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CRITICAL REVIEW DISCUSSION

Emissions From Oil and Gas Operations in the United States And Their Air Quality Implications

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Introduction

10 The 46th Annual A&WMA Critical Review (CR) “Emissions From Oil and Gas Operations in the United States and Their Air Quality Implications” (Allen, 2016) examines air quality impacts that result from changes in energy supplies and use, with an
15 emphasis on changes in greenhouse gas, criteria air pollutants, and air toxics emissions from oil and gas production activities. National emission inventories indicate that VOC and NO_x emissions from oil and gas supply chains in the United States have been
20 increasing significantly; however, some national emission inventories for greenhouse gases showed slight declines over the past decade. The review points out that there are discrepancies in the concentrations reported for greenhouse gases based on whether the
25 assessment is “top-down” or “bottom up.” Bottom-up emission inventory estimates are based on national scale counts of equipment and operational activities (activity factors), multiplied by average emission factors, and therefore these trends are subject to uncer-
30 tainties in activity and emission factors. While uncertainties associated with activity data and missing emission source types can be significant in some situations, multiple recent measurement studies indicate that the greatest uncertainties are associated with emis-
35 sion factors. Top-down estimates atmospheric concentrations of pollutants using measurements acquired from ground, aircraft, and satellite platforms that can be used to infer (using atmospheric models and assumptions) emissions in a region in a process. The
40 CR provides information indicating that some of the discrepancies between the estimation methods could be attributed to unaccounted-for differences in source emission factors. For example, in many source

categories, small groups of devices or sites contribute a large fraction of emissions. Collectively, these sources 45 have been referred to as “super-emitters.” When super-emitters are accounted for, multiple measurement approaches, at multiple scales, can produce similar results for estimated emissions. Overall, this review was timely, and especially with the recent issues relating 50 to large accidental releases of CH₄, the importance of super-emitters was especially relevant. This review dealt with potential health effects as a peripheral issue and did not go into this in depth. It should be noted that unprocessed natural gas contains low concentrations of 55 many contaminants that are known to be toxic and carcinogenic. Contaminants such as benzene, toluene, ethyl benzene, xylene, and radon have been reported (Hildebrand et al., 2016; Mitchell et al., 2016). The effects of chronic exposures to low levels of these com- 60 pounds to human health represent an area that should receive greater consideration.

This critical review discussion presents written submissions from four invited discussants, followed by a response from the original author. Each discus- 65 sion is self-contained, and joint authorship of this article does not imply that a discussant subscribes to the opinions expressed by others. A discussant’s commentary does not necessarily reflect the position of his or her respective organization. Invited discus- 70 sants are as follows:

- (1) Michael T. Kleinman is an adjunct professor in the Department of Medicine, University of California, Irvine. He is the co-director of the Air Pollution Health Effects Laboratory and is 75 the Chair of the A&WMA Critical Review Committee.

- 80 (2) Gary R. Mueller is a principal consultant on air quality for the Shell Projects and Technology (US) Division of Shell Global Solutions, Inc.
- (3) Eric Stevenson is the director of meteorology, measurement, and rules with the Bay Area Air Quality Management District.
- 85 (4) Ramón Alvarez is a lead senior scientist in the Texas office of Environmental Defense Fund.
- (5) Anthony J. Marchese is associate dean of engineering and a professor in the Department of Mechanical Engineering at Colorado State University.
- 90 (6) Dr. David Allen is the Gertz Regents Professor of Chemical Engineering, and director of the Center for Energy and Environmental Resources, at the University of Texas at Austin.

Invited comments from Gary R. Mueller

95 While there are economic and social benefits of the energy renaissance that has resulted from the rapid expansion of the use of hydraulic fracturing as a means to develop the oil and gas resources that previously were locked in shale formations,^{1,2,3} Dr. Allen's review provides a comprehensive look at some of the potential air quality issues that need to be better understood in order to effectively minimize any adverse effects that might result from the development of this resource. The potential environmental impacts of the development of this resource have been evaluated using the best available data, but there will always be a need to build on what is known with new data that will help to evolve and shape how this resource is developed. Dr. Allen's paper points out several areas where significant improvements in our understanding of the emissions associated with oil and gas production are needed.

100 To some extent, Dr. Allen's paper underestimates the challenge of quantifying emissions from the oil and gas sector. Dr. Allen compares the challenge of assessing emissions from the 150 U.S. refineries to the

105 500 natural gas processing facilities. However, the emissions from the production of oil and gas start at the nearly 1 million active oil and gas wells in the United States. The sheer magnitude and dispersed nature of

these facilities make the development of emissions by the emission factor times the activity factor the only manageable way to develop emissions from this sector. Working with academia and stakeholders, the industry has participated in advancing our knowledge of emission sources in the oil and gas sector, and has continued to upgrade and improve work practices to further mitigate any potential environmental impacts. A key component of insuring improvements in our understanding of the environmental implications of developing this resource is keeping an open dialogue with stakeholders, with a continuing desire to learn from our current operations.

125 While Dr. Allen does point out reasons why the line between production and gathering is blurred, he leaves it to the reader to assess why the gap between total natural gas withdrawals and total marketed production or consumption is so large (6.96 BCF/yr in 2014). Failure to mention diversion of some produced gas for use in the compression and power generation sector of the supply chain can leave the impression, for those not familiar with the industry, that all of these losses escape to the atmosphere. In fact, the expected losses from the supply chain are but a fraction of this amount, and this warrants overt mention in the paper.

140 The NO_x value in Table 1 is not the value for the petroleum and related industries, but rather the total anthropogenic NO_x emissions for 2011. The correct value is 0.69 million tons. It should also be overtly pointed out that in fact the numbers in this table are not from the oil and gas sector, as traditionally defined, but rather for the larger category, petroleum and related industries. This warrants mention by the author and some attempt to elucidate how much is the relative contribution from other portions of this category (refining, distribution, and retail), as this could lead to an apples to oranges comparison by some readers.

150 The use of National Emission Inventory numbers in Figure 4, while instructive in illustrating the estimated increase in emissions, also belies the fact that reported emission inventory data exist for this period. Granted, there are still improvements to be made in reported emission numbers, but they probably are more indicative of emission increases observed than the 3-year straight-line projections used in the NEI methodology.

¹Marcellus Shale exceeds economic expectations. <http://energyindepth.org/marcellus/marcellus-shale-exceeds-economic-expectations>

²Considine, T.J., et al. The Pennsylvania Marcellus natural gas industry: Status, economic impacts and future potential. <http://marcelluscoalition.org/wp-content/uploads/2011/07/Final-2011-PA-Marcellus-Economic-Impacts.pdf>

³Mason, C.F., et al. The economics of shale gas development. <http://www.rff.org/files/sharepoint/WorkImages/Download/RFF-DP-14-42.pdf>

165 The author mentions that this marked increase is due
to both increased activity and “more comprehensive
reporting.” Assuming that emission factors may not
have changed over this time period, it seems also quot-
ing the differences in activity values in the NEI for this
170 same period would give the reader some means to
assess how much of the NEI increase was related to
“increased activity” versus “more comprehensive
reporting.”

175 The expression of reported methane greenhouse gas
emissions in Table 3 in tons of CO₂eq/yr, followed by
the use of emissions in Tg CH₄/yr in Table 6 of the
bottoms-up/tops-down comparison, will make it diffi-
cult for some readers to make a comparison. In such
cases, it would be advisable to either use consistent
units in the paper, or supply both sets of units used
180 throughout the paper.

It is difficult to assess what the major sources listed
in Table 5 are, due to the inconsistent use of commas in
the source listing strings.

185 The suggestion that the large difference in satellite
NO₂ column observations and results of photochemical
modeling results in rural regions may be caused by
underestimation of NO_x emissions from the oil and
gas sector would appear to be tenuous at best from
the data presented in the paper.

190 This reviewer appreciates Dr. Allen’s paper and the
comprehensive review of many of the areas that still
need to be improved in reporting of emissions from
this industry sector. It is only through the continued
review of available data, and continued attempts to fill
195 potential data and knowledge gaps, that both the
improvements in emissions data and improvement in
industry practices will be achieved. This is a position
that this reviewer maintains the oil and gas industry has
always taken and will continue to take going forward.
200 Several of the case studies cited in this paper by
Dr. Allen serve to validate this point. The case study
of the large VOC emission discrepancy in the
Houston–Galveston airshed led to the formation of an
independent industry research consortium,
205 International Flaring Consortium, that began efforts
to assess the impacts of vent gas composition, assist
gas rates, and cross winds on flare combustion efficien-
cies in the same time frame when these emission dis-
crepancies were being uncovered.^{4,5} Likewise, when

winter ozone exceedance began to occur in the Green 210
River Basin of Wyoming after an expansion in shale gas
production, the local agency and industry responded
with additional controls, such that based upon
2013–2015 data; this airshed is once again in attain-
ment with the National Ambient Air Quality Standard.⁶ 215
This constructive dialogue between stakeholders is key
to not only allowing the development of a much needed
energy source, but also creating a progressive and
learning environment where both data quality and
operational practice can be improved. 220

Invited comments from Eric Stevenson

The 2016 Critical Review (CR) provides significant and
compelling evidence that the changing energy supply
infrastructure has resulted in significant air quality
impacts. In addition, the article points out that it is 225
likely that emissions inventories for VOC, NO_x, and
particularly greenhouse gases (GHG) are underesti-
mated when based on traditional “bottom-up”
approaches. The article also points out that large por-
tions of these emissions can be attributed to “super- 230
emitters,” which can “dominate total emissions and
atmospheric photochemistry.” However, the CR does
not address means to better measure emissions at the
source, the compositional nature of the VOCs, or
methodologies to systematically identify and address 235
how these emissions may be reduced and/or elimi-
nated. In addition, the CR does not address how chang-
ing supply may affect emissions from processing oil
and gas, particularly at refineries. This information is
critical to allow the industry to react to these findings 240
and government agencies to develop emissions reduc-
tion regulation strategies.

Since the CR does not address a means to better
measure emissions at the sources, there is potential
for disagreement on the best and most cost effective 245
means to determine and address these emissions. While
leak detection and repair (LDAR) processes can address
some of the emissions and their sources, to some
extent, LDAR programs may not be frequent enough
to “catch” super-emitters early enough or during times 250
when the emissions are most likely to occur. The arti-
cle, while discussing specific components that can be
problematic, does not identify the contribution to

⁴Gogolek, P., et al. Emissions from elevated flares—A survey of the literature. Submitted to *Progress in Energy and Combustion Science*, Elsevier Ltd.

⁵Mueller, G.R., et al. Combustion of mixtures: A modified IFC approach. Presented at Ethylene Producers Conference, 2012 AIChE Spring meeting, April 2, 2012.

⁶Wyoming Department of Environmental Quality—Air Quality Division. Upper Green River Basin Ozone Strategy. https://www.epa.gov/sites/production/files/2016-05/documents/ugrb_ozone_strategy.may_2016.pdf

emissions of various processes and equipment and, as a result, it is difficult to determine which should be addressed first to provide the most effective emissions reductions.

Investigation of compounds emitted and the means to accurately identify these compounds and the processes and equipment responsible for the emissions is critical to enabling regulatory agencies and industry to prioritize their efforts to minimize impacts on public health and the environment. Since many toxic air contaminants are included in VOCs, compositional information is necessary to determine if certain emissions have greater impact on public health than others. Ideally, this more detailed emissions information would be used to deploy real-time measurement technologies to appropriate areas so that emissions are minimized as leaks develop. This would allow better assessment of the extent to which those emissions are likely to impact public health as oil and gas move from the field to processing and, ultimately, to the consumer.

A thorough discussion of how the changes in oil and gas production affect emissions at processing plants would have enabled industry and regulatory agencies to better address the potential for these changes to increase emissions. For example, since California and Alaskan crude oil declines will be made up with new sources of crude oil, modifications at refineries that process California and Alaskan oil will need to be made. This may result in emission increases and changes in emission composition. While the CR describes the complexity and variability of the new sources of oil and gas, a more in-depth discussion of how the necessary changes to processing and the potential issues involved may affect emissions as these changes take place would have been extremely useful.

Regulatory agencies will be under pressure to ensure that public health and the global environment are protected as new oil and gas resources are discovered, developed and processed. The CR identifies that there are emissions increases, sometimes significant, as these resources are developed. By omission, it also points out that significant work is required to better identify measurement technologies capable of locating where those emissions are occurring, the component makeup of those emissions, and the potential emissions impacts of processing these sources of oil and gas.

Invited comments from Ramón Alvarez

Two factors that should be further emphasized are methane's life-cycle implications and the role of liquid storage tanks as sources of unplanned emissions. Keeping in mind that methane contributes to about

25% of today's radiative forcing, second only to carbon dioxide (~50%) in contributing to current warming, methane is considered a short-lived climate pollutant (IPCC AR5). Methane is more rapidly reduced by atmospheric processes than CO₂, with a half residence time of about 8 years for CH₄ versus about 40 years for CO₂. The implication is that the contribution of CH₄ to direct and indirect warming can be reduced over time if emissions are curbed. Recent top-down estimations of the impact of CH₄ releases at 7 production sites in various parts of the United States suggest that ~2% of the produced gas is lost to the atmosphere, representing 40 Mg per production site released as fugitive gas per hour. However, these numbers represent more or less normal operations. A recent study of 8,220 well pads, selected by random stratified sampling, in 7 production basins identified 494 high-intensity emission sources over 327 different production sites. About 92% of these high emission sites were storage tanks. The opportunity to mitigate this problem should not be ignored. Appropriate technology already exists, but proper design, maintenance, and inspection programs are critical to ensure the effectiveness of control systems. Enhanced monitoring programs to identify high-intensity sources should be more widely instituted.

Invited comments from Anthony J. Marchese

The collection of natural gas from shale is a relatively recent phenomenon in the United States, increasing nearly 30-fold from about 1 billion cubic feet per day in 2000 to about 26 billion cubic feet per day in 2013. An important factor that was not emphasized in the review is that transmission and storage of this gas at key central locations are necessary for efficient distribution of the gas to industries and consumers. The inadvertent releases of CH₄ from this nationwide network of distribution and storage facilities represents a significant contribution to the GHG release inventory (GHGI). In 2012 the U.S. EPA listed a total of 445,000 miles of gathering pipeline, 17 "large gathering stations," and 136 "large reciprocating compressors" that contributed 404 Gg of CH₄, or about 7% of total emissions to the GHGI. The 2016 GHGI has significantly revised this estimate, indicating that gathering operations now account for 27% of all methane emissions. There are large uncertainties in these estimates because of the large variability and inconsistent reporting of these emissions, which are ubiquitous, are potentially persistent, and often consist of unprocessed gas. Improvements are needed in developing simulation and modeling methods to provide activity weighted emission factors for use in future inventories.

Author's response to comments

The discussants have added insights and comments on topics that were either not addressed or only briefly addressed in the Critical Review. This is to be expected, since emissions from oil and gas operations is a complex and multifaceted area of research, and even in an extended publication format such as the Critical Review, not all topics can be covered in depth. This response provides some additional depth in the areas identified by the discussants. Responses to the comments are here organized by topical area, rather than by the individual making the comment.

A first topic addressed by the discussants is the scope of what is meant by the term "oil and gas operations." The definition, as it is used in the literature cited in the Critical Review, is context driven. For example, in the U.S. EPA's National Emission Inventory (EPA, 2015a), the term includes production, processing, transmission, and distribution operations of both petroleum and natural gas supply chains. In other U.S. EPA inventories, natural gas and petroleum operations are reported separately (EPA, 2015b, 2015c). This separate reporting requires that rules be established for assigning emissions from sites that produce both oil and gas to either the petroleum or natural gas supply chains. Literature reports of emissions from oil and gas production regions also vary in what emission sources are included. The emissions included in these reports are from sources that are physically located in the basin in which the measurement was made. For example, emissions reported from the portion of the Marcellus Shale in northeastern Pennsylvania, a dry gas production region, would include natural gas production and gathering operations, together with some gas processing and transmission. Emissions reported from the Eagle Ford Shale in south Texas, a dry gas, wet gas and oil production region, would include emissions from both gas and oil production, and gathering operations. Also included would be some gas processing and transmission, but no petroleum refining. The Critical Review used the definitions of oil and gas operations employed in the original sources. The discussants are correct to point out that inter-comparisons between various emission inventories, and comparisons between inventories and field observations, should carefully reconcile the portions of the petroleum and natural gas systems that are included in the data being compared.

An additional topic on which the literature can be confusing is in the choice of emission units. Again, the use of units is driven by context. Using methane emissions as an example, a greenhouse gas inventory

may report emissions as carbon dioxide equivalents, assuming a specific value for the Global Warming Potential of methane. Different sources of information may use different Global Warming Potentials for methane. Methane emissions might also be reported as a rate (e.g., annual average emissions) or as a percentage of gas produced. If reported as a percentage, the percentage might be defined as the mass of emissions, divided by one of several production-related quantities, including the mass of methane produced, the amount of methane withdrawn, the amount of natural gas produced, or the amount of natural gas withdrawn. The Critical Review generally reported data in units used by the original source. As various data are compared, units of reporting need to be carefully reconciled. Examples of the importance of clearly defining the metrics of reporting are provided by Zavala-Araiza et al. (2015).

As multiple discussants noted, the Critical Review emphasized the current state of understanding of emissions from oil and gas operations and expressed only very general recommendations about how to improve measurements and potential opportunities for emission reductions. The current state of understanding of emissions has a number of gaps, in particular, emissions from flares and storage tanks. These are active areas of research. Ongoing research will also undoubtedly produce advances in measurement methods, perhaps greatly expanding understanding of emissions. The work underway in new measurement methods is broad and could be a topic for another Critical Review. Finally, regulators are tasked with the challenges of weighing costs and benefits of a variety of approaches to emission reduction. An example of cost assessments and magnitudes of potential emission reductions, for methane emissions, was provided in the Critical Review (ICF, 2014). Again, however, the work underway is very broad and could only be touched on briefly in the Critical Review.

While these comments and responses have improved the Critical Review, they still leave some topics untouched or only briefly mentioned. The Critical Review can hopefully serve as a starting point for additional analyses, measurements, and tool development activities. As noted in the discussant comments, future activities can be strengthened by engagement by a wide range of stakeholders.

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