

August 3, 2017

MEMORANDUM

To: Julie McDill; MARAMA
Cc: Tom Moore; WESTAR-WRAP
From: John Grant, Rajashi Parikh, Amnon Bar-Ilan; Ramboll Environ
Subject: National Oil and Gas Emissions Analysis, Task 2: Marcellus Basin Regional Analysis

This memorandum describes the Marcellus Basin¹ literature review of emissions from abandoned oil and gas (O&G) wells developed as part of the National Oil and Gas Emissions Analysis, Task 2: Regional Analysis.

When a well reaches the end of its producing life, it must be plugged to prevent formation fluid from migrating up the well bore, potentially contaminating other formations and/or groundwater aquifers. Wells that are drilled, but never produce also need to be plugged. In Pennsylvania (PA), an abandoned well is defined as any well that has not produced for at least a year or any well that was not completed for production within 60 days of being drilled (Pennsylvania Department of Environmental Protection, 2000). An orphaned well is a well that was abandoned prior to April 18, 1985 which meets the following criteria: (1) the well has not been affected or operated by the current landowner or operator and (2) the current landowner or operator has not received any economic benefit from the well (Pennsylvania Department of Environmental Protection, 2000).

Plugged wells are abandoned wells that have been filled completely or across specific depths with mechanical or cement plugs to prevent oil and gas fluid flow in accordance with Subchapter D, Section 78 of Pennsylvania Code. Due to safety considerations, plugged wells in coal areas are typically plugged across producing formations and vented to the atmosphere to impede deep gas intrusion to coal seams in case of plug failure or are plugged solid (i.e. entirely filled with cement).

Emissions of natural gas occur at abandoned O&G wells when natural gas leaks are emitted to the atmosphere. Ho (2016) notes that leaks occur primarily due to mechanical integrity failure of wellhead equipment, well casing failure, or cement failure. Boothroyd (2016) found that abandoned well leaks develop early in the post-production life of the well. Abandoned well emissions are a function of abandoned well counts and abandoned well emission leak rates. Literature that is currently available focuses on methane (not volatile organic compound [VOC]) emissions from abandoned wells; however, gas emitted from abandoned well leaks is also expected to include heavier hydrocarbons present in geologic source formations (e.g. ethane, propane, butanes, pentanes, hexanes, heptanes, and octanes).

¹ For this analysis the Marcellus Basin is defined according to the American Association of Petroleum Geologists (AAPG) Appalachian Basin (Eastern Overthrust Area). Counties in the Appalachian Basin (Eastern Overthrust Area) outside of PA are not considered in this analysis.

Figure 1 shows maps of (1) identified abandoned and orphaned², (2) plugged wells, and (3) the extent of shale plays in PA.

The following articles are the primary sources for this analysis:

- Kang et al. (2014) developed methane emission rate estimates from abandoned wells in PA based on close to 20 field measurements at abandoned well sites.
- Kang et al. (2016) developed methane emission rate estimates from abandoned wells in PA based on over 150 field measurements.
- Townsend-Small et al. (2016) developed methane emission rates estimates from abandoned wells in the Eastern US based on measurements at 12 wells.
- Pelepko et al. (2017) developed methane emission rate estimates from abandoned wells in PA based on over 130 site visits and methane emission rate measurements at five well sites.

² Abandoned wells with no responsible party other than the state.

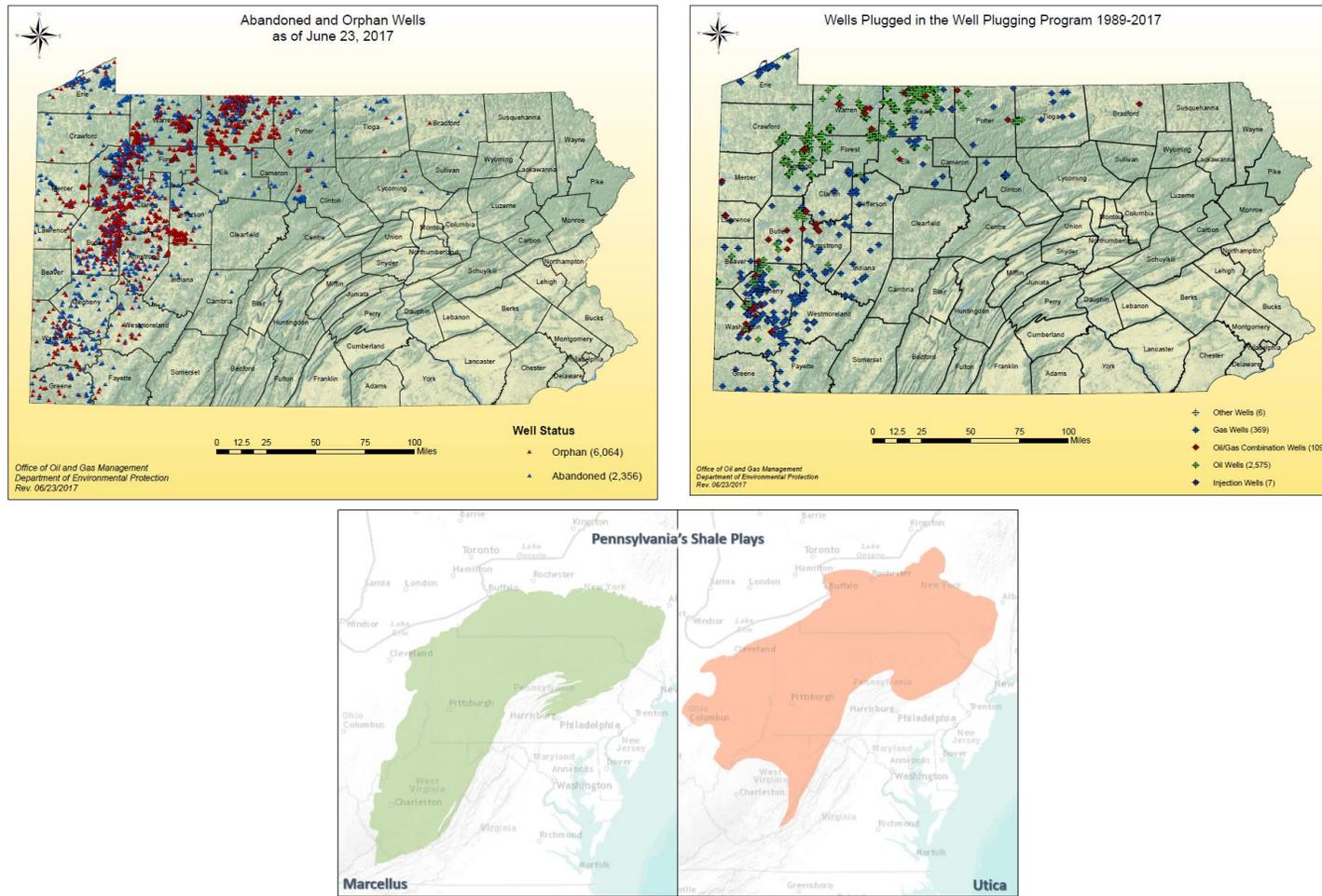


Figure 1. Map of PA abandoned and orphaned wells³ (upper left panel), plugged wells³ (upper right panel), and shale plays⁴ (bottom panel).

³ PADEQ Abandoned & Orphan Well Program, <http://www.dep.pa.gov/Business/Energy/OilandGasPrograms/OilandGasMgmt/Pages/Abandoned-and-Orphan-Well-Program.aspx>

⁴ PADEQ 2016 Oil and Gas Annual Report, <http://www.depgis.state.pa.us/oilgasannualreport/index.html>

Table 1 summarizes key results of the reference studies. Up to 750,000 abandoned wells have been estimated statewide; precise counts are unable to be developed because historical records of well drilling are incomplete⁵ and abandoned wells are difficult to identify based on surface features.

Table 1. Key parameters from relevant literature reviewed.

Parameter		Kang et al. (2016)	Kang et al. (2014)	Pelepko et al. (2017)	Townsend-Small et al. (2016)
Study Area		PA (statewide)	PA (statewide)	PA ^B	Ohio ^A
No. of Measurements		163 measurements (88 wells)	42 measurements (19 wells)	5 measurements (136 well visits)	12 measurements (12 wells)
No. of Abandoned Wells		300,000 - 500,000	300,000 - 500,000	58,997 ^B	not available ^A
Average Methane Emission Rate (g CH ₄ /h/well)		see Table 2	11	10 ^D	14 (all wells) 0 (plugged) 28 (unplugged)
Pennsylvania Abandoned Well Methane Emission Inventory	(Mega tonnes ^C CH ₄ /yr)	0.040 - 0.066	0.03 - 0.05	0.003 - 0.004 ^D	not available ^A
	[Mega tonnes ^C CO ₂ e/yr]	1.0 - 1.7	0.8 - 1	0.007 - 0.010	

^A Measurements conducted in Ohio in the Appalachian Basin. Study area does not include PA.

^B Only includes wells identified as abandoned/orphaned and plugged wells in the PA Department of Environmental Protection abandoned well database. Does not include wells that have not yet been identified.

^C Metric tonnes

^D Calculated

Figure 2 shows photographs of example abandoned well locations from Pelepko et al. (2017); notably there is no evidence of the presence of an abandoned well at some locations where an abandoned well is expected to be located.

⁵ The first well in Pennsylvania was drilled in 1859. Kang et al. (2016) estimates 65%-76% of abandoned wells are oil wells.



Figure 2. Field images of well locations; source Pelepko et al. (2017; Figure 2).

Kang et al. (2016) is the most comprehensive abandoned well study conducted to-date. Kang et al. (2016) includes estimates of methane emission rates by well type (see Table 2) based on measurements from 88 abandoned wells in western Pennsylvania. The following results are presented in Kang et al. (2016):

- Abandoned well methane emission rates correlate most strongly to well type, plugging status, and coal area designation⁶.
- Abandoned well methane emission rates are not strongly correlated with well depth, distance to nearest unconventional well, or distance to nearest underground natural gas storage field.
- The highest emission rates are observed from abandoned gas wells. Unplugged gas wells located in non-coal areas have the highest methane emissions per well and plugged⁷ gas wells in coal areas have the second highest methane emissions per well.
- Similar to other fugitive O&G sector sources, methane emissions from abandoned wells appear to be strongly influenced by relatively few high emitters⁸.
- Abandoned wells with the highest methane emissions also had strong thermogenic signatures, indicating gas from source formations as opposed to biogenic (microbial) sources.
- Tests conducted over two years indicated that high emitters sustained high emission levels; low emitters showed more temporal variation in emission levels.

⁶ Defined in Kang et al. (2016) as wells that overlap with one or more workable coal seams.

⁷ Plugged wells in coal areas are typically (1) plugged across producing formations and vented to the atmosphere to impede deep gas intrusion to coal seams in case of plug failure or (2) plugged solid (i.e. entirely filled with cement).

⁸ Defined in Kang et al. (2016) as wells with emissions greater than or equal to 10,000 mg/hr/well.

Table 2. Methane emission factors by coal designation area and well type based on measurements from 88 abandoned wells in western Pennsylvania, source Kang et al. (2016; Table 2).

Coal Area Designation	Emission Factor (g CH ₄ /h/well)		No. Abandoned Wells Measured (count)	
	Unplugged	Plugged	Unplugged	Plugged
All Wells				
None	22	15	53	35
Coal	1.2	43	17	12
Non-coal	31	0.45	36	23
Oil and Combined Oil and Gas				
None	0.19	0.033	34	13
Coal	0.0011	0.000012	13	1
Non-coal	0.31	0.036	21	12
Gas				
None	60	24	19	22
Coal	5.2	47	4	11
Non-coal	75	0.54	15	11

Abandoned O&G Well VOC emissions

To-date, studies of emissions from abandoned wells have focused on methane; results have shown that methane emissions from abandoned wells are substantial (e.g. Kang et al. [2016] found that methane emissions from abandoned O&G wells account for 5-8% of annual anthropogenic methane emissions in Pennsylvania). VOCs are also expected to be a component of gas leaked from abandoned wells. Depending upon the gas composition of the formation from which a well is leaking; VOC emissions could represent a substantial fraction of emitted gas.

Kang (2016) measured the composition of ethane, propane, and n-butane concentrations in gas emitted from abandoned wells; for high emitters, the mass ratio ranged from 0.01-0.20 grams per mole of the summation of ethane, propane, and n-butane components to grams per mole of methane. In addition to ethane, propane, and n-butane, heavier hydrocarbons not measured in Kang et al. (2016) could be present in leaked gas (e.g. pentanes, hexanes, heptanes, octanes).

The US Environmental Protection Agency (EPA) O&G Tool (version 1.5) indicates a range of VOC to methane weight ratios from 0.15 for gas and coalbed methane wells to 0.94 for oil wells for completion gas. Applying the EPA O&G Tool gas well VOC to methane ratio of 0.15 to Kang et al. (2016) methane emission results of 0.040 - 0.066 megatonnes of methane per year according to Equation 1 yields VOC emissions of 6,400 to 11,000 short tons per year (tpy), representing 6% to 10% of PA state-wide 2014 O&G Production VOC emissions⁹.

⁹ 2014 National Emissions Inventory (NEI), Version 1.0, <https://www.epa.gov/air-emissions-inventories/2014-national-emissions-inventory-nei-data>, accessed online July 11, 2017

$$E_{VOC} = E_{CH_4} \times R \times C \quad (1)$$

where:

E_{VOC} = Pennsylvania state-wide VOC emissions from abandoned wells (short tons/year)

E_{CH_4} = Pennsylvania state-wide methane emissions from abandoned wells (megatonnes/year)

R = VOC to methane ratio

C = Conversion factor (1,102,311 short tons per metric megatonne)

Recommendations

Further study is needed to characterize VOC emission levels from abandoned O&G wells in PA. Based on a combination of methane emission estimates from Kang et al. (2016) and methane to VOC ratios available in the EPA O&G Tool, we estimated annual PA state-wide VOC emissions from abandoned wells of 6,400 to 11,000 tpy. To develop VOC emissions from abandoned wells in Pennsylvania, (1) the spatial distribution of abandoned wells by county should be estimated to allow for development of county-level VOC emission estimates for incorporation into the NEI and (2) additional study should be performed to develop representative gas compositions from abandoned wells to enhance the accuracy of VOC emissions estimates from abandoned wells. County-level abandoned well counts and abandoned well gas compositions should be combined with abandoned well emission rates from Kang et al. (2016) to develop county-level VOC emissions from abandoned wells to incorporate into the NEI.

References

- Boothroyd, I.M., S. Almonda, S.Qassim, F. Worralla, R. Davies. 2016. Fugitive emissions of methane from abandoned, decommissioned oil and gas wells. *Science of the Total Environment*. Vol. 547, 461-469. doi: 10.1016/j.scitotenv.2015.12.096
- Ho, J., A. Krupnick, K. McLaughlin, C. Munnings, J. Shih. 2016. Plugging the Gaps in Inactive Well Policy. *Resources for the Future*. May
- Kang, M., C. Kanno, M. Reid, X. Zhang, D. Mauzeralla, M. Celiaa, Y. Chenc, T. Onstott. 2014. Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania. Vol. 111, no. 51, 18173-18177. doi: 10.1073/pnas.1408315111
- Kang, S. Christian, M. Celia, D. Mauzerall, M. Bill, A. Miller, Y. Chen, M. Conrad, T. Darrah, R. Jackson. 2016. Identification and characterization of high methane-emitting abandoned oil and gas wells. *Proceedings of the National Academy of Sciences of the United States of America*. Vol. 113, no. 48, 13636-13641. doi: 10.1073/pnas.1605913113.
- Pelepko, S., L. Byron, S. Beattie, D. Catalano, R. Swand. 2017. Pennsylvania Legacy Well Integrity and Emissions Study: Part 1. Pennsylvania Department of Environmental Protection: Bureau of Oil and Gas Planning Program Management, Well Plugging and Subsurface Activities Division.
- Townsend-Small, A., T. Ferrara, D. Lyon, A. Fries, B. Lamb. 2016. Emissions of coalbed and natural gas methane from abandoned oil and gas wells in the United States. *Geophysical Research Letters*. Vol. 43, no. 5, 2283–2290. doi: 10.1002/2015GL067623
- Pennsylvania Department of Environmental Protection. 2000. Pennsylvania’s Plan for Addressing Problem Abandoned Wells and Orphaned Wells. Bureau of Oil and Gas Management. 550-0800-001. April. <http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-48262/550-0800-001.pdf>