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

1.   Background

Methane emissions from abandoned oil and gas wells are not currently included in the Inventory of U.S. Greenhouse Gas Emissions and Sinks (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 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 emission factors (in units of 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 Emission Factors 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	1.5[a]	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

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

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
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[b]	3.9	32
Noncoal	15	11	75	0.54	29	0.51

a - Corrected from value originally published in journal article, based on conversation with author.
b - 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 emission factors 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 emission factors is reproduced from the Townsend-Small et al. study.

Table 2. Methane Emission Factors 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 emission factors 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 emission factors. 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 emission factors based on region/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 trends.

3.   Available Activity Data

EPA is identifying and reviewing available activity data to pair with methane emission factors 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 emission factor(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) and approximately 3 million (Brandt et al. 2014).

EPA is considering 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.

For the first approach, EPA might use DrillingInfo data to develop national estimates of abandoned wells in each year of the time series through analyzing, for example, the reported dates of installation (spud date and/or completion date and/or first reported production date) and of last production. As an example, EPA could apply count criteria such as: PRODUCTION_TYPE does not contain "INJ[ECTION]"; and LAST_PROD_DATE before [year]—or LAST_PROD_DATE is null but spud, completion, or FIRST_PROD_DATE are before [year].

For the second approach, EPA might use statistics published by the U.S. Department of Energy's Energy Information Administration (EIA). EIA offers data sets including:
- U.S. Crude Oil Exploratory and Developmental Wells Drilled (1949–2010)[5]
- U.S. Natural Gas Exploratory and Developmental Wells Drilled (1949–2010)[6]
- U.S. Dry Exploratory and Developmental Wells Drilled (1949–2010)[7]
- U.S. Number of Producing Gas Wells (1989–2015)[8]
- U.S. Crude Oil Producing Wells (1954–2011)[9]

EPA might use a combination of the approaches and data sources above to develop full time series coverage, and to verify estimates.

To account for very old wells with installation and abandonment pre-dating DrillingInfo coverage, EPA might review historical records such as those published in The Derrick's Handbook of Petroleum[10] and the United States Geological Survey's (USGS) Mineral Resources of the United States Annual Yearbooks[11]. EPA could compare the counts of abandoned wells estimated using DrillingInfo for a given

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[5] https://www.eia.gov/dnav/ng/hist/e_ertwo_xwc0_nus_cA.htm

[6] https://www.eia.gov/dnav/ng/hist/e_ertwg_xwc0_nus_ca.htm

[7] https://www.eia.gov/dnav/ng/hist/e_ertwd_xwc0_nus_cA.htm

[8] https://www.eia.gov/dnav/ng/ng_prod_wells_s1_a.htm

[9] https://www.eia.gov/totalenergy/data/annual/showtext.php?t=ptb0502

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

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

year's estimate based on historical records (Derrick's Handbook or the USGS publications) to determine how many abandoned wells may be missing from the DrillingInfo data set. EPA developed a preliminary comparison for the year 1975. As of 1975, approximately 2.56 million wells (characterized as oil, gas, or dry) had been drilled in the U.S. based on historical records. In 1975, approximately 630,000 oil and gas wells were operating in the U.S., based on USGS estimates. Therefore, EPA estimates 1.93 million abandoned wells existed in 1975 (2.56 million – 630,000 = 1.93 million). Based on querying the DrillingInfo data set's key date fields as described above, 764,000 wells in the database could be considered abandoned as of 1975 (had stopped reporting production at least one year prior to 1975 or been installed at least one year prior to 1975 and never reported production). Comparing the counts, EPA estimates that 1.2 million abandoned wells in the U.S. are not captured in DrillingInfo.

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

3.2   Plugging Status Assignment

If separate emission factors for plugged versus unplugged wells are used in the GHGI, EPA will split the total abandoned well counts between plugged and unplugged wells in each year of the GHGI time series. EPA is considering several data sources to generate the estimated split 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 small sample size 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), these data might not represent the national population split for purposes of developing GHGI estimates.

EPA is considering using status codes in the DrillingInfo database as part of the process 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 3. 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 3 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.

Table 3. 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 3, and assigning * as "unplugged" for codes except "All other" a preliminary estimate is that, 69 percent of wells might be considered unplugged, and 31 percent of 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.

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[12], 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 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 emission factors 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

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[12] https://www.npc.org/Prudent_Development-Topic_Papers/2-25_Well_Plugging_and_Abandonment_Paper.pdf

June 2017

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, EPA might develop point estimates of the plugged versus unplugged split in an early year and a later year, then use interpolation to assign the split in intermediate years. For example, EPA might assume 0 percent plugged (100 percent unplugged) in year 1950, 33 percent plugged (67 percent unplugged) in year 2016, and linearly interpolate to assign the split in intermediate years. EPA seeks feedback on this issue in Section 6.

4.   Preliminary Estimates of Methane from Abandoned Wells

As discussed in Section 3, EPA is reviewing available data sources to develop a time series of national level activity data that includes the complete universe of abandoned wells, dating to the 1800s. EPA developed preliminary estimates of abandoned wells by querying the DrillingInfo data set's key date fields as described in Section 3.1 (in a given year, counting wells that had stopped reporting production at least one year prior, or had been installed at least one year prior and never reported production), and excluding any wells where production type indicated injection. These preliminary estimates are summarized in the second column of Table 4 below. This approach resulted in an estimate of roughly 2.0 million abandoned wells in the U.S. in 2016. Based on an assessment of historical data sources also described in Section 3.1, 1.2 million abandoned wells counts are likely not included in the DrillingInfo data set; EPA added this figure to the counts from DrillingInfo to obtain preliminary estimates of total abandoned well counts shown in Table 4.

Table 4. Preliminary Estimates of Total Abandoned Wells as of Specified Year

Year	Abandoned Well Count from DrillingInfo (millions)	Abandoned Wells Not included in DrillingInfo[a] (millions)	Total Abandoned Well Count (millions)[b]
1990	1.19	1.16	2.35
1995	1.34	1.16	2.50
2000	1.48	1.16	2.65
2005	1.61	1.16	2.77
2010	1.73	1.16	2.89
2015	1.90	1.16	3.06
2016	1.96	1.16	3.12

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 columns show rounded values; totals shown may not equal sum.

EPA allocated the total abandoned well counts shown in Table 4 to gas and oil production categories to support incorporation into the GHGI, 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 surrounding date of installation (with production not reported), 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 5 below shows preliminary estimates of abandoned well counts by production type.

Table 5. Preliminary Estimates of Abandoned Wells as of Specified Year, by Production Type

Year	Abandoned Well Count (millions)		
	Total[a]	Gas	Oil
1990	2.35	0.32	2.04
1995	2.50	0.35	2.16
2000	2.65	0.37	2.28
2005	2.77	0.40	2.37
2010	2.89	0.44	2.45
2015	3.06	0.52	2.54
2016	3.12	0.55	2.57

a - Production type-specific columns show rounded values; totals shown may not equal sum.

Using the following preliminary inputs, EPA estimates that national methane emissions in year 2016 might be approximately 3.9 MMT CO_2 Eq. for abandoned oil wells in petroleum systems and 0.8 MMT CO_2 Eq. for abandoned gas wells in natural gas systems:
- Estimates of gas and oil abandoned wells developed from DrillingInfo and historical data (Table 5);
- Plugging status split of 31 percent plugged and 69 percent unplugged from analyzing reported status codes in DrillingInfo (Section 3.2); and
- Townsend-Small national average emission factors for plugged wells (0.002 g/h/well) and for unplugged wells (10.02 g/h/well) (Table 2).

An approach implemented in the GHGI would show increasing emissions over the time series. From 1990 forward, emissions would increase as more wells become abandoned; however, the annual data for 1990-2016 would likely show a growing proportion of the abandoned wells population being plugged over the same timeframe.

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 emission factors. 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 emission factor 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 record of 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?

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 emission factors for abandoned wells?
2. 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?
3. 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)?
4. 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 dates of installation (spud date and/or completion date and/or first reported production date) and of last

production. A count of wells not included in the DrillingInfo data set might 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. Preliminary activity data developed by this approach for various time series years are presented in Table 4. EPA seeks feedback on this approach.

- o Section 3.1 also discusses an approach in which counts of wells active in a given year (e.g., based on current GHGI estimates) might be subtracted from counts of wells drilled before that year. Note, to implement this approach over the entire GHGI time series would require a data source with ongoing estimates of wells drilled in recent years (EIA coverage ends in 2010). This approach would also involve the addition of historical data, e.g., from Derrick's Handbook of Petroleum and USGS publications as described above. EPA seeks feedback on this approach.
- o What other data sources and/or methodologies might EPA consider?

5. 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)?
    - o 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 3. 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 3 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.
    - o What other data sources and/or methodology might EPA consider?

6. 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)?

7. What data are available to answer the research questions posed in Section 5, regarding additional considerations for calculating emission estimates for this source?

8. 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?

9. Are data sources and methods available to estimate emission factors and activity data for related derelict infrastructure (e.g., flow lines)?