang et al. 2016 – All production types, noncoal areas	23	0.45
Townsend-Small et al. 2016 – Eastern U.S.	6	0
Combined	29	0.36
Unplugged wells		
Kang et al. 2016 – All production types, noncoal areas	36	31
Townsend-Small et al. 2016 – Eastern U.S.	6	28.01
Combined	42	30.57

Based on stakeholder feedback, EPA has calculated abandoned well emissions through three different approaches using the plugging status-specific EFs presented in Table 2 and Table 3 above:

- Scenario 1: Townsend-Small "entire U.S." EFs (Table 2) apply to all abandoned wells (scenario presented in previous version of this memo).
- Scenario 2: "Appalachian" EFs (Table 3) apply to abandoned wells in the Appalachian Basin region (within Ohio, Pennsylvania, West Virginia, New York, Kentucky, and Tennessee), while Townsend-Small "entire U.S." EFs apply to all other abandoned wells.
- Scenario 3: "Appalachian" EFs apply to abandoned wells in the Appalachian Basin region, while Townsend-Small "entire U.S." EFs apply to abandoned wells in Texas, and Townsend-Small "western U.S." EFs apply to all other abandoned wells.

Emission estimates for each scenario are discussed further and presented in Section 4.

3. Available Activity Data

EPA is identifying and reviewing available activity data to pair with methane EFs described above. Activity data for this source are counts of abandoned wells in each year of the 1990-2016 time series; counts might be subcategorized by attributes such as plugging status and/or location/producing formation, depending on the selected EF(s).

3.1 Total Abandoned Well Counts

Estimates in the literature for the total national population of abandoned onshore wells in the U.S. in recent years range from over 2.3 million (Townsend-Small et al. 2016) to approximately 3 million (Brandt et al. 2014).

EPA considered multiple approaches to developing the count of total abandoned wells in each year of the time series. For example: (1) Counting the total number of wells existing but no longer reporting production as of a given year; or (2) Counting wells drilled as of a given year, then subtracting the number of actively producing wells in that year (refer to the June 2017 memo for additional information on this approach).

For the 2018 GHGI, EPA is considering using DrillingInfo data to develop national estimates of abandoned wells in each year of the time series through analyzing key fields in the DrillingInfo data set to count wells existing but no

longer reporting production as of a given year. EPA's draft methodology for counting abandoned wells in each year is (note, DrillingInfo field names are shown in parentheses):

- Abandoned oil wells: last date of reported production (LAST_PROD_DATE) is before [year], cumulative hydrocarbon liquids production (LIQ_CUM) is greater than zero, and cumulative gas production (GAS_CUM) is either zero or results in gas-to-oil ratio of less than 100 mcf/bbl.
- Abandoned gas wells: last date of reported production (LAST_PROD_DATE) is before [year], cumulative gas production (GAS_CUM) is greater than zero, and cumulative hydrocarbon liquids production (LIQ_CUM) is either zero or results in gas-to-oil ratio of equal to or greater than 100 mcf/bbl.
- Abandoned dry wells: last date of reported production (LAST_PROD_DATE) is null; and spud date (SPUD_DATE) is before [year], or spud date is null and completion date (COMP_DATE) is before [year]; and status (STATUS) is not reported as injection.

To account for very old wells with installation and abandonment pre-dating DrillingInfo coverage, EPA developed an independent estimate of abandoned wells existing in 1975 through reviewing historical records. The DrillingInfo data set is likely relatively complete beginning ca. 1975, but sparsely populated before this timeframe. Where available (e.g., for Texas), EPA used data from state online databases containing historical drilling records by year and production type. EPA also compiled estimates such as those published in The Derrick's Handbook of Petroleum[5] and the United States Geological Survey's (USGS) Mineral Resources of the United States Annual Yearbooks[6]. Based on historical records, EPA estimates approximately 2.56 million wells (characterized as oil, gas, or dry) had been drilled in the U.S. by 1973 (and could be assumed to be producing in 1975 if not shutdown/dry). In 1975, approximately 630,000 oil and gas wells were operating in the U.S., based on USGS estimates[7]. Therefore, EPA estimates 1.93 million abandoned wells existed in 1975 (2.56 million – 630,000 = 1.93 million). See Appendix A for additional details on how this estimate was developed. Based on querying the DrillingInfo data set's key date fields as described above, 776,000 wells in the DrillingInfo database could be considered abandoned as of 1975 (i.e., had stopped reporting production prior to 1975 or been installed prior to 1975 and never reported production) (see note below regarding an update to this estimate compared to EPA's June 2017 memo). Comparing the counts (i.e. 1.93 million abandoned wells from analysis of historical records and USGS data, and 776,000 abandoned wells in the DrillingInfo database), EPA estimates that 1.15 million abandoned wells in the U.S. are not captured in the DrillingInfo-based methodology. EPA could add this 1.15 million abandoned well count to the DrillingInfo-based total to develop a complete count of abandoned wells existing in each year of the time series, as shown in Section 4.

For the most recent year of the 2018 GHGI time series (year 2016), the DrillingInfo query approach would likely overestimate abandoned well counts, because many wells might be spud and not reporting production—not because they are dry/abandoned, but due to the time required for completion. Additionally, many wells might have relatively recent production but were temporarily shut in (paused production) during 2015, and would therefore be counted in the query result. Therefore, EPA might use year 2015 abandoned well counts as a surrogate estimate for year 2016, and a similar approach in future GHGIs (use the next-to-most-recent year as a surrogate for the most recent year).

[5] The Derrick's Handbook of Petroleum: A Complete Chronological and Statistical Review of Petroleum Developments From 1859 to 1898 (V.1), (1898-1899) (V.2)

[6] https://minerals.usgs.gov/minerals/pubs/usbmmyb.html

[7] http://images.library.wisc.edu/EcoNatRes/EFacs2/MineralsYearBk/MinYB1975v1/reference/econatres.minyb1975v1.gkoelling.pdf (Table 6) and http://images.library.wisc.edu/EcoNatRes/EFacs2/MineralsYearBk/MinYB1975v1/reference/econatres.minyb1975v1.wharper.pdf (Table 10)

After developing a total count of abandoned wells, EPA will then separate the total abandoned well population into subcategories based on plugging status to assign appropriate EFs (as discussed in Section 2). Considerations toward plugging status assignment are discussed further in Section 3.2.

EPA might also separate the abandoned well population into state groupings to assign region-specific EFs, as discussed in Section 2. Both the historical data sets and the DrillingInfo data set provide counts at a state level which can be used to develop activity data for such an approach. Emission estimates for various state-level activity data grouping scenarios are presented in Section 4.

A note regarding the previous draft analysis presented in the June 2017 version of this memo:
In finalizing the previous draft DrillingInfo data set query logic to develop abandoned well counts across the time series, EPA implemented two refinements described below. These changes together led to DrillingInfo-based abandoned well counts increasing slightly over the time series, and subsequently the addition factor built around analyzing year 1975 decreasing from 1.19 to 1.15 million. Refer to Section 4 for updated activity data across the time series.

1) The previous draft analysis (in the June 2017 memo) query logic employed a "look back" period for LAST_PROD_DATE of 2 years (e.g., a well is counted as abandoned in year 2012 if LAST_PROD_DATE was before 2011) with the intention being that for recent time series years, wells that were inactive only because they hadn't been completed and brought into production yet would not be counted. The updated query logic (in this memo) employs a "look back" to only the previous year (e.g., a well is counted as abandoned in year 2012 if LAST_PROD_DATE was before 2012), since this methodology makes the most sense for all but the most recent year of the time series. For the most recent year, EPA is considering using the next-to-most-recent values as surrogate activity as described above. This update increased DrillingInfo-based counts slightly for all time series years.
2) The previous draft analysis (in the June 2017 memo) query logic for counting "dry" wells was slightly over-inclusive. If a well was spud and completed in different calendar years it would be counted twice. Adding additional query criteria (in this memo) to avoid counting a well in this scenario resulted in a slight decrease to DrillingInfo-based counts for all time series years.

3.2 Plugging Status Assignment

EPA considered several data sources to generate the estimated split between plugged and unplugged abandoned well counts for each year.

Townsend-Small et al. offer limited observations that might be considered a “snapshot” of plugging status based on wells encountered for testing in year 2015 in the eastern and western U.S. As shown in Table 2 above, 50 percent of the 12 eastern wells tested were plugged; and 90 percent of the 126 western wells tested were plugged. The Kang et al. 2016 Pennsylvania study observed that of the 88 wells sampled, 40 percent were plugged. For both studies, due to the relatively small sample size compared to the national abandoned wells population and other factors of study design (e.g., certain wells could not be located based on records, and certain wells could not be physically accessed), other data sets or approaches might better represent the national population split between plugged and unplugged for purposes of developing GHGI estimates.

For the 2018 GHGI, EPA is considering using status codes in the DrillingInfo database to split the population of abandoned wells into the plugged and unplugged categories. The DrillingInfo database contains the reported status for nearly 3.6 million wells. The status code is updated on an ongoing basis as reported to states (i.e., is not modified or standardized by DrillingInfo); the definition of a given status code might vary by state. As of early 2017, over 95 percent of well records in the DrillingInfo database report the status codes identified in the left-most column of Table 4. EPA is developing an approach that would identify status codes that represent

abandoned wells (e.g., inactive, P&A, abandoned, shut in, plugged), then assign the count of wells reporting each such code as plugged or unplugged. The right-most column of Table 4 indicates assigned plugging status using an approach that considers wells with the status codes "P&A (plugged and abandoned)" and "PLUGGED" to be plugged. EPA continues to seek feedback on how to assign plugging status, particularly for codes with * in this column; as a default approach, EPA might assign "unplugged" status to these codes.

Table 4. DrillingInfo Status Codes Reported as of Early 2017

Status Code	Number of Wells (millions)	Percent of All Wells in DrillingInfo	Abandoned Well Assigned Plugging Status
INACTIVE	1.5	42%	*
ACTIVE	0.9	27%	n/a
P&A (plugged and abandoned)	0.7	20%	Plugged
DRY	0.1	3%	*
ACTIVE INJ (active injection)	0.07	2%	n/a
ABANDONED	0.03	1%	*
EXPIRED PERMIT	0.03	1%	n/a
SHUT IN	0.02	1%	*
PLUGGED	0.02	1%	Plugged
All other codes	0.1	1%	*

* EPA seeks stakeholder feedback on assigning as plugged or unplugged.
n/a – Status code does not indicate likely abandonment.

This approach would allow EPA to approximate the split representing the most recent time series year(s). Using the assigned plugging status values shown in the last column of Table 4, and assigning * as "unplugged" for codes, except "All other", a preliminary estimate is that 69 percent of abandoned wells might be considered unplugged, and 31 percent of abandoned wells plugged. Since this data set likely does not include the oldest wells in the U.S., this value might over-estimate the fraction of the well population that is currently plugged. Because this approach is based on the most recent available state data as compiled by DrillingInfo, it reflects impacts of state- or industry-led plugging efforts (e.g., orphaned well plugging programs[8]), assuming that plugging status is generally kept up to date in state databases.

Regarding the status code "INACTIVE" in the DrillingInfo database, the vast majority of wells reporting this code are not included in the GHGI active well count data. Some wells with INACTIVE status might also report production within a given calendar year, and therefore be counted in the GHGI as active wells. However, the methodologies under consideration presented in this memo avoid double counting of wells between the abandoned wells and the active wells categories in the GHGI. The methodology discussed here for activity data relies on the DrillingInfo status field only for estimating the abandoned wells population split between plugged and unplugged. The approaches discussed in this memo to develop national estimates of abandoned wells would exclude any wells that report production within the given year. The current GHGI estimates emissions from wells that report production within a given year. Therefore, implementing a revision to the GHGI as described in this memo will not result in double-counting of wells as both active and abandoned.

The National Petroleum Council (NPC) Paper #2-25[9], released in 2011, describes the historical evolution of plugging approaches and effectiveness. Oil and gas drilling in the U.S. began in Pennsylvania in 1859, and 1893 in

[8] Examples include California's Idle and Orphan Well Program; Louisiana's Oilfield Site Restoration Program; Michigan's Orphan Well Program; Ohio's Orphan Well Program; Pennsylvania's Abandoned and Orphan Well Plugging Program.
[9] https://www.npc.org/Prudent_Development-Topic_Papers/2-25_Well_Plugging_and_Abandonment_Paper.pdf

Texas. For decades, regulations regarding plugging did not exist. Over time, states began instituting guidance and regulations regarding plugging; but in the meantime, wells were being drilled with very limited documentation of locations, etc. Regulations grew more stringent in the 1950s, requiring cement for sealing the producing intervals and the top of the wellbore. Prior to the 1950s, thousands of wells were left unplugged or ineffectively plugged (e.g., using very little cement). In the 1970s, regulations developed further to focus on environmental protection. According to NPC, "modern regulatory standards in all U.S. jurisdictions require specific provisions for plugging and documenting oil and natural gas wells before they are abandoned. Most wells are still plugged with cement using methods and materials developed in the 1970s."

Based on this information, EPA might consider wells drilled and abandoned prior to a certain year (e.g., 1950 or 1970) to be most accurately represented by EFs developed for unplugged wells regardless of plugging status in DrillingInfo or other data sources. While various programs and efforts have identified and plugged some abandoned wells, due to the estimated order of magnitude of these very old wells (approximately 2 million), most of this population might still be unplugged or ineffectively plugged. This assumption is generally supported by the DrillingInfo analysis discussed above (two-thirds of abandoned wells are currently unplugged).

To develop activity data over the GHGI time series as shown in Section 4, EPA developed point estimates of the plugged versus unplugged split in 1950 (100 percent unplugged) and 2016 (69 percent unplugged), then used interpolation to assign the split in intermediate years.

4. Estimates of Methane from Abandoned Wells

Table 5 shows estimates of total abandoned wells developed by querying the DrillingInfo data set and incorporating an assessment of historical data sources, as described in Section 3.1.

Table 6 shows estimates of abandoned well counts by production type. EPA allocated the total abandoned well counts shown in Table 5 to gas and oil production categories to support incorporation into the GHGI natural gas and petroleum systems source categories, respectively, using the following methodology:

- The abandoned wells not included in the DrillingInfo database (i.e., counted based on review of historical data sources) are reported by production type within the historical data source—as gas, oil, or dry. EPA assigned gas wells as gas wells, and oil wells as oil wells (as data are not consistently available to assign production type using the GOR-based method used for wells in the GHGI).
- For wells resulting from the DrillingInfo query surrounding date of last production, EPA applied the existing GHGI convention to analyze the cumulative reported production from each well—if the ratio of cumulative gas to oil production exceeded 100 mcf/bbl, EPA counted the well as gas; otherwise, it was counted as oil.
- For wells resulting from the DrillingInfo query to count wells reporting spud date but no production, EPA assigned these wells as "dry."
- Lastly, for the total count of "dry" wells in a given year (from historical data sources and DrillingInfo), EPA allocated such wells to gas and oil categories based on the split already calculated for such year.

Table 7 shows estimates of abandoned well counts by production type and plugging status, using the approach described in Section 3.2 (assuming 100 percent unplugged in 1950, 69 percent unplugged in 2016, and interpolation to assign the split in intermediate years).

In response to stakeholder feedback, and as described in Section 2, EPA is assessing various approaches for using region-specific EFs. EPA has calculated abandoned well emissions through three different scenarios that use

plugging status-specific EFs shown in Table 2 and Table 3 in conjunction with state-level activity data that underlie the data in Table 7:

- Scenario 1: Townsend-Small "entire U.S." EFs (Table 2) apply to all abandoned wells.
- Scenario 2: "Appalachian" EFs (Table 3) apply to abandoned wells in the Appalachian Basin region (within Ohio, Pennsylvania, West Virginia, New York, Kentucky, and Tennessee), while Townsend-Small "entire U.S." EFs apply to all other abandoned wells.
- Scenario 3: "Appalachian" EFs apply to abandoned wells in the Appalachian Basin region, while Townsend-Small "entire U.S." EFs apply to abandoned wells in Texas, and Townsend-Small "western U.S." EFs apply to all other abandoned wells.

Scenarios 2 and 3 use region-specific EFs to develop national estimates. Scenario 2 assigns "entire U.S." EFs to all non-Appalachian states, and Scenario 3 is an example of how non-Appalachia might be further parsed—in this example, retaining the national-average EF for Texas (which alone accounts for approximately one-third of national total abandoned wells over the time series; but has not been included in any measurement studies under consideration; and which has both significant historical drilling, similar to Appalachia, and newer development, similar to the "western U.S." locations analyzed by Townsend-Small), but assigning the Western EFs to all other non-Appalachia states. EPA seeks feedback on whether the available data warrant an approach that might use region-specific factors such as "Appalachian" and “Western” EFs.

Figure 1 below illustrates how national total abandoned well counts are split into the EF categories for each scenario described above, for years 1990 (2.37 million total abandoned wells) and 2015 (3.11 million total abandoned wells).

Table 8 and Figure 2 show estimated emissions from abandoned wells in years 1990 and 2015 under each scenario.

Table 5. Estimates of Total Abandoned Wells Over the GHGI Time Series (millions)

Year	'90	'91	'92	'93	'94	'95	'96	'97	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15
DrillingInfo (Raw)	1.22	1.25	1.28	1.31	1.34	1.37	1.40	1.42	1.45	1.48	1.52	1.54	1.57	1.59	1.61	1.63	1.65	1.68	1.70	1.73	1.76	1.79	1.82	1.85	1.90	1.96
Not included in DrillingInfo[a]	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
Total[b]	2.37	2.40	2.43	2.46	2.49	2.52	2.55	2.57	2.60	2.63	2.67	2.69	2.72	2.74	2.76	2.78	2.80	2.83	2.85	2.88	2.91	2.94	2.97	3.00	3.05	3.11

a – Based on assessment of historical data sources including Derrick's Handbook of Petroleum and the USGS Mineral Resources of the United States Annual Yearbooks, as described in Section 3.1.

b – Previous rows show rounded values; totals shown may not equal sum.

Table 6. Estimates of Total Abandoned Wells Over the GHGI Time Series, by Production Type (millions)

Year	'90	'91	'92	'93	'94	'95	'96	'97	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15
Total[a]	2.37	2.40	2.43	2.46	2.49	2.52	2.55	2.57	2.60	2.63	2.67	2.69	2.72	2.74	2.76	2.78	2.80	2.83	2.85	2.88	2.91	2.94	2.97	3.00	3.05	3.11
Gas[b]	0.32	0.32	0.33	0.34	0.34	0.35	0.35	0.36	0.36	0.37	0.37	0.38	0.39	0.39	0.40	0.40	0.41	0.42	0.43	0.44	0.45	0.47	0.48	0.50	0.52	0.55
Oil[b]	2.05	2.07	2.10	2.12	2.15	2.17	2.19	2.22	2.24	2.26	2.30	2.31	2.33	2.35	2.36	2.38	2.39	2.41	2.42	2.44	2.46	2.47	2.49	2.51	2.52	2.56

a – Rounded values; totals shown may not equal sum of rows below.

b – Including allocated dry hole counts.

Table 7. Estimates of Plugged and Unplugged Abandoned Wells Over the GHGI Time Series, by Production Type

Year	'90	'91	'92	'93	'94	'95	'96	'97	'98	'99	'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	'13	'14	'15
Total (millions)[a]	2.37	2.40	2.43	2.46	2.49	2.52	2.55	2.57	2.60	2.63	2.67	2.69	2.72	2.74	2.76	2.78	2.80	2.83	2.85	2.88	2.91	2.94	2.97	3.00	3.05	3.11
Unplugged (%)	81%	81%	80%	80%	79%	79%	79%	78%	78%	77%	77%	76%	76%	75%	75%	74%	74%	73%	73%	72%	72%	72%	71%	71%	70%	70%
Plugged (%)	19%	19%	20%	20%	21%	21%	21%	22%	22%	23%	23%	24%	24%	25%	25%	26%	26%	27%	27%	28%	28%	28%	29%	29%	30%	30%
Gas[b] (millions)	0.32	0.32	0.33	0.34	0.34	0.35	0.35	0.36	0.36	0.37	0.37	0.38	0.39	0.39	0.40	0.40	0.41	0.42	0.43	0.44	0.45	0.47	0.48	0.50	0.52	0.55
Unplugged	0.26	0.26	0.27	0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.29	0.29	0.29	0.29	0.30	0.30	0.30	0.31	0.31	0.32	0.33	0.33	0.34	0.35	0.37	0.38
Plugged	0.06	0.06	0.06	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.10	0.10	0.10	0.11	0.11	0.12	0.12	0.13	0.13	0.14	0.15	0.16	0.17
Oil[b] (millions)	2.05	2.07	2.10	2.12	2.15	2.17	2.19	2.22	2.24	2.26	2.30	2.31	2.33	2.35	2.36	2.38	2.39	2.41	2.42	2.44	2.46	2.47	2.49	2.51	2.52	2.56
Unplugged	1.67	1.68	1.69	1.70	1.71	1.71	1.72	1.73	1.74	1.75	1.76	1.76	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.77	1.78
Plugged	0.38	0.40	0.41	0.43	0.44	0.46	0.47	0.49	0.50	0.52	0.54	0.55	0.57	0.58	0.60	0.61	0.63	0.64	0.66	0.67	0.69	0.70	0.72	0.74	0.75	0.78

a – Rounded values; totals shown may not equal sum of rows below.

b – Including allocated dry hole counts. Rounded values; totals shown may not equal sum of rows below.

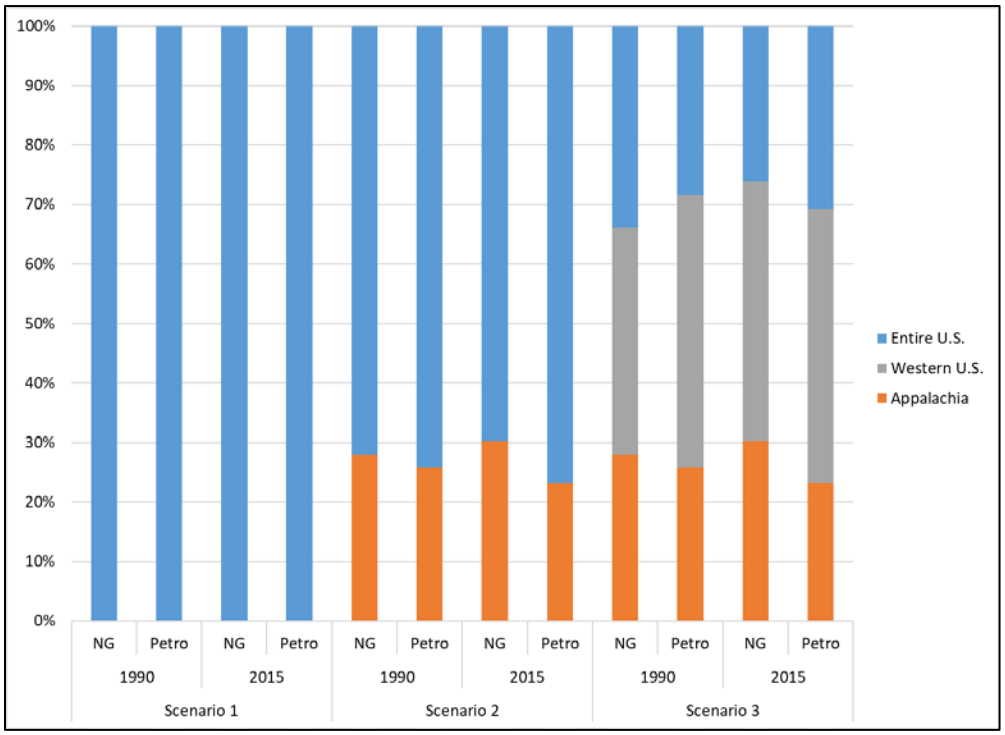

Figure 1. Fraction of Abandoned Wells in Each EF Category, by Scenario

Table 8. Estimates of Abandoned Well CH_4 Emissions over GHGI Time Series, for Multiple Scenarios (MMT CO_2e)

Well Type	Scenario 1[a]		Scenario 2[b]		Scenario 3[c]	
	1990	2015	1990	2015	1990	2015
Total	4.23	4.76	6.50	7.16	4.93	5.35
Gas	0.57	0.84	0.90	1.37	0.72	1.06
Oil	3.66	3.91	5.60	5.79	4.21	4.29

a - Townsend-Small "entire U.S." EFs apply to all abandoned wells.
b - "Appalachian" EFs apply to abandoned wells in the Appalachian Basin region (within Ohio, Pennsylvania, West Virginia, New York, Kentucky, and Tennessee), while Townsend-Small "entire U.S." EFs apply to all other abandoned wells.
c - "Appalachian" EFs apply to abandoned wells in the Appalachian Basin region, while Townsend-Small "entire U.S." EFs apply to abandoned wells in Texas, and Townsend-Small "western U.S." EFs apply to all other abandoned wells.

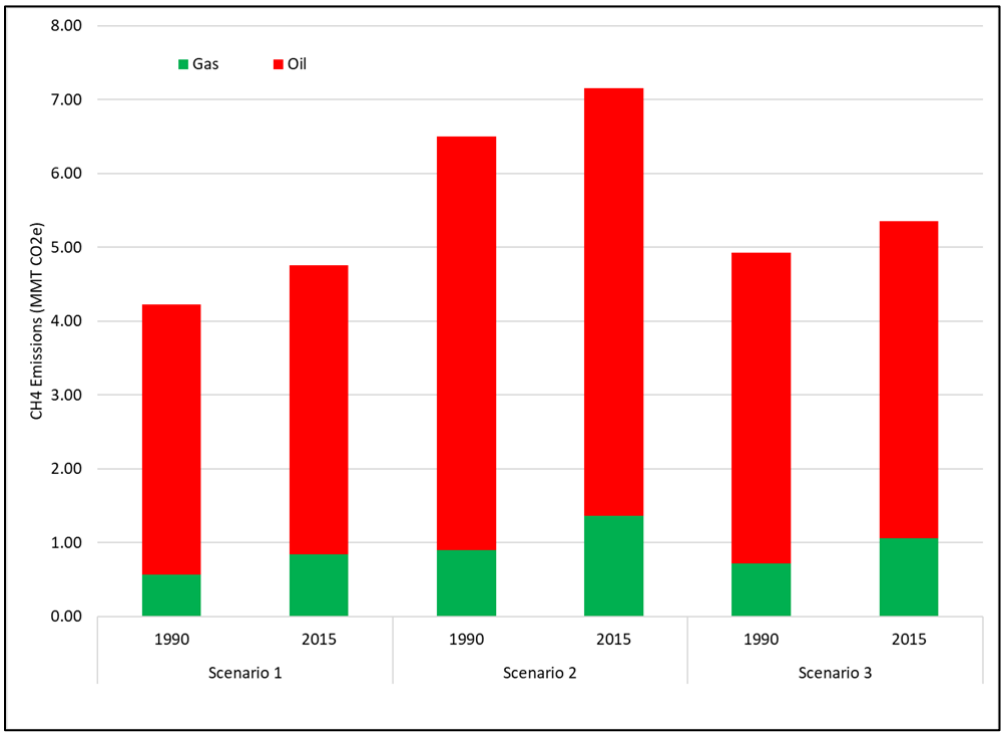

Figure 2. Estimates of Abandoned Well CH4 Emissions over GHGI Time Series, for Multiple Scenarios (MMT CO_2e)

5. Additional Considerations

5.1 Emission Factors

Recent studies summarized in this memorandum suggest additional considerations (listed below) regarding the representativeness of the data used to develop EFs. EPA will review additional data relevant to these research questions as data emerge.

- What is the impact of nearby production or storage on emissions from abandoned wells?
- Are average emissions rates from abandoned wells in unstudied major production areas in the U.S. (e.g., Texas) similar to those in studied areas?
- What further subcategorization (e.g., well plugging timeframe, well type) is appropriate for EF development?
- How do methane flow rates from abandoned wells vary over long periods of time?

Regarding the last consideration above, for purposes of developing an estimate in the GHGI, EPA might assume that abandoned wells leak over long periods of time at relatively steady rates, based on available data. In the Townsend-Small et al. data set, 6 out of 138 wells were found to have measurable emissions in 2015. Based on available records, three such wells were completed prior to the 1950s, and therefore likely became abandoned several years, or even decades, prior to the Townsend-Small et al. measurement campaign (the state does not have a record of the last reported production for these wells). This supports an assumption that even very old wells (that produced in the late 1800s and early 1900s) might continue to leak over long periods of time, if left unplugged or ineffectively plugged. Kang et al. 2016 conducted repeat measurements over a time span of two years and observed that flow rates of high emitters are sustained through that period of time.

5.2 Activity Data

Recent studies also suggest additional considerations (listed below) regarding the representativeness and completeness of activity data estimates that might be used in the GHGI. EPA will review additional relevant data as they emerge.

- What is the magnitude of undocumented abandoned wells?
- Should certain types of wells be included in the national count—for example, injection wells drilled for enhanced oil recovery, and dry wells?
- What data sources and methodology might be used to estimate national total activity for vented abandoned wells, such as the coal area wells measured in the Kang studies in Pennsylvania? Do other states have similar venting requirements as Pennsylvania?

6. Requests for Stakeholder Feedback:

EPA seeks feedback on the following considerations for developing an estimate for this emission source in the 2018 GHGI.

1. What additional data sources are available to estimate EFs for abandoned wells?
2. How might the EFs presented in Section 2 be used to estimate national emissions? As detailed in Section 4, EPA has calculated abandoned well emissions through three different scenarios that use various combinations of "Entire U.S.", "Appalachian" and "Western U.S." EFs. EPA seeks stakeholder feedback on which scenario best represents U.S. emissions from abandoned wells, or alternative approaches to consider.
3. What subcategories of abandoned wells should be represented in the GHGI (taking into account data availability and differences between emissions rates for subcategories). For example:
    - plugging status
    - production type (e.g., oil, gas, dry, injection, other)
    - region (e.g., east versus west)
    - unplugged wells abandoned while shut-in versus while orphaned (i.e., no responsible owner on record, usually applying to very old wells)
    - other?
4. What additional data sources and methods are available to estimate the total population of wells abandoned prior to 1990 (considering that the production phase of many such wells likely pre-dates DrillingInfo coverage)?
5. What additional data sources or methodologies might be appropriate to estimate the total population of abandoned wells existing in each year of the time series (1990–2016)?
    - Section 3.1 discusses an approach in which certain DrillingInfo date fields are analyzed to count abandoned wells as of a given year. For example, the reported date of spud/completion and of last production. A count of wells not included in the DrillingInfo data set can be developed from historical data sources (based on review of Derrick's Handbook of Petroleum, the USGS Mineral Resources of the United States Annual Yearbooks, and/or EIA historical drilling records). This value would be added to the abandoned well counts developed from DrillingInfo. Activity data developed by this approach for various time series years are presented in Table 5. EPA seeks feedback on this approach.
    - What other data sources and/or methodologies might EPA consider?
6. For the most recent year of the 2018 GHGI time series (year 2016), the DrillingInfo query approach described in Section 3.1 might overestimate abandoned well counts, because many wells might be

spud and not reporting production—not because they are dry/abandoned, but due to the time required for completion. Therefore, EPA might use year 2015 abandoned well counts as a surrogate estimate for year 2016, and a similar approach in future GHGIs (use the next-to-most-recent year as surrogate for most recent year). EPA seeks feedback on this approach or other approaches to consider.

7. Are additional data sources or methodologies available to estimate the split between plugged and unplugged wells existing in each year of the time series (1990–2016)?
    - Section 3.2 discusses available data in the DrillingInfo database to characterize wells in recent year(s), an NPC 2011 paper to characterize wells in early years, and an interpolation approach that might be used. EPA seeks feedback on this approach, including on how might the DrillingInfo "Status" field be interpreted to indicate plugging status, considering the list of most commonly reported status codes described in Table 4. EPA is considering an approach that would identify status codes that represent abandoned wells (e.g., inactive, P&A, abandoned, shut in, plugged), then assign the count of wells reporting each such code as plugged or unplugged. The right-most column of Table 4 indicates assigned plugging status using an option that considers wells with the status codes "P&A (plugged and abandoned)" and "PLUGGED" to be plugged. EPA seeks feedback on how to assign plugging status, particularly for codes with * in this column.
    - What other data sources and/or methodology might EPA consider?
8. Based on the discussion of historical plugging effectiveness in Section 3.2, what year (e.g., 1950) might be appropriate to assume that zero percent of existing abandoned wells were effectively plugged (such an estimate would serve as a tie point for use in interpolation to develop plugged versus unplugged activity fractions)?
9. What data are available to answer the research questions posed in Section 5, regarding additional considerations for calculating emission estimates for this source?
10. Are there any additional ongoing or planned studies related to abandoned wells that may be incorporated for the 2018 GHGI, or used to refine future GHGIs?
11. Are data sources and methods available to estimate EFs and activity data for related derelict infrastructure (e.g., flow lines)?

Appendix A.
Development of independent estimate of abandoned wells existing in 1975 through reviewing historical records

Table A-1 shows estimates compiled from historical data sources of wells drilled in each state, by production type (including dry), from 1871 to 1973. Where available (e.g., for Texas), EPA used data from state online databases containing historical drilling records by year and production type. For most counts, EPA relied on estimates published in United States Geological Survey's (USGS) Mineral Resources of the United States Annual Yearbooks. Note that these state-level estimates were compiled for the purpose of developing a national-level total. In several instances, historical data sources presented counts for a combined set of states, and the table below attributes counts to one of the multiple states represented; therefore, the state-level totals shown below might be inaccurate for certain states, although the national totals would not be impacted. The righthand column of Table A-1 generally notes where this occurred.

Table A-2 shows estimates from USGS of wells producing in each state, by production type, as of 1975.

To develop an estimate of abandoned wells existing in 1975, EPA subtracted the total producing oil and gas wells as of 1975 from the total drilled by 1973 (wells drilled by 1973 were assumed to be producing by 1975, if not shutdown).

2,556,411 (wells drilled, see Table A-1) – 630,697 (wells producing, see Table A-2) = 1,925,714 abandoned wells in 1975.

Table A-1. Wells Drilled by State and Production Type (1871-1973)

State	Gas	Oil	Dry	Citation	Notes
AK	56	66	559	State data[a]	
AL	33	512	121	State data[b]	
AR	1,527	14,120	9,016	USGS[c]	State data[d] were also reviewed; USGS appeared to be more complete.
CA	2,388	77,518	19,975	USGS[c]	
CO	1,943	5,240	12,764	USGS[c]	Includes some UT, WY wells (states reported together in USGS for certain years)
FL	0	214	445	State data[e]	The analysis attributed O&G wells to oil.
IL	1,263	66,910	39,721	USGS[c]	
IN	9,668	26,662	19,895	USGS[c]	Derrick's Handbook[f] data were also reviewed; USGS appeared to be more complete.
KS	17,485	95,786	65,115	USGS[c]	
KY	8,351	42,594	29,168	USGS[c]	
LA	14,684	63,249	45,887	USGS[c]	
MI	2,263	11,082	13,942	USGS[c]	
MS	434	5,807	9,166	USGS[c]	
ND	1	1,250	1,686	USGS[c]	
NE	133	3,648	8,131	USGS[c]	
MT	1,839	8,355	9,004	USGS[c]	
NM	9,032	21,943	8,949	USGS[c]	
NY	2,458	4,434	1,079	USGS[c]	Partial totals, some counts included in PA total (states reported together in USGS for certain years). Derrick's Handbook[f] data were also reviewed.
OH	24,515	101,447	32,974	USGS[c]	Partial totals, some counts included in PA total (states reported together in USGS for certain years). Derrick's Handbook[f] data were also reviewed.
OK	22,535	195,237	87,437	USGS[c]	State data[g] were also reviewed; USGS seemed more complete.
PA	46,289	272,674	49,394	USGS[c]	Includes some OH, NY, WV wells (states reported together in USGS for certain years). State data[h] and Derrick's Handbook[f] data were also reviewed.
SD	0	41	344	USGS[c]	
TN	121	380	855	USGS[c]	
TX	79,716	447,527	277,630	State data[i], USGS[c]	State data[i] where available, otherwise USGS.
UT	5	2	17	USGS[c]	Partial totals, some wells included with WY and CO.
VA	321	34	135	State data[j]	
WV	28,951	26,094	11,727	USGS[c]	Partial totals, some counts included in PA total (states reported together in USGS for certain years).

WY	1,675	17,333	13,430	USGS[c]	Partial totals, some counts included in CO total (states reported together in USGS for certain years).
Subtotal	***277,686***	***1,510,159***	***768,566***		
Total	**2,556,411**				

a. Alaska Oil and Gas Conservation Commission, http://doa.alaska.gov/ogc/publicdb.html
b. Geological Survey of Alabama, Oil & Gas Board, https://www.gsa.state.al.us/ogb/
c. United States Geological Survey's (USGS) Mineral Resources of the United States Annual Yearbooks, https://minerals.usgs.gov/minerals/pubs/usbmmyb.html
d. Arkansas Geological & Conservation Commission, "List of Oil & Gas Wells - Data From November 1, 1936 to January 1, 1955.", http://www.geology.ar.gov/pdf/IC-10%20SUPPLEMENT_v.pdf
e. Florida Department of Environmental Protection - Oil and Gas Program, http://www.dep.state.fl.us/water/mines/oil_gas/index.htm
f. The Derrick's Handbook of Petroleum: A Complete Chronological and Statistical Review of Petroleum Developments From 1859 to 1898 (V.1), (1898-1899) (V.2)
g. "Oklahoma Oil: Past, Present, and Future." Oklahoma Geology Notes, Oklahoma Geological Survey v. 62 no. 3, 2002 pp .97-106
h. Pennsylvania Department of Environmental Protection, Oil and Gas Reports - Oil and Gas Operator Well Inventory. http://www.portal.state.pa.us/portal/server.pt/community/oil_and_gas_reports/20297
i. Texas Railroad Commission, Oil and Gas Division, "History of Texas Initial Crude Oil, Annual Production and Producing Wells, Crude Oil Production and Well Counts (since 1935)." http://www.rrc.state.tx.us/oil-gas/research-and-statistics/production-data/historical-production-data/crude-oil-production-and-well-counts-since-1935/
j. Virginia Department of Mines Minerals and Energy, "Wells Drilled for Oil and Gas in Virginia prior to 1962.", Virginia Division of Mineral Resources, https://www.dmme.virginia.gov/commercedocs/MRR_4.pdf.

Table A-2. Producing Wells by State and Production Type in 1975 from USGS Data[10]

State	Gas	Oil
AK	61	205
AL	9	608
AR	1,128	7,308
AZ	1	28
CA	1,585	41,029
CO	1,662	2,450
FL	0	143
IL	41	23,373
IN	478	4,798
KS	8,865	41,945
KY	7,386	13,905
LA	9,182	27,734
MD	15	0
MI	209	3,655
MO	3	163
MS	248	2,237
MT	1,235	3,247
ND	18	1,994
NE	19	1,190
NM	10,352	13,715
NV	0	6
NY	900	4,975
OH	10,382	16,611
OK	9,769	71,576
PA	17,500	32,095
SD	20	38
TN	5	172
TX	26,184	160,603
UT	271	1,323
VA	186	7
WV	21,700	13,750
WY	950	9,450
Subtotal	***130,364***	***500,333***
Total	630,697	

[10] Same reference as [12]. Specific to 1975, the publications are available at: http://images.library.wisc.edu/EcoNatRes/EFacs2/MineralsYearBk/MinYB1975v1/reference/econatres.minyb1975v1.gkoelling.pdf (Gas wells, Table 6); and http://images.library.wisc.edu/EcoNatRes/EFacs2/MineralsYearBk/MinYB1975v1/reference/econatres.minyb1975v1.wharper.pdf (Oil wells, Table 10)