Reducing methane emissions from abandoned oil and gas wells: strategies and costs

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Abstract

Well plugging, the main strategy for reducing methane emissions from millions of unplugged abandoned oil and gas (AOG) wells in the U.S. and abroad, is expensive and many wells remain unplugged. In addition, plugging does not necessarily reduce methane emissions and some categories of plugged wells are high methane emitters. We analyze strategies and costs of five options for reducing methane emissions from high-emitting AOG wells, which are unplugged and plugged/vented gas wells. The five options are: plugging without gas venting, plugging with gas venting and flaring, plugging with gas venting and usage, gas flaring only, and gas capture/usage only. Average plugging costs ($37,000 per well) can be offset by the social cost of methane, which considers air quality, climate, and human/ecosystem impacts. Savings as measured by natural gas prices and alternative energy credits can offset low plugging costs (<$15,400 per well) but are not large enough to offset average plugging costs. Nonetheless, reducing methane emissions from AOG wells is a cost-effective strategy that is comparable to mitigation options currently considered in efforts to tackle climate

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change. Therefore, we recommend including the mitigation of AOG wells in climate and energy policies in the U.S., Canada, and other oil-and-gas-producing regions.
Keywords: methane emissions, greenhouse gas emissions, mitigation, abandoned wells, oil and gas, costs

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1. Introduction

Measurements show that unplugged and plugged abandoned oil and gas (AOG) wells are emitting methane into the atmosphere (Kang et al., 2014; Townsend-Small et al., 2016) and may have been doing so for decades (Kang et al., 2016). AOG wells are estimated to be responsible for approximately 5 to 8% of annual state-wide anthropogenic methane emissions in Pennsylvania (Kang et al., 2016). Across the U.S., there are more than three million AOG wells (Brandt et al., 2014; King and Valencia, 2014), with millions more in other countries around the world. AOG wells have recently been included in the U.S. GHG emissions inventories (U.S. Environmental Protection Agency, 2018) but are not yet considered in methane emission reduction scenarios. Therefore, we seek to answer the question: can mitigating methane emissions from AOG wells be a cost-effective methane emissions reduction strategy?

Methane is a powerful greenhouse gas (GHG) with a global warming potential (GWP) 34 times greater than carbon dioxide over a 100-year time period and 86 times greater than carbon dioxide over a 20-year time period (IPCC, 2013). These high GWP values mean that methane mitigation provides an opportunity to reduce climate warming in the near term (UNEP, 2011; Shindell et al., 2012; Saunois et al., 2016). The social cost of methane emissions (SCM), which includes costs of climate impacts such as floods, is substantially higher than costs estimated using the social cost of carbon dioxide and GWP (Marten and Newbold, 2012). The SCM currently used by the U.S. government is $1143 per tonne of methane emissions (for 2015 at a 3% discount rate in 2015 USD, used throughout this paper) (Interagency Working Group on Social Cost of

Greenhouse Gases, United States Government, 2016; Environment and Climate Change Canada, 2016). However, these SCMs do not include air quality-related costs and impacts of emitting fossil methane, which increase the SCM to $4822 per tonne of methane emissions (Shindell et al., 2017).

Costs of emitting methane from AOG wells depend on the emission rate, which can vary by many orders of magnitude (Kang et al., 2014, 2016; Townsend-Small et al., 2016). Methane emissions from AOG wells follow extreme distributions with the largest 16% of leaks (>0.09 tonne yr^{-1} $well^{-1}$ or >10^4 mg h^{-1} $well^{-1}$) accounting for 98% of the total leakage volume (Kang et al., 2014, 2016; Brandt et al., 2016). Therefore, reducing emissions from high methane-emitting AOG wells can lead to cost-effective environmental benefits. Measurements and database analysis for AOG wells in Pennsylvania showed that unplugged gas wells in noncoal areas and plugged and vented gas wells in coal areas are high emitters with average methane emissions of 0.66 tonne yr^{-1} $well^{-1}$ and 0.41 tonne yr^{-1} $well^{-1}$ respectively (Kang et al., 2016). To minimize costs associated with finding high emitters, we focus on these two high methane-emitting categories of wells.

According to regulations today, the main mitigation strategy for oil and gas wells at abandonment is plugging (King and Valencia, 2014). There are many methods to plug a well, but in general, a plug (often cement) is placed in an AOG well throughout intervals that intersect geologic formations containing oil and gas, coal layers, and groundwater aquifers. Plugging is designed to limit both gas migration from these isolated layers to overlying formations, and gas emissions at the surface. Plugged wells (without vents) have been found to be low emitters (Kang et al., 2014, 2016; Townsend-Small et al., 2016; Boothroyd et al., 2016; Riddick et al., 2019). Wells in Pennsylvania that are plugged in coal areas are required to have gas vents, which are designed to release methane and other gases to the atmosphere in order to prevent explosions (PA DEP, 1998). These plugged but vented wells have been found to be very high emitters (Kang et al., 2016). To reduce methane emissions, strategies other than, or in addition to, plugging are needed.

Identifying cost-effective mitigation strategies for AOG wells is important given that the responsible party for many old AOG wells is a government agency with limited funds (Davies et al., 2014; Ho et al., 2016). For example, of the tens to hundreds of thousands of AOG wells in Pennsylvania that the Pennsylvania Department of Environmental Protection (DEP) is responsible for plugging, 1679 wells were plugged by the DEP in the decade spanning from 2004 to 2013. Elsewhere, for example, in Canada, there is growing concern regarding wells abandoned by bankrupt companies due to the few incentives for companies to clean them up (Muehlenbachs, 2015). Plugging can be expensive at ∼\$10,000 to ∼\$1,000,000 per well, and alternative or supplementary mitigation strategies and their costs need to be explored.

Methane emissions reduction strategies that are currently available and have been implemented for active oil and gas systems and coal mines can be applied to AOG wells. These strategies can be broadly categorized as (1) plugging, (2) flaring, and (3) recovery/utilization of emitted gases (Delhotal et al., 2006; International Energy Agency, 2009; Economic Commission for Europe Methane to Markets Partnership, 2010; UNEP, 2011; Yusuf et al., 2012; Karakurt et al., 2012). Flaring technologies involve burning methane, converting it to CO_2 and water. Utilization options include direct use as a fuel, connection to natural gas pipelines for off-site use, and re-injection for enhanced oil recovery (Yusuf et al., 2012; Karakurt et al., 2012). Flaring and utilization may be performed at both plugged and unplugged AOG wells.

In this paper, we evaluate costs of currently available methane emissions reduction options for high methane-emitting plugged and unplugged AOG wells. We first review published measurements of methane emissions from AOG wells to evaluate emission factors of high methane-emitting well categories. We then evaluate five mitigation options for high emitters that are combinations of well plugging, capture/usage of emitted gas, and flaring. We analyze plugging costs, natural gas prices, SCM, alternative energy credit prices, and flaring/utilization infrastructure costs to estimate the overall cost of each mitigation option.

2. High methane-emitting AOG wells in Pennsylvania

Average measurements of methane emissions from AOG wells across the US and the UK range from 0.03 to 15 tonne yr^{-1} $well^{-1}$ for unplugged wells and 1.8×10^{-5} to 0.13 tonne yr^{-1} $well^{-1}$ for plugged wells (Table 1). All studies other than Kang et al. (2016) do not specify if a plugged well is vented or present no measurements of plugged and vented wells. The large orders-of-magnitude variation in the emission rates implies that plugging status (based solely on whether or not a well is plugged) is not sufficient for identifying high emitters, which may be defined as having emissions greater than 0.1 tonne yr^{-1} $well^{-1}$ (Kang et al., 2016).

Table 1: Summary of average published methane emission rates

	Average Methane Emissions (tonne yr^{-1} $well^{-1}$)		Number of Measurements		
Reference	Unplugged	Plugged	Unplugged	Plugged	Study Region
Kang et al. (2016)	0.19	0.13	53	35	Pennsylvania, USA
Riddick et al. (2019)	0.03	8.8×10^{-4}	147	112	West Virginia, USA
Boothroyd et al. (2016)	0.36	0.015	1	102	United Kingdom
Townsend-Small et al. (2016)	0.09	1.8×10^{-5}	19	119	Colorado, Wyoming, Utah, Ohio, USA
Etiope et al. (2013)	15	Not applicable	1	0	Pennsylvania, USA

Methane emission factors (IPCC, 2006), q, have been estimated per well for different types of AOG wells, categorized based on plugging status, coal area designation, and well type (Kang et al., 2016). Two well categories are found to have high methane emission factors: (1) unplugged gas wells in non-coal

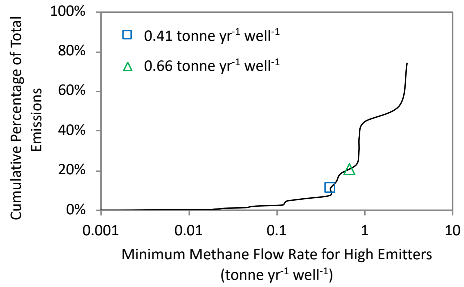

Figure 1: Cumulative percentage of total measured methane emissions in Pennsylvania with respect to methane flow rates. The two methane emission rates or emission factors used in this paper are shown: the average methane emission rate for plugged (and vented) gas wells in coal areas (blue square); and the average methane emission rate for unplugged gas wells in noncoal areas (green triangle). Data is from Kang et al. (2016).

areas, with $q = 0.66$ tonne/yr/well (7.5×10^4 mg/h/well) and (2) plugged and vented gas wells in coal areas, with $q = 0.41$ tonne/yr/well (4.7×10^4 mg/h/well) (Figure 1). These two high-emitter categories represent 2.2% (705 wells) and 12% of the wells in the Pennsylvania DEP database, respectively (PA DEP, 2015). We focus our analysis on these two high-emitter categories to eliminate the challenge of finding high emitters, thereby reducing costs.

3. Mitigation

3.1. Techniques and options

Three currently available mitigation techniques that can reduce methane emissions are: (1) well plugging, (2) capture and use of emitted gases, and (3) gas flaring. We assume that well plugging is performed following Pennsylvania regulations (Pennsylvania Code Chapter 78), and that plugging without gas venting will reduce methane emissions such that the well is no longer a high emitter. This is consistent with measurements that show plugged wells without vents are not high emitters (Kang et al., 2016). There are many ways to capture and use emitted gases (Yusuf et al., 2012; Karakurt et al., 2012). One example is the connection of an AOG well to a natural gas user such as a household, which would otherwise obtain natural gas from other sources. The gas can also be used as fuel for on-site electricity generation or can be routed to natural gas pipelines for off-site use (Yusuf et al., 2012; Karakurt et al., 2012). Another option is to flare the gas at the surface using a combustion device.

We identify mitigation options based on combinations of the three currently-available techniques that are applicable to the two classes of high emitters (abandoned unplugged gas wells in non-coal areas, and abandoned plugged/vented gas wells in coal areas). The mitigation options are:

1. Plugging without gas venting,
2. Plugging with gas venting and flaring,
3. Plugging with gas venting and usage,
4. Gas flaring without plugging, and
5. Gas capture/usage without plugging.

The first option is only applicable to unplugged wells in non-coal areas, where venting is not required. The remaining four options are applicable to any AOG well. We allow for the option of replugging plugged wells and for the option of leaving unplugged wells unplugged. We also assume that implementation of mitigation options does not impact nearby wells.

We note that, of the options considered here, only the first three options (involving plugging) can address other potential concerns associated with well leakage including contamination of groundwater resources. This is because a properly installed well plug will protect groundwater, as specified by regulations. The last two options do not include plugging and therefore, while they can reduce methane emissions to the atmosphere and can be economically advantageous, they do not provide any additional protection to subsurface resources including groundwater.

Plugged wells are not required to be maintained or monitored and all plugging costs are upfront. Flaring and capture/utilization costs are dominated by upfront costs but include operation and maintenance costs. The upfront costs are converted to USD per tonne of methane emissions avoided by considering the total methane emissions over a specified lifetime. Therefore, we assume that a tonne of methane emissions in any year over the specified lifetime is equivalent to a tonne of methane emissions in the year of analysis (2015). However, we note that this is a conservative assumption as a given amount of methane emissions made in a future with higher GHG concentrations in the atmosphere and increased global temperatures lead to larger damages and social costs (Marten and Newbold, 2012; Shindell et al., 2017).

Here, we describe costs associated with the various mitigation options in the context of Pennsylvania. Unless otherwise noted, we present costs in 2015 U.S. Dollars (USD) per tonne of methane (CH_4) emissions avoided (Figure 3), adjusted for average inflation of 1.69% per year from 2007 to 2015, 1.38% per year from 2008 to 2015, 1.32% per year from 2011 to 2015, and 1.94% per year from 2015 to 2018 (U.S. Bureau of Labor Statistics).

3.2. Costs associated with mitigation options

3.2.1. Plugging costs

Plugging costs vary widely based on the source of the estimate, well depth, well location, well type, well condition, and accessibility of the well (Andersen and Coupal, 2009; Mitchell and Casman, 2011; Ho et al., 2016, 2018). The Interstate Oil & Gas Compact Commission (IOGGC) compiled records of funds expended to plug wells and the corresponding number of wells plugged in 26 states across the U.S. Based on four years (1992, 1996, 1999, and 2006) of data, they report average plugging costs ranging from $360 to $110,000 per well (IOGCC, 2008) (Figure 2(a)). The mean and median of these plugging costs are $18,000 and $11,000 per well respectively. For Pennsylvania, the average plugging cost is reported to be $10,063 per well. We also acquired and analyzed well plugging contract data (PA DEP, 2018) from 1988 to 2013 for Pennsylvania. These data reveal higher plugging costs, averaging at $36,535 and $57,774 per well for all wells and gas wells only, respectively (Figure 2(b)). The median values ($22,603 and $46,617 per well for all wells and gas wells only respectively) are lower than the average values, indicating that the averages are skewed upward by relatively few high costs (Figure 2(b)). The Pennsylvania data show that the main variables driving cost are rig time, trucking costs, and freshwater usage (PA DEP, 2018). Other important factors are location differences (i.e., certain contractors prefer to work in certain geographic areas) and site conditions (i.e., distance to the road, distance between wells, and site slope). However, previous studies have found depth to be one of the strongest predictors of plugging cost (Andersen and Coupal, 2009); and others have linked very high costs to site reclamation (Ho et al., 2016). To be consistent with our strategy of mitigating high emitters, which are gas wells (see Section 2), we use the average and median costs for gas wells only.

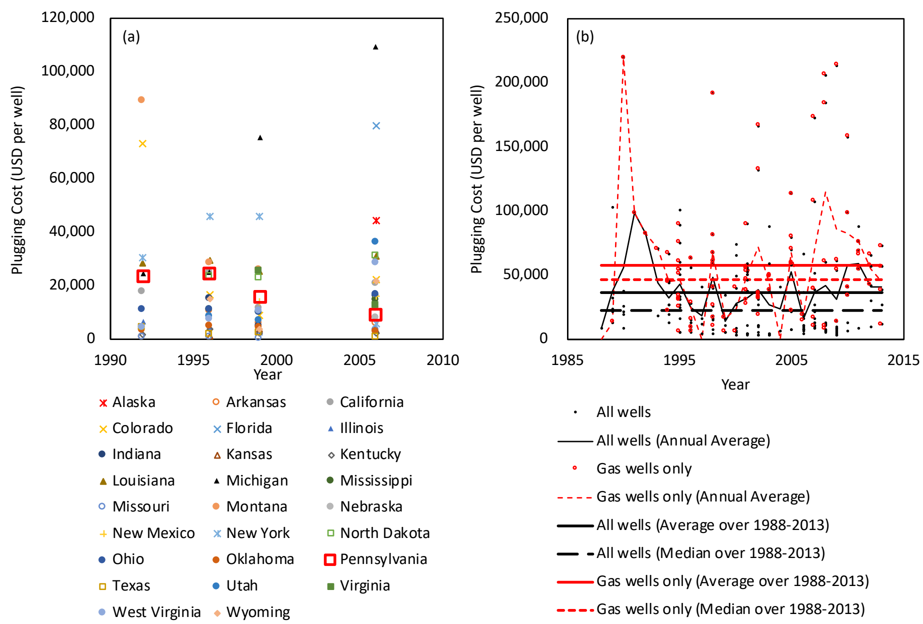

Figure 2: Plugging cost in 2015 USD per well (a) by state (IOGCC, 2008) and (b) in Pennsylvania (PA DEP, 2018).

The plugging costs per well, $c_{p,well}$, can be converted to the cost of plugging per tonne of CH_4 emitted over time period t, $c_{p,t}$ (\$ per tonne CH_4), as follows:

$$c_{p,t} = c_{p,well}/m_t, \quad (1)$$

where $m_t = q \cdot t$ is the mass (tonne) of methane emissions avoided per well over time period t, t is the number of years of methane emissions avoided, and q is the mass flow rate of methane emitted per well. Throughout the plug lifetime, we assume that methane emission rates can be viewed as constant (Kang et al., 2016). The time periods (t) are chosen to reflect the lifetime of a plug, which is uncertain but assumed to range from 50 to 100 years. For the two high emitter categories (0.41 and 0.66 tonne yr^{-1} well^{-1}), the costs range from \$1774 to \$3565 per tonne of methane emissions avoided for a 50-year plug lifetime and from \$877 to \$1782 per tonne of methane emissions avoided for a 100-year plug lifetime (Figure 3).

3.2.2. Cost of identifying and measuring methane emissions

Field evidence shows that high emitters can be identified with cheap handheld gas sensors. For example, in one sampling campaign (June 2015) (Kang et al., 2016), we consistently screened wells with a handheld sensor and found six wells with gas concentrations in the >0.1% Lower Explosive Limit (LEL) range (i.e., 2.5% methane = 50% LEL). The methane emissions from these wells were 2.2×10^3, 4.2×10^3, 2.3×10^4, 4.6×10^4, 5.4×10^4, and 2.9×10^5 mg/h/well. Therefore, resources for detailed and more costly measurement can be focused on wells identified to be high emitters.

Screening wells for high emitters using handheld gas sensors can be performed at very low cost. These types of gas sensors can cost as little as \$156 (e.g., the *General Tools* sensor from *Home Depot*) to ∼\$420 (e.g., *Sensit HXG-2d*). These light and portable sensors can easily be used at many sites and a few sensors should be sufficient to serve the needs of an entire county. These sensors do not require special training and can be easily used by local residents and landowners at many wells. Therefore, with hand-held sensors and community involvement, the cost of screening is likely a few cents per well and are not included in our analysis.

Plugged-and-vented gas wells and unplugged gas wells have been identified as high emitters (Kang et al., 2016). Focusing on locations with these types of wells can substantially reduce well finding costs. Nevertheless, the cost of finding AOG wells is difficult to estimate and depends on many factors, including financial incentives, liability issues, and industrial services. Based on field evidence (Kang et al., 2014, 2016), local residents can be instrumental in finding wells but need to be incentivized to search for and more importantly, report AOG wells. Main barriers to finding AOG wells are potential liability of landowners, ownership and mineral rights issues, and future costs associated with plugging and other potential environmental impacts. Although the regulations in Pennsylvania and elsewhere currently require landowners and others to notify the DEP or equivalent agency of AOG wells, there is little incentive to do so and minimal enforcement. In Pennsylvania, volunteer environmental groups such as SaveOurStreamsPA and the Senior Environmental Corps have successfully identified thousands of wells in state parks and game reserves and reported them to the DEP. Despite these efforts, hundreds of thousands of wells likely remain lost. However, financial incentives and new policies on oil and gas development, climate change, and alternative energy development may motivate identification of AOG wells.

Currently, methane emissions from AOG wells are primarily identified and measured for scientific reasons and depend on research funding, often from government sources. Measurements of methane emissions are critical for national greenhouse gas inventories, which are compiled annually by countries and submitted to international bodies (i.e., the Intergovernmental Panel on Climate Change). For these inventories, there is a need for additional measurements of methane emissions from AOG wells to improve estimates and reduce uncertainties (U.S. Environmental Protection Agency, 2018). In addition, industry can benefit from AOG well identification and measurement as operators are required to find and monitor wells around new developments, such as hydraulically-fractured oil/gas wells (Pennsylvania Code Chapter 78).

For wells identified as high emitters in the screening process, we estimate detailed methane emission measurement costs to be \$50 per well for equipment, supplies, and analysis. We estimate \$5 per well for equipment costs (flux chamber, which can be used at least 20 times), \$20 per well for supplies (i.e., needles, syringes, vials, stopcocks, and tubing), \$15 per well for laboratory analysis (assuming five samples analyzed at an external laboratory (e.g., University of California- Davis Stable Isotope Facility)), and \$10 per well for overhead (e.g., use of laboratory space and administrative support). As an alternative to laboratory analysis, industry or government agencies providing the measurement service can acquire or may already have a sensor for methane and ethane, which cost ∼\$30,000 (e.g., *CEA* or *Sensit*) and can be used for a wide range of leak quantification applications (e.g., from landfills and other oil and gas infrastructure). Costs per well decrease as the number of wells measured increases (e.g., for laboratory analysis and shipping costs) and with improved methods and technology (e.g., low-cost sensors). Therefore, at the low end, we assume \$20 per well. Assuming fewer measurements per unit equipment (i.e., chambers and sensors), we assume the high end estimate to be \$200 per well.

The costs of measuring methane emissions per well, $c_{m,well}$, can be converted to the measurement cost per tonne of CH_4 emitted over time period t, $c_{m,t}$ (USD per tonne CH_4), as follows:

$$c_{m,t} = c_{m,well}/m_t, \tag{2}$$

where $m_t = q \cdot t$ is the mass (tonne) of methane emissions avoided per well over time period t, t is the number of years of methane emissions avoided, and q is the mass flow rate of methane emitted per well. Using the \$50 per well measured as the best estimate with \$20 per well and \$200 per well as the low and high end estimates respectively and the flow rates of the two high-emitter categories, we get a best estimate of \$5 per tonne CH_4 (Figure 3) with a low end of \$0.3 per tonne CH_4 and a high end of \$24 per tonne CH_4.

3.2.3. Cost of flaring

For flares at natural gas production sites, the Methane Challenge Program Partners of the U.S. Environmental Protection Agency's Natural Gas STAR Program report capital costs for implementation of \$3161 per flare, with a possible range of \$1054 to \$5269 (U.S. Environmental Protection Agency, 2016b). The EPA notes an implementation cost of ∼\$22,000, implying the installation costs are six times the cost of the flare. However, these costs are for natural gas production sites and assumed to be not applicable here. The operating and maintenance (O&M) costs are reported to be \$1897 to \$4426 per year but are primarily associated with fuel needed to increase the heat content above 300 Btu per standard cubic foot (scf) (U.S. Environmental Protection Agency, 2016b). The gas emitted from AOG wells is comparable to natural gas in composition - primarily methane with heavier hydrocarbons (Kang et al., 2014, 2016). Heat content of natural gas in Pennsylvania measured from 2013-2016 hovers around 1040 Btu per scf (U.S. Energy Information Administration, 2017a), which is slightly higher than that of methane at 1010 Btu per scf. Therefore, the heat content of the emitted gas is much higher than the flare operating requirements of 300 Btu per scf. However, we may require an electronic ignition system similar to those used for gas lanterns, which has a capital cost of ∼\$453 (Flambeaux Lighting, 2018). Here, we assume O&M costs are negligible but consider the scenario of adding electronic ignition systems.

The cost of flaring methane leaking from AOG wells over time period, t, is calculated as:

$$c_{f,t} = c_{f,well}/m_t \tag{3}$$

where $c_{f,well}$ is the cost of flaring per well and m_t is the mass of methane flared over time period, t (as defined above). Assuming flare lifetimes of 20 and 50 years, the capital costs outlined in U.S. Environmental Protection Agency (2016b), and using the emission factor of the two high-emitter categories described above, we estimate the cost of flaring to range from \$32 to 640 per tonne CH_4, with a mean of \$219 per tonne CH_4 (Figure 3). If we add the cost of electronic ignition systems, the costs increase by \$14 to \$55 per tonne CH_4 emissions avoided. Based on UK data, the cost of flaring (including capital and O&M) for on-shore oil and gas production activity is estimated to be 73-103 Euros per tonne CH_4 (Höglund-Isaksson and Mechler, 2005) in 2000 prices. This cost is equivalent to approximately \$110-\$150 per tonne CH_4. In other words, the UK costs fall within the range of our estimates.

3.2.4. Cost of capture/utilization of emitted gases

The usage of the emitted gas is assumed to occur primarily within several hundred meters of the AOG well. In the study of Kang et al. (2016), there are 14 wells with methane flow rates above 0.1 tonne year^{-1} well^{-1} (10^4 mg h^{-1} well^{-1}). Ten out of the 14 wells (71%) are located within 500 m of a residence or other building (e.g., school), with a range of 20 m to 400 m and an average distance of 177 m. The remaining four wells are located 1.3 km to 3 km from a building that is able to use the gas.

Given the high heat content of the emitted gas with 86% to 98% methane (Kang et al., 2016), the emitted gas can be consumed directly for heating and other uses. We estimate costs by considering the cost of adding a natural gas service line in homes using online estimation tools: FIXR (2017) and Homewyse (2017). FIXR estimates installation costs range from \$47 to \$943 USD, with the low end representing a do-it-yourself project with material cost only and the upper end representing professional installation with upgraded materials. Homewyse's default parameters consider basic labor, supplies, and equipment allowance and estimate costs of \$545 to \$718 per line. The Methane Challenge Program Partners report an average cost of \$4531 to connect casing to vapor recovery units (U.S. Environmental Protection Agency, 2016a), which varies based on factors such as gas pressure and composition. We expect gas pressures in natural gas production sites to be much higher than at AOG wells, and note higher pressures likely correspond to higher costs. The Methane Challenge Program Partners report operation and maintenance (O&M) costs of \$3583 per year for increased electricity requirements of the vapor recovery unit, which is not applicable here. Furthermore, landfill gas recovery pipeline systems, which are more complex, are estimated to have negligible O&M costs (Landfill Methane Outreach Program, 2016). Therefore, we assume that O&M costs are negligible over the considered lifetimes of 20 and 50 years.

The cost of capture/utilization of emitted gas over time period, t, of methane emissions reductions is calculated as:

$$c_{u,t} = c_{u,well}/m_t \tag{4}$$

where $c_{u,well}$ is the cost of capture/utilization per well and m_t is the mass of methane emissions captured/utilized per well over t (as defined above). Assuming 20- and 50-year infrastructure lifetimes, we calculate gas usage costs to range from \$2 per tonne of CH_4 to \$550 per tonne of CH_4, with an average of \$79 per tonne of CH_4 (Figure 3). This cost is small relative to savings from avoiding the purchase of natural gas (Section 3.3.2).

3.3. Savings associated with mitigation option

3.3.1. Social cost of methane

The social cost of methane (SCM) represents the cost of damages due to climate change (Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, 2016) and costs associated with air quality and health/ecosystem impacts (Shindell et al., 2017). The SCM with and without air quality and health/ecosystem impacts are \$1143 per tonne CH_4 (Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, 2016) and \$4625 per tonne CH_4 (Shindell et al., 2017) respectively for emissions made in 2015 and assuming a 3% discount rate (adjusted to 2015 USD based on the U.S. inflation rate from the Bureau of Labor Statistics, as discussed in Section 3.1). The SCM including air quality and health/ecosystem impacts is referred to here as SCM for biogenic methane following Shindell et al. (2017). For fossil methane, the SCM also includes additional emissions associated with oil and gas production (Shindell et al., 2017) and is therefore higher at \$4822 per tonne CH_4. The SCM for gases emitted from AOG wells likely falls in between the SCM for biogenic and fossil methane because we do not need to consider the emissions associated with other components of oil and gas production. To be conservative, we use the SCM for biogenic methane emissions (\$4625 per tonne CH_4) and the 95th Percentile SCM of \$3201 per tonne CH_4 (Interagency

Working Group on Social Cost of Greenhouse Gases, United States Government, 2016).

3.3.2. *Value of emitted gas*

Natural gas users can utilize captured gases, thereby generating savings by avoiding the purchase of natural gas. We compile annual U.S. natural gas prices from 2010 to 2015, which average \$10.79, \$8.56, and \$4.61 per thousand cubic feet for residential, commercial, and industrial users respectively (U.S. Energy Information Administration, 2017b). We convert the average natural gas prices (USD per thousand cubic feet) to savings associated with the value of emitted gas, s_v (USD per tonne CH_4 emissions avoided) assuming the density of methane at 1 atm and 25°C (0.66 kg/m^3). The potential savings range from \$160 to \$610 per tonne CH_4 emissions avoided. The variability depends strongly on the type of user, with the lowest natural gas prices associated with industrial users and the highest prices associated with residential users. The savings for the residential user, who we assume to be the most likely user, average \$580 per tonne CH_4 emissions avoided (Figure 3). The standard deviation is \$22 per tonne CH_4 for residential prices over the 6-year time frame (2010-2015), which shows that relative to differences in natural gas prices among users, year-to-year price fluctuations are small. We note that U.S.-wide natural gas prices used here are lower than prices for Pennsylvania, where residential users can expect higher average savings of ∼\$640 per tonne CH_4 emissions avoided.

3.3.3. *Alternative energy credits*

Gases emitted from AOG wells may be considered to be an alternative energy resource under Pennsylvania's Alternative Energy Portfolio Standard (AEPS) program. The AEPS is a state renewable energy portfolio standard that also includes several non-renewable sources. Alternative energy sources in the AEPS are categorized as either Tier I or Tier II. Tier I consists primarily of renewable sources (e.g. solar, wind, and biomass) but also includes coal mine methane, which is similar to gases emitted by AOG wells. Tier II includes large-scale hydropower, demand-side management, and municipal solid waste. The eligibility of gas emitted from AOG wells as an alternative energy resource depends on the interpretation of current regulations and may require an explicit modification of the regulations to include AOG wells.

The AEPS creates demand for alternative energy through alternative energy requirements for electric distribution companies and electric generation suppliers in terms of percentages of total energy sold. It creates monetary incentives through alternative energy credits (AECs), which are earned for every megawatt hour (MWh) of alternative energy produced. For the 2015 energy year, the reported weighted average AEC prices for Tier I and II sources, $s_{\mathrm{a,MWh}}$, were \$12.52 and \$0.12 respectively (PUC Bureau of Technical Utility Services and PA DEP, 2015). Weighted average AEC prices account for "self-generated" AECs for which a price is not available. Self-generated AECs are not sold but used by the electric distribution company or electric generation supplier that generated the alternative energy. AEC prices are volatile, with Tier I prices ranging from \$2.40 to \$47.00 and Tier II prices ranging from \$0.01 to \$15.00 in 2015 (PUC Bureau of Technical Utility Services and PA DEP, 2015).

To convert $s_{\mathrm{a,MWh}}$ to savings associated with AEC prices, s_a (USD per tonne CH_4 emissions avoided), we determine the equivalent amount of natural gas necessary to generate 1 MWh of electricity. Therefore,

$$s_a = \frac{s_{\mathrm{a,MWh}}\ h}{rdC}, \tag{5}$$

where h is the fuel heat content (BTU/ft^3), r is the heat rate (BTU/kWh), d is the density (tonne/m^3), and C is the conversion factor of 28.31682 m^3/Mcf. Using the heat rate for electricity generated with natural gas 7870 (BTU/kWh) (U.S. Energy Information Administration, 2018), the average fuel heat content for marketed and dry natural gas production (1127 BTU/ft^3 and 1037 BTU/ft^3 respectively) (U.S. Energy Information Administration, 2018), and the density of methane (6.6×10^{-4} tonnes/m^3), we get $h/(rdC)$ = 7.34 MWh/tonne. The corresponding savings possible through AECs range from \$0.1 to \$350 per tonne CH_4 emissions avoided (Figure 3), with average Tier I-based and Tier II-based savings of \$92 and \$0.9 per tonne CH_4 emissions avoided respectively (Figure 3). Due to the similarity in gas emitted from coal mines, gases emitted from AOG wells should be considered Tier I.

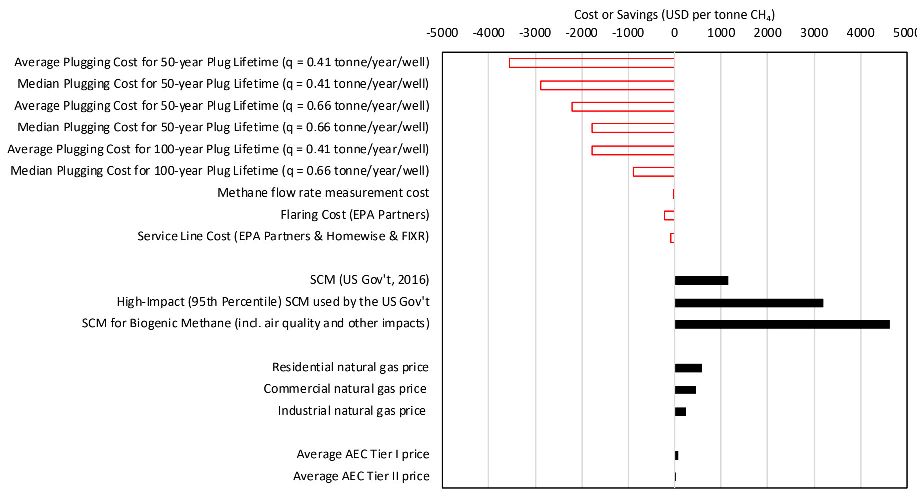

Figure 3: Summary of costs and savings associated with mitigation of AOG wells in 2015 USD per tonne CH_4. The plugging costs are based on the 1988-2013 plugging contract data from DEP.

3.4. Combined costs of mitigation options

We combine the best estimates of costs and savings for the mitigation options (Figure 4). In comparing mitigation options, we assume 50-year plug lifetimes and $q = 0.41$ tonne yr^{-1} $well^{-1}$. We use the average natural gas price for residential users and Tier I AEC pricing. We use the SCM with a 3% discount rate for 2015 (Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, 2016) and for biogenic methane including climate, air quality and other impacts (Shindell et al., 2017).

Savings are possible for all mitigation options and scenarios if we use the SCM including air quality and other impacts (Figure 4). With a lower SCM, options with plugging (i, ii, and iii) produce net costs. However, the net costs can be reduced by up to \$811 per tonne CH_4 (difference between Options ii and iii) through gas usage. In addition, the net costs can be reduced by \$688 per tonne CH_4 if we use the median plugging cost (Option i-2) instead of average plugging cost (Option i-1). Savings are possible via Option iii if plugging costs are less than 15,400 USD per well, which represents 42% and 15% of plugging costs respectively associated with all wells and gas wells only in Pennsylvania (PA DEP, 2018). Without the savings from natural gas and AEPS prices, the SCM minus the measurement cost can offset plugging costs up to \$18,430 per well, which represents 46% and 19% of all wells and gas wells only in Pennsylvania (PA DEP, 2018). If we consider natural gas and AEPS prices along with the SCM, we can offset plugging costs up to \$15,400 per well. If we only consider natural gas prices and the SCM, we can offset plugging costs up to \$13,000 per well. High savings of up to \$5211 per tonne CH_4 (Option v) are possible for options without plugging. These high savings without plugging are comparable to savings associated with mitigation measures for coal mines (Shindell et al., 2017), which are integrated in many policies aimed at addressing climate change.

There are additional costs and savings not considered here. Additional costs include:

- Finding AOG wells,
- Accessing AOG wells,
- Resolving ownership, mineral rights, and potential liability issues, and
- Additional infrastructure/equipment costs for potential gas pressure regulation (e.g., for appliances), fuel mixing, and irregular wellhead casing/connections.

Additional savings include:

- Improved reporting and database of AOG wells,
- Reduced oil and gas and other natural resource development costs,
- Groundwater protection,

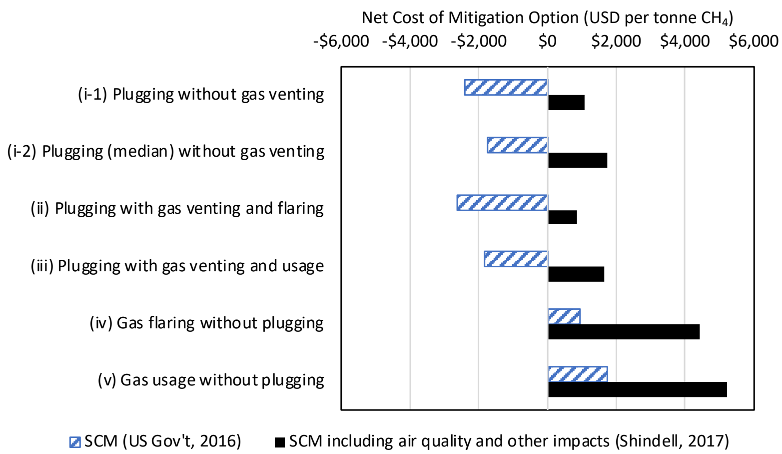

Figure 4: Combined costs (2015 USD per tonne CH_4) based on best estimates provided in Figure 3 for currently available mitigation options. For all options, we use the Average Plugging Cost for 50-year Plug Lifetime (q = 0.32 tonne/year/well), except for option (i-2) that uses the Median Plugging Cost for 50-year Plug Lifetime (q = 0.32 tonne/year/well). We use social costs of methane (SCMs) assuming a 3% discount rate with (Shindell et al., 2017) and without (Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, 2016) air quality and human/ecosystem impacts. Positive net costs represent benefits and savings of mitigation options.

- Improved air quality, and
- Reduced agricultural productivity, human health effects, and ecosystem degradation associated with contaminated water, poor air quality, and changing climate.

Although these additional costs and savings are difficult to quantify, the savings are likely to greatly surpass the costs. Therefore, we anticipate that our combined costs are overestimates while our combined savings are underestimates.

4. Conclusions and policy implications

Plugging costs can be offset by the large social cost of emitting fossil methane (SCM). However, the current SCM used by governments (Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, 2016;

Environment and Climate Change Canada, 2016) are sufficient on its own to justify mitigation when plugging costs are below $18,430 per well. The average plugging cost in Pennsylvania is $37,000 per well but can range from approximately $1000 to $1,000,000 per well due to a wide range of factors including depth, site conditions, and geographic location. These costs need to be characterized and constrained with additional data and analysis to better estimate mitigation costs. The total cost of plugging or re-plugging high-emitting unplugged and plugged abandoned oil and gas (AOG) wells can be large, especially relative to Pennsylvania's abandoned well plugging fund of $92,000 and orphan well plugging fund of $400,000 for the 2017-2018 budget year (Commonwealth of Pennsylvania, Office of the Governor, 2017). An evaluation of bonding requirements across the U.S. show that most are insufficient to cover the average plugging cost (Ho et al., 2018). Therefore, efforts to develop alternative mitigation options, including cheaper plugging and/or other mitigation approaches, should continue to be explored to reduce costs, promote widespread mitigation action, and to better protect the environment. Furthermore, additional measurements to improve characterization of emitted gases and better identify high emitters is needed.

In the case of gas usage, savings through natural gas prices and alternative energy credits can offset low plugging costs (<$15,400 per well) but are not large enough to offset the average plugging cost ($57,774 and $36,535 per well for gas wells only and all wells, respectively). Low plugging costs (<$15,400 per well) represent 42% of all wells and 15% of gas wells in the Pennsylvania's plugging contract database. If we only consider savings through natural gas prices, plugging costs must be lower than $13,000 per well, which represents 38% of available plugging costs. Without plugging costs, gas usage can offset costs for installation even without considering the SCM. However, there are many barriers to gas usage such as safety, potential liability (bonding, mechanical integrity assessment), ownership and mineral rights issues, and future costs associated with plugging and other environmental impacts (e.g., groundwater remediation). Additional research to quantify current gas usage and any impacts are needed to design mitigation strategies that employ gas usage.

Government policies on climate and energy provide an opportunity to encourage methane emissions reduction from AOG wells. In Pennsylvania, there are two state-level policy instruments that can be used to promote reductions in methane emissions from AOG wells: the Climate Action Plan (CAP) and the Alternative Energy Portfolio Standard (AEPS). Mitigation of AOG wells can provide an additional low-cost GHG emissions reduction option for Pennsylvania's CAP. Although the need to better characterize methane emissions from AOG wells is mentioned in Pennsylvania's latest CAP (ICF, 2018), the strategies and policy measures to reduce methane emissions from AOG wells are not presented. In terms of the AEPS, our results show that the savings possible through AEC pricing are relatively small, even if we assume a Tier 1 categorization. Nevertheless, we argue that gases emitted from AOG wells should be considered Tier 1 as they are very similar to coal mine methane. Importantly, the integration of AOG well mitigation in the CAP and/or the AEPS can result in the creation of a database of gas emissions from AOG wells that can be used to further evaluate the environmental impacts of AOG wells and improve mitigation options.

Mitigation of unplugged and plugged abandoned oil and gas (AOG) wells can be a cost-effective methane emissions reduction strategy. This is especially true if we consider the full social cost of emitting methane (SCM), including climate, air quality and human/ecosystem impacts. Plugging costs of up to half of the high-emitting wells can be justified by the SCM, natural gas prices, and alternative energy credits. In addition, reducing emissions at the surface without plugging is cost-effective for all high-emitting wells. Therefore, we recommend the inclusion of methane emissions reduction from AOG wells in climate change and energy policies, and recommend increased government funding at state/provincial and federal levels to manage the growing number of AOG wells in the US, Canada, and abroad.

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References

Andersen, M., Coupal, R., 2009. Economic issues and policies affecting reclamation in wyoming's oil and gas industry. national meeting of the american society of mining and reclamation. National Meeting of the American Society of Mining and Reclamation URL: http://wyofile.com/wp-content/uploads/2012/06/Economic-Issues-and-Policies-Affecting-Reclamation-in-Wyomings-Oil-and-Gas-Industry-Final pdf.

Boothroyd, I., Almond, S., Qassim, S., Worrall, F., Davies, R., 2016. Fugitive emissions of methane from abandoned, decommissioned oil and gas wells. Science of The Total Environment 547, 461–469. doi:10.1016/j.scitotenv.2015.12.096.

Brandt, A.R., Heath, G.A., Cooley, D., 2016. Methane leaks from natural gas systems follow extreme distributions. Environmental Science & Technology 50, 12512–12520. doi:10.1021/acs.est.6b04303. pMID: 27740745.

Brandt, A.R., Heath, G.A., Kort, E.A., O'Sullivan, F., Pétron, G., Jordaan, S.M., Tans, P., Wilcox, J., Gopstein, A.M., Arent, D., Wofsy, S., Brown, N.J., Bradley, R., Stucky, G.D., Eardley, D., Harriss, R., 2014. Methane leaks from North American natural gas systems. Science 343, 733–735. doi:10.1126/science.1247045.

Commonwealth of Pennsylvania, Office of the Governor, 2017. 2017-2018 governor's executive budget. www.budget.pa.gov.

Davies, R.J., Almond, S., Ward, R.S., Jackson, R.B., Adams, C., Worrall, F., Herringshaw, L.G., Gluyas, J.G., Whitehead, M.A., 2014. Oil and gas wells and their integrity: Implications for shale and unconventional resource exploitation. Marine and Petroleum Geology 56, 239 – 254. doi:10.1016/j.marpetgeo.2014.03.001.

Delhotal, K.C., de la Chesnaye, F.C., Gardiner, A., Bates, J., Sankovski, A., 2006. Mitigation of methane and nitrous oxide emissions from waste, energy and industry. The Energy Journal 27, 45–62. URL: http://www.jstor.org/stable/23297075.

Economic Commission for Europe Methane to Markets Partnership, 2010. Best Practice Guidance for Effective Methane Drainage and Use in Coal Mines. ECE Energy Series 31. United Nations. New York and Geneva.

Environment and Climate Change Canada, 2016. Technical Update to Environment and Climate Change Canada's Social Cost of Greenhouse Gas Estimates. Technical Report. Environment and Climate Change Canada. URL: http://ec.gc.ca/cc/default.asp?lang=En&n=BE705779-1.

Etiope, G., Drobniak, A., Schimmelmann, A., 2013. Natural seepage of shale gas and the origin of "eternal flames" in the Northern Appalachian Basin, USA. Marine and Petroleum Geology 43, 178 – 186. doi:10.1016/j.marpetgeo.2013.02.009.

FIXR, 2017. Home remodeling cost guides. www.fixr.com.

Flambeaux Lighting, 2018. Electronic ignition systems for gas lanterns. URL: https://www.flambeauxlighting.com/electronic-ignition/.

Ho, J., Krupnick, A., McLaughlin, K., Munnings, C., Shih, J.S., 2016. Plugging the Gaps in Inactive Well Policy. Technical Report. Resources for the Future. URL: http://www.rff.org/research/publications/plugging-gaps-inactive-well-policy.

Ho, J.S., Shih, J.S., Muehlenbachs, L.A., Munnings, C., Krupnick, A.J., 2018. Managing environmental liability: An evaluation of bonding requirements for oil and gas wells in the united states. Environmental Science & Technology 52, 3908–3916. doi:10.1021/acs.est.7b06609. pMID: 29533660.

Höglund-Isaksson, L., Mechler, R., 2005. The GAINS model for greenhouse gases - Version 1.0: Methane (CH_4). Technical Report IR-05-054. IIASA. IIASA, Laxenburg, Austria.

Homewyse, 2017. www.homewyse.com.

ICF, 2018. Draft Pennsylvania Climate Change Action Plan. Technical Report. PA DEP.

Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, 2016. Addendum to Technical Support Document on Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866: Application of the Methodology to Estimate the Social Cost of Methane and the Social Cost of Nitrous Oxide. Technical Report. United States Government. URL: https://19january2017snapshot.epa.gov/sites/production/files/2016-12/documents/addendum_to_sc-ghg_tsd_august_2016.pdf.

International Energy Agency, 2009. Energy Sector Methane Recovery and Use: The Importance of Policy. Technical Report. International Energy Agency. 9 rue de la Fédération, 75739 Paris Cedex 15, France. URL: www.iea.org/about/copyright.asp.

IOGCC, 2008. Protecting Our Country's Resources: The States' Case Orphaned Well Plugging Initiative. Technical Report. IOGCC.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. Institute for Global Environmental Strategies, Hayama, Japan.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. p. 1535.

Kang, M., Christian, S., Celia, M.A., Mauzerall, D.L., Bill, M., Miller, A.R., Chen, Y., Conrad, M.E., Darrah, T.H., Jackson, R.B., 2016. Identification and characterization of high methane-emitting abandoned oil and gas wells. Proceedings of the National Academy of Sciences 113, 13636–13641. doi:10.1073/pnas.1605913113.

Kang, M., Kanno, C.M., Reid, M.C., Zhang, X., Mauzerall, D.L., Celia, M.A., Chen, Y., Onstott, T.C., 2014. Direct measurements of methane emissions from abandoned oil and gas wells in Pennsylvania. Proceedings of the National Academy of Sciences 111, 18173—18177. doi:10.1073/pnas.1408315111.

Karakurt, I., Aydin, G., Aydiner, K., 2012. Sources and mitigation of methane emissions by sectors: A critical review. Renewable Energy 39, 40 – 48. doi:10.1016/j.renene.2011.09.006.

King, G.E., Valencia, R.L., 2014. Environmental risk and well integrity of plugged and abandoned wells, in: SPE Annual Technical Conference and Exhibition, Society of Petroleum Engineers, Amsterdam, The Netherlands. doi:10.2118/170949-MS.

Landfill Methane Outreach Program, 2016. LFG Energy Project Development Handbook. Technical Report. U.S. Environmental Protection Agency.

Marten, A.L., Newbold, S.C., 2012. Estimating the social cost of non-CO_2 ghg emissions: Methane and nitrous oxide. Energy Policy 51, 957 – 972. doi:10.1016/j.enpol.2012.09.073.

Mitchell, A.L., Casman, E.A., 2011. Economic incentives and regulatory framework for shale gas well site reclamation in pennsylvania. Environ. Sci. Technol. 45, 9506–9514. doi:10.1021/es2021796.

Muehlenbachs, L., 2015. A dynamic model of cleanup: Estimating sunk costs in oil and gas production. International Economic Review 56, 155–185. doi:10.1111/iere.12098.

PA DEP, 1998. Oil and Gas Well Drilling Permits and Related Approvals. Technical Report 550-2100-003. PA DEP.

PA DEP, 2015. Oil and Gas Reports. www.dep.pa.gov.

PA DEP, 2018. Database of well plugging contract cost.

PUC Bureau of Technical Utility Services, PA DEP, 2015. 2015 Annual Report: Alternative Energy Portfolio Standards Act of 2004. Technical Report. Pennsylvania Public Utility Commission. P.O. Box 3265, Harrisburg, PA 17105-3265.

Riddick, S., Mauzerall, D.L., Celia, M.A., Kang, M., Bressler, K., Chu, C., Gum, C., 2019. Measuring methane emissions from abandoned and active oil and gas wells in West Virginia. Science of The Total Environment 651, 1849–1856. doi:10.1016/j.scitotenv.2018.10.082.

Saunois, M., Jackson, R.B., Bousquet, P., Poulter, B., Canadell, J.G., 2016. The growing role of methane in anthropogenic climate change. Environmental Research Letters 11, 120207. doi:10.1088/1748-9326/11/12/120207.

Shindell, D., Borgford-Parnell, N., Brauer, M., Haines, A., Kuylenstierna, J.C.I., Leonard, S.A., Ramanathan, V., Ravishankara, A., Amann, M., Srivastava, L., 2017. A climate policy pathway for near- and long-term benefits. Science 356, 493–494. doi:10.1126/science.aak9521.

Shindell, D., Kuylenstierna, J.C.I., Vignati, E., van Dingenen, R., Amann, M., Klimont, Z., Anenberg, S.C., Muller, N., Janssens-Maenhout, G., Raes, F., Schwartz, J., Faluvegi, G., Pozzoli, L., Kupiainen, K., Höglund-Isaksson, L., Emberson, L., Streets, D., Ramanathan, V., Hicks, K., Oanh, N.T.K., Milly, G., Williams, M., Demkine, V., Fowler, D., 2012. Simultaneously mitigating near-term climate change and improving human health and food security. Science 335, 183–189. doi:10.1126/science.1210026.

Townsend-Small, A., Ferrara, T.W., Lyon, D.R., Fries, A.E., Lamb, B.K., 2016. Emissions of coalbed and natural gas methane from abandoned oil and gas wells in the United States. Geophysical Research Letters 43, 2283–2290. doi:10.1002/2015GL067623. 2015GL067623.

UNEP, 2011. Near-term Climate Protection and Clean Air Benefits: Actions for Controlling Short-Lived Climate Forcers. A UNEP Synthesis Report. United Nations Environment Programme (UNEP). Nairobi, Kenya.

U.S. Energy Information Administration, 2017a. Heat content of natural gas consumed. www.eia.gov.

U.S. Energy Information Administration, 2017b. Independent statistics and analysis. www.eia.gov.

U.S. Energy Information Administration, 2018. June 2018 Monthly Energy Review. Technical Report DOE/EIA-0035(2018/6). U.S. Energy Information Administration.

U.S. Environmental Protection Agency, 2016a. Partner Reported Opportunities (PROs) for Reducing Methane Emissions, Connect Casing to Vapor Recovery, PRO Fact Sheet No. 701. www.epa.gov.

U.S. Environmental Protection Agency, 2016b. Partner Reported Opportunities (PROs) for Reducing Methane Emissions, Install Flares, PRO Fact Sheet No. 904. www.epa.gov.

U.S. Environmental Protection Agency, 2018. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2016. Technical Report EPA 430-R-18-003. U.S. Environmental Protection Agency.

Yusuf, R.O., Noor, Z.Z., Abba, A.H., Hassan, M.A.A., Din, M.F.M., 2012. Methane emission by sectors: A comprehensive review of emission sources and mitigation methods. Renewable and Sustainable Energy Reviews 16, 5059 – 5070. doi:10.1016/j.rser.2012.04.008.