Atmospheric Environment 144 (2016) 1–7

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

Technical note

Methane emissions measurements of natural gas components using a utility terrain vehicle and portable methane quantification system

Derek Johnson*, Robert Heltzel

Center for Alternative Fuels, Engines, and Emissions, Mechanical and Aerospace Engineering Department, West Virginia University, United States

HIGHLIGHTS

- A UTV was outfitted with a methane quantification system to access remote sites.
- Natural gas audits were conducted at 11 remote sites – 7 had methane emissions.
- The minimum cumulative methane emissions rate was 5.3 ± 0.23 kg per hour.
- The average emissions from 5 coalbed methane wells was 1.9 g per hour.
- A non-leaking coalbed well was later found to be vented at a rate of 15.8 SCFM.

ARTICLE INFO

Article history:
Received 12 April 2016
Received in revised form
22 August 2016
Accepted 23 August 2016
Available online 24 August 2016

Keywords:
Natural gas
Greenhouse gases
Methane emissions

ABSTRACT

Greenhouse Gas (GHG) emissions are a growing problem in the United States (US). Methane (CH_4) is a potent GHG produced by several stages of the natural gas sector. Current scrutiny focuses on the natural gas boom associated with unconventional shale gas; however, focus should still be given to conventional wells and outdated equipment. In an attempt to quantify these emissions, researchers modified an off-road utility terrain vehicle (UTV) to include a Full Flow Sampling system (FFS) for methane quantification. GHG emissions were measured from non-producing and remote low throughput natural gas components in the Marcellus region. Site audits were conducted at eleven locations and leaks were identified and quantified at seven locations including at a low throughput conventional gas and oil well, two out-of-service gathering compressors, a conventional natural gas well, a coalbed methane well, and two conventional and operating gathering compressors. No leaks were detected at the four remaining sites, all of which were coal bed methane wells. The total methane emissions rate from all sources measured was 5.3 ± 0.23 kg/hr, at a minimum.

1. Introduction

Recent reports yield confusion around the climatic implications of natural gas (Burnham et al., 2012; Wigley, 2011). On one side of the argument, proponents of natural gas focus on its ability to mitigate climatic degradation due to its lower carbon content per unit energy in comparison to coal or oil. Conversely, those who argue against the utilization of natural gas, stress methane's greenhouse gas (GHG) potency (as compared to that of carbon dioxide (CO_2)) combined with leakage across the supply chain could outweigh its climate benefits (Alvarez et al., 2012). Methane's (CH_4) global warming potential (GWP) ranges from 21 to 85 depending on period for analysis, source, and carbon feedback (Global Warming Potentials; US Environmental Protection Agency; IPCC, 2007; Environmental Defense Fund). Significant focus has been placed on CH_4 and other emissions from the growth in new shale wells. However, data gaps remain regarding sound emissions rates for natural gas components, such as older remote wells and conventional equipment.

The geological deposit containing significant natural gas reserves located deep beneath portions of five Northeastern states (West Virginia (WV), Pennsylvania (PA), Ohio, Maryland, and New York) is known as the Marcellus Shale. The Marcellus Shale has been described as among the largest natural gas 'plays' in the world and is the largest producing shale play in the United States (US) (US Energy Information Administration). Covering approximately 34 million acres, geoscientists estimate it will yield nearly 500 trillion

* Corresponding author.
E-mail address: Derek.johnson@mail.wvu.edu (D. Johnson).

http://dx.doi.org/10.1016/j.atmosenv.2016.08.065

cubic feet of natural gas, enough to supply the US for 20–45 years (Engelder et al., 2009). According to the US Energy Information Administration (EIA), the total number of natural gas and condensate wells peaked in 2011 at 514,637 (US Environmental Information Administration). The EIA also suggests that annual natural gas consumption is forecasted to grow from 25.6 trillion cubic feet (TCF) in 2012 to 31.6 TCF in 2040 (US Environmental Information Administration).

Approximately 350,000 oil and gas wells have been drilled in PA and the locations of approximately 100,000 of these are unknown (Brantley et al., 2014). The PA Department of Environmental Protection (DEP) operates a searchable geographical interface system (GIS) database. Fig. 1 shows results for conventional wells that have been identified as plugged, abandoned, DEP orphaned, DEP plugged, DEP abandoned, regulatory inactive, for PA, along with issued well permits for oil, gas, and combined wells within WV (Pennsylvania Department of Environmental Protection). A search of the WV DEP database for abandoned wells in 2015 yielded 10,109 results (West Virginia Department of Environmental Protection). The WV DEP reported this value to be 12,491 in 2012, with over 54,000 wells whose status and location could not be confirmed (Abandoned Wells). The reduced number of abandoned wells could be due to plugging. However, the exact number is not known, as issuance of plugging permits does not indicate immediate plugging of the well. The WV Geological and Economic Survey site includes the ability to search for information on over 145,000 oil and gas wells in WV (WVGES).

The natural gas collection and distribution system is composed of the following main components: gas wells, gathering pipelines and stations, transmission lines, processing plants, pipeline compressor stations, storage facilities, gate stations and metering facilities, and the consumer distribution system. Multiple research programs are underway that examine new gas wells during development and completion, and midstream and downstream components. There is a significant lack of data, however, regarding the overall gathering systems and their CH_4 emissions. We communicated directly with the WV DEP Division of Air Quality and determined that there is no database for small gathering stations within WV. Prior to 2011, the Pennsylvania Utility Commission (PUC) did not have jurisdiction over gathering lines in PA and the PUC currently does not offer locations of gathering stations or maps of compressors (Shale Gas Roundtable). The Pipeline and Hazardous Materials Safety Administration (PHSMA) does offer state-by-state mileage of gathering and transmission lines. In 2014, PHMSA reported 831 gathering miles and 9914 transmission miles for PA and 440 gathering miles and 3823 transmission miles for WV (Pipeline Hazardous Materials Safety Administration, 2010). However, PMSHA notes that only about 5% of gathering pipelines are subject to their regulations (Pipeline Hazardous Materials Safety Administration, 2010) and as such, the data above do not include smaller gathering lines and their components. Assuming the above data only represent 5% of the total gathering system, WV and PA could have over 25,000 miles of gathering lines.

In addition to conventional vertical gas wells, the Marcellus shale region is also home to coalbed methane (CBM) wells. Fig. 2 shows CBM wells throughout WV and PA (Pennsylvania Department of Environmental Protection; WVDEP). WV currently has 1313 registered CBM wells (WVDEP). While research continues to focus on development of unconventional resources, there is sparse data regarding older lower-throughput components and these components could be contributing disproportionally to CH_4 emissions due to lack of regulations and maintenance that is afforded to larger, more profitable natural gas components.

Recent studies have shown that top-down methods estimate

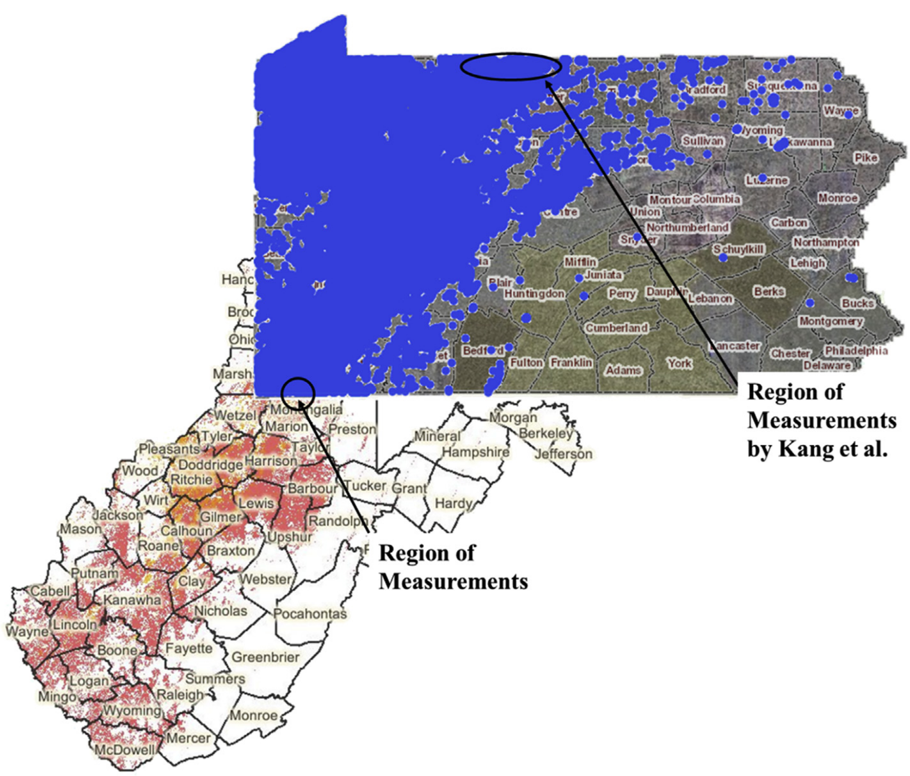

Fig. 1. PA - blue dots, all natural gas wells excluding coal bed methane. WV – red dots for gas wells and yellow dots for combination gas and oil wells, excluding coal bed methane wells. Regional locations for our measurements and those by Kang et al. are presented (Pennsylvania Department of Environmental Protection; WVGES; Kang et al., 2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

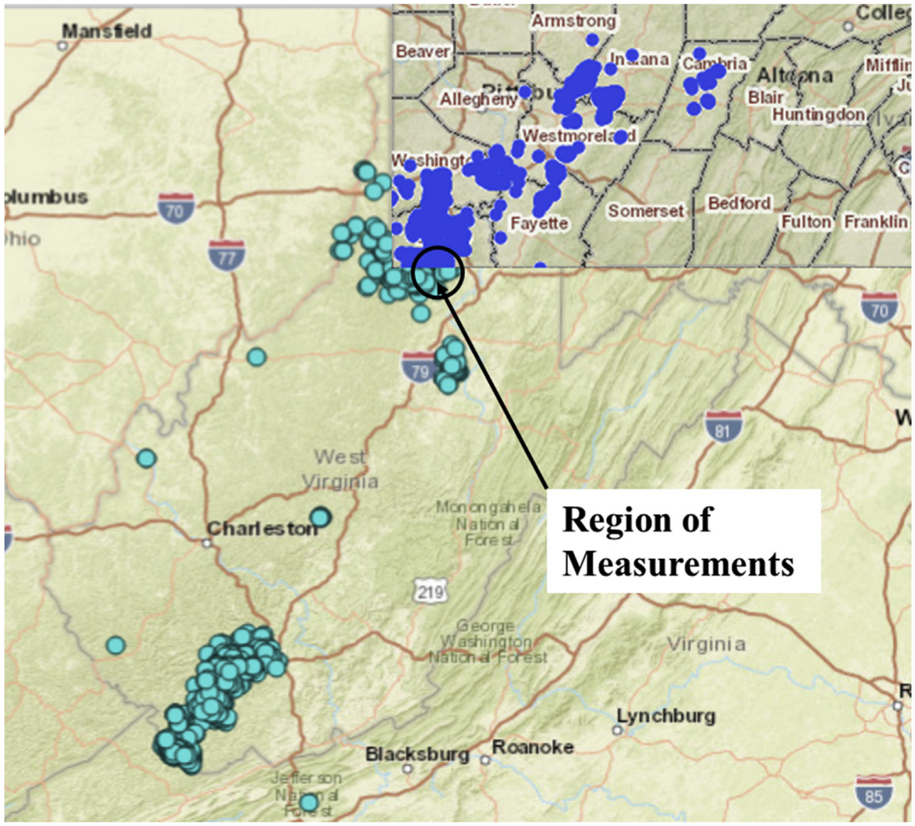

Fig. 2. CBM wells within PA and WV Marcellus region (Pennsylvania Department of Environmental Protection; WVDEP).

larger CH_4 emissions than those developed by current inventory methods (Caulton et al., 2014; Brandt et al., 2014). Some of the underestimation may occur due to a lack of data – count, location, activity - from remote natural gas components, such as those quantified in this study. With the hope of obtaining some insight into the CH_4 emissions from remote and low throughput sites (not accessible from paved roadways) and a method to access these sites, we completed CH_4 emissions measurements at local gathering stations, remote conventional and coal-bed CH_4 wells, and other low throughput oil and gas components.

2. Experimental methods

The investigated sites were located in Monongalia County, WV and Green County, PA. Some of the sites were only accessible via off-road utility vehicle paths. In order to conduct these measurements, researchers outfitted a four-wheel drive utility terrain vehicle (UTV). The UTV had a two-person cab and external work bed for transportation of necessary equipment. The work bed housed all equipment needed for quantification of leaks. A gasoline generator provided remote power. The vehicle was also equipped with a roof mounted temperature sensor, solar sensor, global position antenna, and ultra-sonic anemometer. These measurements recorded at a rate of 1 Hz.

Researchers used handheld, Eagle II methane detectors (RKI Instruments) to audit sites for leaks. The lower detection limit of these handheld units was five parts per million (ppm) above background. Once a leak was detected, researchers used the Full Flow Sampling system (FFS) to quantify the leak. The FFS included an explosion proof blower capable of dilution flow rates of 150 standard cubic feet per minute (SCFM). The system included grounded sampling lines, a mass airflow sensor calibrated against a laminar flow element, sampling section, and an Ultraportable Greenhouse Gas Analyzer (UGGA) (Los Gators Research, Inc.). The UGGA measured CH_4, CO_2, and water vapor (H_2O). The laser-based system reported only methane emissions as opposed to other systems that reported total hydrocarbons. The system was capable of capturing the entire leak plus dilution air. Local background sampling was conducted to eliminate contamination from nearby leaks and local dispersion. All measurements were background corrected. It is noted that the portable generator may have produced methane emissions but the exhaust was always placed downwind and any effects would be eliminated through local background correction.

We previously completed leak and loss audits at natural gas compressor stations and storage facilities using a similar system (previously referred to as the High Volume Sampling System) (Johnson et al., 2015a). Additional details on the system components, operation, and previous use are found in (Johnson et al., 2015a, 2015b). Fig. 3 shows an example of one of the sites measured and a portion of the FFS mounted in the bed of the UTV used.

3. Results

Table 1 provides a summary of the sites containing leaks that were measured. Leaks were considered any traceable CH_4 concentration more than 15 ppm above the local background as detected by a handheld unit. Note that volumetric and mass conversions utilized a standard temperature and pressure of 68 °F and 14.7 pounds per square inch.

Fig. 4 shows the distribution of measurements including error

Fig. 3. Site 3 was an out of service gathering station with a significant number of leaking components. The FFS system, mounted in the back of the UTV, can be seen in the bottom right corner of the figure.

Table 1
Leak Rates of CH_4 at Sites in grams per hour (g/hr) and standard cubic feet per hour (SCFH) (Measurement uncertainty ± 4.4% of reported value).

Site	Component	CH_4 (g/hr)	CH_4 (SCFH)
1: Conventional Oil and Gas Well	Sealed Vertical Flange	297.9	14.7
	Top of Gathering Tank	5.3	0.3
2: Out of service gathering station	Top of Storage Tank	350.7	17.4
	Horizontal Flange on Ground Line	7.7	0.4
3: Out of service gathering station	Fuel Regulator	18.6	0.9
	Vertical Flange	786.7	38.9
	90° Elbow	820.4	40.6
	Connection to Storage Tank	25.8	1.3
4: Non-producing gas well	Well Casing	796.2	39.4
5: Operational gathering station	Exhaust	828.8	41.0
6: Operational gathering station	Fuel Regulator	164.5	8.1
	Packing Vent	282.4	14.0
	Top of Storage Tank	29.7	1.5
	Slop Tank	7.2	0.4
	Exhaust	865.0	42.3
7: CBM well	Cracked Fitting	1.9	0.1

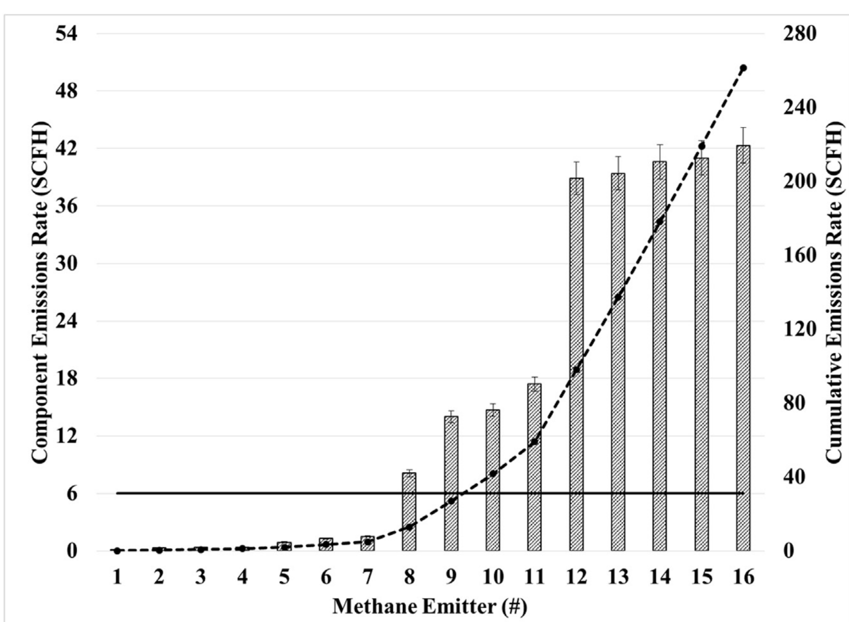

Fig. 4. Distribution of leaks, including measurement uncertainty, and cumulative leak rate.

bars of ± 4.4% (measurement error). The Advanced Research Projects Administration is currently funding the development of technologies to accurately detect and quantify methane emissions at similar sites at the level of six SCFH (Advanced Research Projects Administration). Fifty-six percent of CH_4 sources were above six SCFH but these sources accounted for 98.2% of emissions. In fact, the top five emitters (31%) accounted for 77.4% of the total emissions. Also shown is the cumulative leak rate for all emitters. The total emissions rate was 261.3 SCFH.

3.1. Note - remote conventional well

Site 4 was a remote conventional well that was labeled with operator and American Petroleum Institute (API) information. The well had significant CH_4 emissions between the casing and the pipe. The leak was visible without the use of infrared imaging equipment (refraction against the background). The leak was not fully captured, as an enclosure system was not available. This meant that the leak rate of 796.2 g/hr that was minimum value. A search of the Pennsylvania Oil and Gas Reporting System showed that the well had not reported any production in eight reports from 2000 to 2013 and was classified as a conventional vertical well (Pennsylvania Department of Environmental Protection).

3.2. Note - coal bed methane wells

During this measurement campaign, researchers located five remote CBM wells. These sites were overgrown with vegetation and accessible only with the UTV. The wells did not have specific API numbers. However, using a GIS and PA and WV databases, we were able to identify each of the wells. Four of the five wells last reported production in 2006 and were classified as active and located in PA. The fifth site was classified as abandoned and last reported production in 2004. Of these five wells, only one leak was identified – a cracked fitting with a leak rate of 1.9 g/hr. This leak occurred at the well that last produced in 2006 and is noted in Table 1 as Site 7.

Since data were originally collected, the well that last produced in 2004, is currently undergoing the plugging process. Metering equipment was removed and the well was being vented to the atmosphere at a rate of 15.8 SCFM or 947.4 SCFH. This rate was 3.6 times higher than the cumulative leak rate of all seven sites noted above. The last report from 2004 showed a production rate of 6463 thousand standard cubic feet per year (MSCFY) for an average production rate of 737.8 SCFH. This production rate was 22% lower than its current vent rate. The total production of the well over its four-year life was 63.2 MMSCF. Alvarez et al. presented estimates of maximum leak rates necessary to see immediate climatic benefits from fuel switching to natural gas for light-duty gasoline cars, heavy-duty diesel fueled trucks, and coal fired power plants (Alvarez et al., 2012). The overall leak thresholds were 1.6, 1.0, and 3.2%, respectively. Typically, these leak rates are based on current leak rates and current throughput of the system analyzed. However, this well is no longer in production (denominator equal to zero), but we examined previous annual production rates to determine a lifetime based leak rate compared to overall production. Based on total production and vent rate, these three thresholds – from a lifetime perspective – would be exceeded in 45, 28, and 89 days respectively. At the time of writing this paper, the well had been vented for 14 days.

Note the emissions rate of this well venting was 2.6 times higher than the emissions rate of a natural gas storage facility audited in the Barnett shale region. For comparison, the storage facility saw daily average throughputs of 0.9 MMSCF (Johnson et al., 2014). Without knowing the frequency of this type of action, it is difficult to ascertain its effects on emissions inventories but could likely be a contributor to variations between top down and bottom up methods, if such actions are standard practice and not reported.

3.3. Background sampling

When traveling from site to site in the UTV, continuous monitoring of atmospheric CH_4 was conducted using the UGGA without the FFS. Ambient CO_2 and H_2O, wind speed, temperature, solar loading, and position were also recorded. This allowed areas of high background CH_4 to be observed. Fig. 5 shows a map of the UTV position, ambient methane concentrations, and site locations.

4. Discussion and recommendations

Our instrumentation of a UTV to include a CH_4 detection and quantification system made it possible to locate, access, and measure CH_4 emissions from a number of sites that were identified as possible CH_4 emitters. Eleven sites were audited for CH_4 emissions. Seven of the visited sites had measurable CH_4 emissions. The four sites that had no measurable leak were all remote CBM wells. Not all sites were fully audited due to access restrictions. The exhausts of the operating engines were quantified with CH_4 emission rates of 828.8 and 865.0 g/hr, respectively with a combined emissions rate of 1.69 kg per hour (kg/hr), at a minimum. The remaining non-exhaust measurements yielded a CH_4 emissions rate of 3.6 kg/hr. Other studies that focused on larger natural gas facilities also found that a majority of emissions were attributed to uncombusted methane from onsite natural gas engines (Johnson et al., 2015a; Zimmerle et al., 2015). These sources from just a few remote wells were deemed significant, as recent research has suggested that a leak of just six SCFH is of interest (Advanced Research Projects Administration). The total emissions rate from all sites and sources measured was 5.3 ± 0.23 kg/hr, at a minimum (Note: one of the major leaks could not be fully captured). As an additional reference, the emissions from this limited data set are approximately 5% of the emissions from the five larger natural gas facilities audited during the Barnett Coordinated Campaign (Johnson et al., 2015a). However, the total emissions of these sites represented 66% of the emissions from the single lowest emitting site of the Barnett Coordinated Campaign.

Kang et al. recently measured CH_4 fluxes from 19 plugged or unplugged abandoned wells in north-central Pennsylvania (Kang et al., 2014). Their measurement technique focused on enclosing the entire wellhead and surrounding ground area to quantify a flux from the entire location, whereas we focused only on leaks above ground and did not account for methane from the soil surrounding the components. The average CH_4 flux reported by Kang et al. was 0.27 kg/day/well. The CH_4 emissions of the five CBM wells measured in this study were 9.12×10^{-3} kg/day/well or about 30 times lower than the average abandoned well flux reported by Kang et al. (Kang et al., 2014). However, if the two conventional wells were included the minimum average CH_4 emissions were 3.76 kg/day/well, about 15 times higher than (Kang et al., 2014). WV DEP reported 1313 CBM wells while the PA DEP reported 1275 (Pennsylvania Department of Environmental Protection; Markowski, 2013). If each had an emissions rate of 9.12×10^{-3} kg/day/well, this would yield contribute nearly 8.6 metric tons of methane emissions in the heart of the Marcellus, which is also home to methane emissions from conventional wells, unconventional wells, and coal mining applications.

Allen et al. completed measurement campaigns for a variety of natural gas components and reported equipment leak rates at wells sites to be 1.23 ± 44 g per minute (Allen et al., 2013). These leak rates were nearly 193 times higher than the average of our values for CBM wells; however, the Allen et al. data were for conventional

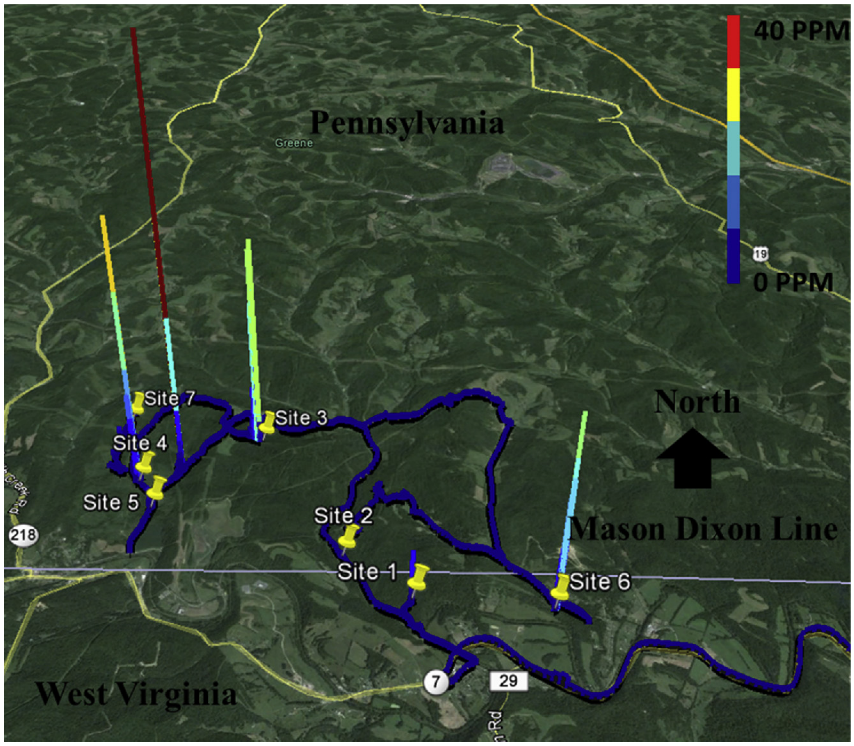

Fig. 5. A map of position of the UTV measurement sites for the entire trip and ambient methane concentration. Highlighted are the seven sites with identifiable leaks, see Table 1. See the corresponding. KML file for calculated leak rates at each site as well as ambient methane concentrations over the entire trip.

and hydraulically fractured wells where as our measurements were conducted at non-producing wells. Regarding our two conventional wells, the emissions rate was 7.4 times higher and it was noted that neither of these wells were producing natural gas. Rella et al. conducted downwind sampling of both leaking and non-leaking well pads and estimated the average well pad leak rate to be 18.3 g per hour (Rella et al., 2015). This is nearly two times the emissions rate from the two conventional wells we surveyed. It is noted that their indirect measurement technique sampled at downwind distances of 20–150 m, which was nearly impossible at the types of sites sampled in our limited campaign, due to terrain and access.

Alternatively, we compared the leaking emission to the average residential consumption for 2009–89.6 million British thermal units (MMBTU)/customer/year (US Energy Information Administration). This yielded an average hourly consumption rate of 0.202 kg/hr. The total emissions from these few sites are the equivalent of about 26 households showing that these emissions are may not only be unaccounted by current inventory methods but also represent wasted energy.

We recommend that continued research focus on not only sources of CH_4 emissions from new unconventional sources, but on remote, abandoned, and aging conventional natural gas components. Since the UTV platform provided access to remote sites, we plan to measure additional remote and abandoned natural gas components in the Marcellus region. We also plan to revisit the measured sites to examine temporal variations in emissions and determine if well/site closures affect emissions rates from these sources.

5. Acronyms

American Petroleum Institute; CBM, coal bed methane; CH_4, methane; CO_2, carbon dioxide; DEP, Department of Environmental Protection; EIA, Energy Information Administration; FFS, full flow sampling system; GIS, geographical interface system; g/hr, grams per hour; GHG, greenhouse gases; GWP, Global Warming Potential; Hz, Hertz; H_2O, water vapor; kg/hr, kilogram per hour; MMBTU, million British thermal units; MSCFY, thousand standard cubic feet per year; MMSCF, million standard cubic feet, PA, Pennsylvania; PUC, Pennsylvania Utility Commission; PMSHA, Pipeline and Hazardous Materials Safety Administration; ppm, parts per million; SCFH, standard cubic feet per hour; SCFM, standard cubic feet per minute; TCF, trillion cubic feet; UGGA, Ultraportable Greenhouse Gas Analyzer; US, United States; UTV, utility terrain vehicle; WV, West Virginia.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2016.08.065.

References

Abandoned Wells: Authority and Responsibilities Performance Audit; http://www.dep.wv.gov/oil-and-gas/Resources/Documents/OCT%2024,%202012%20WORKSHOP%20PRESENTATION%20ABANDONED%20WELLS-%20Dave%20Belcher.pdf.

Advanced Research Projects Administration – Energy - MONITOR Program Overview; http://arpa-e.energy.gov/sites/default/files/documents/files/MONITOR_ProgramOverview.pdf.

Allen, D.T., Torres, V.M., Thomas, D., Sullivan, D.W., Harrison, M., Hendler, A., Herdon, S.C., Kolb, C.E., Fraser, M.P., Hill, A.D., et al., 2013. Measurements of methane emissions at natural gas production-sites in the United States. Proc. Natl. Acad. Sci. 110 (44), 17768–17773. http://dx.doi.org/10.1073/pnas.1304880110.

Alvarez, R., Pacala, S., Winebrake, J., Chameides, W., Hamburg, S., 2012. Greater focus needed on methane leakage from natural gas infrastructure. Proc. Natl. Acad. Sci. 109 (17), 6435–6440. http://dx.doi.org/10.1073/pnas.1202407109.

Brandt, A.R., Heath, G.A., Kort, E.A., O'Sullivan, F., Petron, G., Jordaan, S.M., Tans, P., Wilcox, J., Gopstein, A.M., Arent, D., Wofsy, S., Brown, N.J., Bradly, R., Stucky, G.D., Eardley, D., Harriss, R., 2014. Methane leaks from north american natural gas systems. Science 343, 375–733. http://dx.doi.org/10.1126/

science.1247045.
Brantley, S.L., Yoxtheimer, D., Arjmand, S., Grieve, P., Vidic, R., Pollak, J., Llewellyn, G.T., Abad, J., Simon, C., 2014. Water resource impacts during unconventional shale gas development: the Pennsylvania experience. Int. J. Coal Geol. 126, 140–156. http://dx.doi.org/10.1016/j.coal.2013.12.017.
Burnham, A., Han, J., Clark, C.E., Wang, M., Dunn, J., Palou-Rivera, I., 2012. Life-cycle greenhouse gas emissions of shale gas, natural gas, coal and Petroleum. Environ. Sci. Technol. 46 (2), 619–627. http://dx.doi.org/10.1021/es201942m.
Caulton, D.R., Shepson, P.B., Santoro, R.L., Sparks, J.P., Howarth, R.W., Ingraffea, A.R., Cambaliza, M.O.L., Sweeney, C., Karion, A., Davis, K.J., Stirm, B.H., Montzka, S.A., Miller, B.R., 2014. Toward a better understanding and quantification of methane emissions from shale gas development. Proc. Natl. Acad. Sci. 111 (17), 6237–6242. http://dx.doi.org/10.1073/pnas.1316546111.
Engelder, T., Lash, G.G., Uzcategui, R.S., 2009. Joint sets that enhance production from middle and upper devonian gas shales of the appalachian basin. AAPG Bull. 93 (7), 857–889. http://dx.doi.org/10.1306/03230908032.
Environmental Defense Fund - FAQs to PNAS Paper on Natural Gas; https://www.edf.org/energy/faqs-pnas-paper-natural-gas#four.
Global Warming Potentials; http://unfccc.int/ghg_data/items/3825.php.
IPCC, 2007. Fourth Assessment Report: Climate Change. https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html.
Johnson, D., Covington, A., Clark, N., 2014. Environmental and economic assessment of leak and loss audits at natural gas compressor and storage facilities. Energy Technol. 2 (12), 1027–1032. http://dx.doi.org/10.1002/ente.201402086.
Johnson, D., Covington, A., Clark, N., 2015. Methane emissions from leak and loss audits of natural gas compressor stations and storage facilities. Environ. Sci. Technol. 49 (13), 8132–8138. http://dx.doi.org/10.1021/es506163m.
Johnson, D., Covington, A., Clark, N., 2015. Design and use of full flow sampling system (FFS) for the quantification of methane emissions. J. Vis. Exp. (JoVE) 112. DOI:103791/54179.
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. Proc. Natl. Acad. Sci. 111 (51), 18173–18177. http://dx.doi.org/10.1073/pnas.1408315111.
Markowski, A., 2013. Pennsylvania Coalbed Methane Update. Am. Assoc. Petroleum Geol. (AAPG). Annual Convention and Exhibition. http://www.searchanddiscovery.com/documents/2014/80353markowski/ndx_markowski.pdf.
Pennsylvania Department of Environmental Protection – PA Oil and Gas Mapping; http://www.depgis.state.pa.us/PaOilAndGasMapping/.
Pennsylvania Department of Environmental Protection - PA DEP Oil and Gas Reporting Website – Production Reports – by County; https://www.paoilandgasreporting.state.pa.us/publicreports/Modules/Production/ProductionByCounty.aspx.
Pipeline Hazardous Materials Safety Administration, 2010. Pipeline Miles and Facilities. https://hip.phmsa.dot.gov/analyticsSOAP/saw.dll?Portalpages.
Rella, C., Tsai, T., Botkin, C., Crosson, E., Steele, D., 2015. Measuring emissions from oil and natural gas well pads using mobile flux plan technique. Environ. Sci. Technol. 49 (7), 4742–4748. http://dx.doi.org/10.1021/acs.est.5b00099.
Shale Gas Roundtable - Midstream Development in Pennsylvania; http://www.iop.pitt.edu/shalegas/pdf/midstream_f.pdf.
US Energy Information Administration – Today in Energy; https://www.eia.gov/todayinenergy/detail.cfm?id=17411.
US Energy Information Administration - Residential Energy Consumption Survey; http://www.eia.gov/consumption/residential/reports/2009/consumption-down.cfm.
US Environmental Information Administration – Natural Gas; http://www.eia.gov/dnav/ng/hist/na1170_nus_8a.htm.
US Environmental Protection Agency - Overview of Greenhouse Gases; http://www3.epa.gov/climatechange/ghgemissions/gases/CH4.html.
West Virginia Department of Environmental Protection; https://apps.dep.wv.gov/oog/welllist_new.cfm.
Wigley, T.M.L., 2011. Coal to gas: the influence of methane leakage. Clim. Change 108 (3), 601–608. http://dx.doi.org/10.1007/s10584-011-0217-3.
WVDEP Office of Oil & Gas Permit Locations; https://apps.dep.wv.gov/oog/welllist_new.cfm.
WVGES – Oil and Gas Wells of West Virginia; http://ims.wvgs.wvnet.edu/WVOG/viewer.htm.
Zimmerle, D., Williams, L., Vaughn, T., Quinn, C., Subramanian, R., Duggan, G., Wilson, B., Opsomer, J., Marchese, A., Martinez, D., Robinson, A., 2015. Methane emissions from the natural gas transmission and storage system in the United States. Environ. Sci. Technol. 49 (5), 3252–3261. http://dx.doi.org/10.1021/acs.est.5b01669.