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Abstract Title: Rising to the Methane Challenge – A Synopsis of the Evolution of Corporate and National Methane Policy

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Abstract:

In the United States (U.S.), the national average estimated methane leakage emissions from the natural gas sector (including natural gas emissions allocated from crude production) in 2015 was approximately1.4% of gross natural gas production. Preventing and reducing methane emissions from the wellhead to the burner tip is imperative to ensure natural gas remains an important contributor to a low-carbon energy future.

The methane policies in the United States related to oil and gas sources range from voluntary programs like the United States Environmental Protection Agency's (EPA) Natural Gas STAR to mandatory regulations at new, modified or reconstructed facilities. Some states have issued regulations that regulate methane directly or methane as a co-benefit to regulating volatile organic compounds (VOCs).

Southwestern Energy (SWN) has invested in methane R&D through various private-public partnerships and the scientific community and has been part of over a dozen peer-reviewed publications on related topics. SWN proactively implemented methane mitigation technologies such as reduced emissions completions, pneumatic device replacement, liquids unloading, and leak detection and repair (LDAR) programs well in advance of U.S. regulatory programs. Our scientific and technical programs have supported our formation of the ONE Future Coalition (ONE Future) and the establishing of a *performance-based* goal of methane emissions rate of less than 1% of gross production from wellhead to burner tip across the natural gas value chain. SWN and ONE Future have worked closely with the U.S. EPA in establishing the ONE Future model as part of the U.S.' national methane strategy under the EPA Methane Challenge program. SWN considers the management of methane emissions as part of our continuous capital efficiency improvement efforts and our social license to operate. This paper reviews the history of U.S. federal oil and gas related methane programs and SWN's experience in promoting "science-based" national policies on methane highlighting our ONE Future initiative and leak detection and repair program.

Background:

Significant growth in the U.S. natural gas supply over the last decade has resulted in low-cost energy, economic growth, and reductions in greenhouse gases. Natural gas is a versatile resource that has applications in every major end-use sector of the economy as both a fuel and a feedstock, and can have an important role in a low carbon energy future[1,2,3,4].

The International Energy Agency (IEA) World Energy Outlook 2017 (WEO)[5] projects the global demand for natural gas will see a compounded average annual growth rate of 0.6-1.9% in the timeframe of 2016-2040[1]. The Energy Information Administration (EIA) and IEA also project that the U.S. will likely become a net exporter of natural gas by early 2020[6,5] and the U.S. will become the largest exporter of Liquefied Natural Gas (LNG) by mid-2020s "with the market share of the United States in inter-regional LNG trade peaking at around 25%.[2]" The U.S. manufacturing renaissance and growth of U.S. LNG is based on ample domestic natural gas supplies and the flexibility it provides to its global customers in terms of long-term supply contracts and diversification of their energy portfolio. The EIA concludes that natural gas has played a significant role in reducing carbon dioxide (CO_2) emissions from the power sector by displacing more carbon intensive fossil fuels[7]. In addition to lower CO_2 emissions on a unit-basis for combustion, natural gas use in the various economic sectors results in lower emissions of hazardous air pollutants like mercury, and other air pollutants like oxides of sulfur (SO_x) and nitrogen (NO_x)[2].

The Trump Administration has promoted "energy dominance" as a theme to ensure energy and economic security as well as for geopolitical strategic purposes. The IEA conveys "[t]he stage is now set for the United States to move from passively influencing the LNG trade towards actively exerting influence, as it becomes one of the world's largest exporters of LNG." Given that there is ample natural gas supply, robust demand, and pricing and expansion flexibility, and since increased natural gas use can result in substantial reductions in CO_2 emissions, what are the potential deterrents to the greater use of natural gas domestically and to the US global "energy dominance" policy? A key concern that remains with the expanded growth of natural gas is the impact of methane emissions arising from production to end-use [8,9,10,11,12]. Methane, the primary component of natural gas is a short-lived, high global warming greenhouse gas[13]. To realize the fullest potential of

[1] WEO 2017 includes multiple scenario: CAAGR for Current Policy Scenario is 1.9%, New Policy Scenario is 1.6% and Sustainable Development Scenario is 0.6%

[2] The WEO 2017 projects "[b]y the end of the *Outlook* period, a total of 1 230 bcm [43.4 tcf] of gas is traded between regions, some 60% of which is LNG, up from just under 40% in 2016"

natural gas under future potential regulatory and policy constraints, methane emissions across the value chain must be mitigated and reduced to the lowest extent possible[5,14,15,16]. Hence, companies should develop a comprehensive strategy to assess the risks and opportunities and implement sustainable policies to ensure success in this "Golden Age" of natural gas and in a future decarbonizing world (See *Supplemental Information (SI)-S.1*). To understand the federal and company specific methane programs, the following sections discuss the evolution of the United States federal methane programs to reduce emissions, and policies set at company levels.

The methane emissions intensity (defined here as methane emissions across the natural gas value chain divided by the gross production of natural gas) of the U.S. natural gas system is about 1.4%[17,18] (See *SI.-2*). Other private estimates have the emissions higher[19,20]. Per the IEA, there is an immediate climatic benefit to fuel switching from coal to natural gas as long as methane leakage is less than 3%. A recent scientific paper[21] concluded that U.S. LNG had lower lifecycle carbon emissions than Russian gas exports or coal for electricity generation and heating as long as the upstream U.S. methane leakage was less than 5%.

The Paris Agreement[22] sought commitment from 195 countries to "holding the increase in the global average temperature to *well below 2°C* above preindustrial levels". The Paris Agreement calls for all signatories to submit "Nationally Determined Contributions" (NDC), which outlines their plans to reduce greenhouse gas emissions in their respective countries. The U.S.' NDC[23] includes reductions from methane emissions in the oil and gas industry. While the Trump Administration has announced its intent to pull the U.S. out of the Paris Agreement, as of this paper, the U.S. is officially part of the Paris Agreement through its ratification in November 2016.

In the U.S., there are state and federal regulations targeting methane emissions from the oil and gas industry. U.S. federal regulations target new or modified facilities and are codified under the Clean Air Act[24]. Many oil and gas producing states like Colorado, Pennsylvania, Wyoming, California, and Ohio also have regulatory standards for oil and gas facilities and some state regulations, like in Colorado and California, also extend to existing facilities. [25] Some courts have required pipeline companies to provide quantitative estimates of greenhouse gases[26] in their Environmental Impact Statements (EIS). Certain investors have targeted oil and gas companies to better disclose their methane emissions programs and issued guidance related to methane disclosures, mitigation programs and shareholder engagements[27–29]. External entities are now analyzing company performance related to methane emissions and ranking companies accordingly[30,31]. In addition to regulatory policy and investor concerns on sustainability issues, some companies have also faced non-compliance issues that have resulted in considerable financial penalties[3].

Southwestern Energy (SWN) is one of the largest natural gas producers in the United States, operating unconventional assets in West Virginia, Pennsylvania and Arkansas. As of December 31, 2017, our proved reserves were estimated at 14.8 trillion cubic feet equivalent (tcfe). Protecting natural resources and being a good steward of the environment are core values of Southwestern Energy Company. These values manifest themselves in everything we do, and we are broadly recognized as a responsible operator that, in accordance with our Formula, SWN does the Right Things with respect to our natural world. Our Formula guides our investments in the communities we operate, the talent we employ and the resources we develop (Figure 1). This paper reviews the history of U.S. federal oil and gas related methane programs and SWN's experience in promoting "science-based" national policies on methane highlighting our ONE Future initiative and our leak detection and repair programs.

Figure 1: The SWN Formula

Federal methane initiatives

The U.S. Environmental Protection Agency (EPA) launched the Natural Gas STAR program aimed at voluntarily sharing best management practices and to encourage the implementation of methane abatement technologies. The program first started with the natural gas transmission and distribution segments in 1993. In 1995, the program expanded to the oil and gas production sector and in 2000 to the gas processing sector[32]. Many of the best practices initially shared through Natural Gas STAR are now standard practices as part of the design and operation of natural gas facilities.

[3] Examples: BP (https://www.environmentalleader.com/2016/07/bps-total-costs-for-deadly-oil-spill-hit-62-billion/), Nobel Energy (https://www.epa.gov/enforcement/noble-energy-inc-settlement)

The Supreme Court decision in Massachusetts v. EPA[33] upheld the EPA's authority to regulate GHGs, including methane under the Clean Air Act. The EPA made an "endangerment finding" for methane itself in the context of its promulgation of greenhouse gas emission standards for motor vehicles. That 2009 endangerment finding covered not only carbon dioxide but also methane and four other types of greenhouse gases.[4] In 2010, the EPA finalized a mandatory reporting rule that established the Greenhouse Gas Reporting Program (GHGRP) requiring annual emissions reporting from major facilities under 40 CFR Part 98[34]. The goal of the GHGRP was to collect data to inform about future regulatory and non-regulatory policies. In 2012, the EPA finalized the New Source Performance Standards (NSPS) regulations targeting volatile organic compounds (VOC) from select emission sources mainly from the production and processing sectors of the natural gas value chain[35]. Methane reductions were recognized as a "co-benefit" to these VOC based regulations. The Obama Administration released "The President's Climate Action Plan" in 2013. This plan called for an "interagency methane strategy" and a "collaborative approach to reducing methane emissions", including collaboration with the private sector[36]. The "Strategy to Reduce Methane Emissions" was released in 2014[37] by the Obama Administration and specifically for the oil and gas sector, it called for reviewing methane reduction options from oil and gas sources, expanding the voluntary program under Natural Gas STAR, and directing the Bureau of Land Management (BLM) to update standards to reduce venting and flaring on public lands. The strategy also focused on improving methane measurement and monitoring, including the development of cost-effective measurement technologies under Department of Energy's ARPA-E program, improving the national greenhouse gas inventory (GHGI) and developing cost-effective measurement technologies.

In January 2015, the Obama Administration announced a goal to reduce methane emissions from the U.S. oil and gas sector by 40 – 45 percent from 2012 levels by 2025[38]. This methane oil and gas strategy called for regulating methane emissions for new and modified sources, collaborating with industry initiatives such as ONE Future to reduce methane emissions at existing facilities, developing control technique guidelines (CTGs) to reduce VOCs, and reducing of methane emissions on federal lands administered by the BLM. In a subsequent communication in March 2015, the Obama Administration believed that these strategies would result in a reduction of 180 billion cubic feet of natural gas by 2025[39].

The EPA proposed direct methane regulations under NSPS OOOOa in September 2015 and finalized the rule on June 3, 2016[24] subject to its authority under Clean Air Act (CAA) Section 111(b).

[4] *See* Environmental Protection Agency, Endangerment and Cause or Contribute Findings for Greenhouse Gases Under Section 202(a) of the Clean Air Act; Final Rule, 70 Fed. Reg. 66496 (Dec. 15, 2009).

While there are both legal and technical challenges to this final rule, it remains the specific methane regulation applied to applicable new, modified or reconstructed facilities in the natural gas value chain. Currently, there is no direct federal regulation of methane for "existing sources" (i.e. facilities that are currently under operations and have not been modified or reconstructed) at natural gas facilities under CAA Section 111(d). The Obama Administration began efforts intended to result in new regulations for existing methane sources, but that effort was delayed by the incoming Trump Administration. It has been generally understood that Section 111(d) of the CAA creates a non-discretionary duty for EPA to direct states to regulate existing sources that meet certain criteria. Even if section 111(d) creates a non-discretionary duty to issue regulations for existing sources once new source standards have been promulgated, the statute does *not* specify the *timing* under which the agency must issue such regulations. EPA's implementing regulations also does not establish a timeframe by which the Agency must establish emission guidelines.[5] Therefore, the EPA could argue that it has substantial discretion as to timing, and could exercise that discretion with a specific and well-developed justification related to the potential of voluntary programs to limit emissions from the sector. Courts have established that "an agency has broad discretion to choose how best to marshal its limited resources and personnel to carry out its delegated responsibilities."[33] In the case of *WildEarth Guardians v. EPA*[40], the D.C. Circuit affirmed the EPA's decision not to issue section 111 rules—including both new source rules under section 111(b) and existing source rules under section 111(d)—for methane emissions from coal mines. Specifically, citing *Massachusetts v. EPA*, the court held that the EPA had significant discretion to determine *when* to list categories of sources of greenhouse gases under section 111.[6] The court in *WildEarth Guardians* held that the EPA's justification— that the Agency was "taking a common-sense, step-by-step approach intended to obtain the most significant greenhouse-gas-emissions reductions through using the most cost-effective measures first"—was a sufficient basis for the court to hold that the EPA had not violated its obligations under the Clean Air Act.[7] Perhaps shortly after the release of the methane goals for oil and gas industry, EPA Administrator Gina McCarthy stated "…there is no time deadline in the statute for us to look at existing source methane regulations for the oil and gas sector …the most important thing to realize is if existing sources aggressively reduce their emissions, then it's not clear that there will be cost-effective reductions that will necessitate regulation of existing facilities"[8]. This concept

[5] 40 CFR § 60.22(a) ("Concurrently upon *or after proposal…*") (emphasis added).
[6] *Id.* at 9 ("the Court in *Massachusetts v. EPA* recognized that an agency has 'significant latitude as to the manner, *timing*, content, and coordination of its regulations. . . .' 549 U.S. at 533 (emphasis added). EPA's decision in this case is about timing, not about whether to regulate…").
[7] *WildEarth Guardians* at 6.

[8] *EPA's McCarthy: Future methane rules depend on industry action*, Erica Martinson, January 16, 2015

was reinforced later in the fall of 2015 by the EPA's Office of Air and Radiation's Senior Counsel, Joe Goffman[9].

SWN's methane initiatives

Reducing methane emissions is a SWN corporate core value and is part of our corporate strategy of "proactive risk management" and "differentiation through environmental and regulatory standards, SWN views methane emissions reductions as a measure of efficiency improvement in our production and midstream operations. We take a rational, science-based approach to environmental issues, including climate change and we seek productive relationships with our stakeholders: the community where we operate, our employees, governmental agencies that regulate our business and our shareholders. Our long-term vision is for safe and responsible development of America's abundant supply of natural gas to remain an essential part of a lower-carbon energy future.

SWN's methane strategy is based on the principle that "sound science drives sound policies". By actively participating in methane research with academia and others and developing appropriate policy frameworks, we believe we can better manage our regulatory and reputational risks, be responsive to our shareholders, customers and investment communities on sustainability issues while improving the efficiency of our product delivery. Sustainability concerns are by no means limited to our methane emissions, but we view the climate benefit of our product as being fundamental to the natural gas value proposition.

At SWN, corporate sustainability programs are embedded in our corporate operating philosophy as strongly as safety issues. Our Board of Directors' Health, Safety, Environment and Corporate Responsibility Committee regularly reviews and assesses environmental and climate-change issues arising out of the our activities and operations and their impact on employees, contractors and the communities in which we operate, and reviews current and emerging trends in social, political and public policy issues that may affect our business and our reputation. SWN's Executive Leadership Team (ELT) and Board of Directors view measurement, mitigation, reporting and engagement of sustainability programs as an integral part of the long-term corporate success. The positive climate and environmental attributes of natural gas are essential keys to our growth when compared to other fossil fuels such as coal (while there are more "BTUs" of coal reserves than oil and gas combined, environmental factors are one major reason why coal consumption has declined in the United States).

[9] *EPA evaluating scope of proposed methane rules*, Jean Chemick, September 29, 2015

Over the last several years, SWN has voluntarily participated in a number of scientific studies with regulatory agencies, academia and non-governmental organizations that have led to over a dozen peer-reviewed papers on methane emissions from oil and gas operations (See SI-3). In one such study, SWN engaged in collaboration with other industry partners, the Environmental Defense Fund (EDF) and the University of Texas (UT). This project conducted methane measurements across various oil and gas production sites and led to publication of the results in the Proceedings of National Academy of Sciences[41]. This campaign led to additional peer reviewed studies focused on two of the highest emitting source categories[42,43]. In addition, three peer-reviewed publications[44,45,46] resulted from field campaigns focused on gathering and boosting facilities in SWN's collaboration with Colorado State University, industry partners and the EDF. These studies now form the basis for methane emission factors from gathering and boosting facilities. In 2015, SWN and four other industry sponsors collaborated with Colorado School of Mines, Colorado State University, National Renewable Energy Laboratory, National Oceanic and Atmospheric Administration, University of Colorado Boulder, on a 5 million dollar methane measurement study to reconcile top-down and bottom-up measurement studies. This study has resulted in publication of multiple peer-reviewed publications and provide new insights that will enable both the scientific community and policy-makers to advance understanding of methane emissions[47]. We are also partners with IBM[48] and GE[49] in developing technology related to novel methane detection and monitoring technologies.

Many of these publications form the basis for current worldwide methane emissions knowledge. These studies have greatly informed SWN's internal methane management strategy, including our LDAR program that has been in place since 2013 and the establishment of the ONE Future performance-based model to manage methane emissions. Under a performance-based policy, instead of prescribing a set of technologies or work-practices for every applicable emission sources, a science-based performance goal is established and allows firms the flexibility to achieve these goals and report their performance against these goals in a transparent and consistent manner. In other words, performance-based programs focus on the outcome (e.g. a certain maximum methane leakage rate), while leaving the process for achieving those outcomes to the discretion of the firm[50,51]. We also remain actively involved in new peer-reviewed methane research – all of which are consistent with our corporate philosophy and strategies.

SWN founded the ONE Future Coalition which is a group of 11 companies across the value chain aiming to achieve or maintain a methane leakage rate below 1% from the "well-head to the burner-tip" (see additional details in later sections). In addition, SWN has participated in the EPA

Natural Gas STAR program since 2005 and reduced over 47 billion cubic feet (bcf) or over 900,000 metric tons of reduced methane emissions through December 2017 (see Figure 2[10]).

Additionally, SWN was a founding member and the only U.S. based oil and gas firm to participate in the Climate and Clean Air Coalition's Oil and Gas Methane Partnership (OGMP)[11]. Unlike ONE Future which advances a performance-based target policy framework, the OGMP used a technology-based design that focused on methane mitigation from nine core sources. For reporting years, 2015 and 2016, SWN accounted for over 98% of the total methane emissions reported by all participants in the program for both years[52,53].

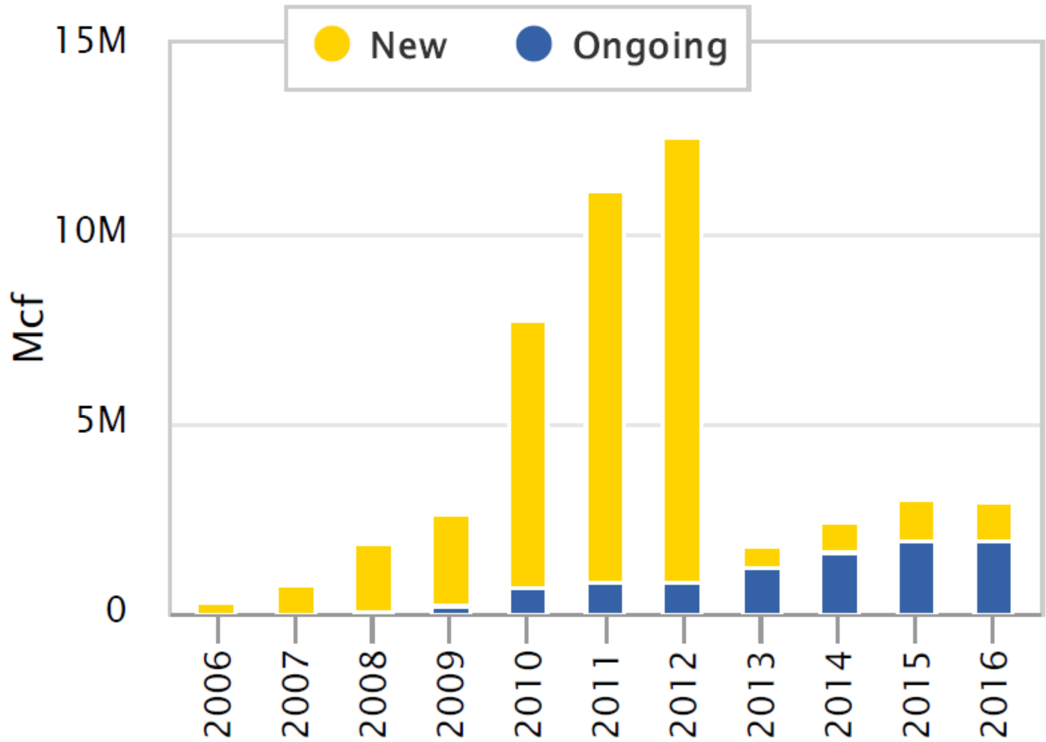

Figure 2: Annual Reductions for SWN (Source: EPA Natural Gas STAR, 2018)

[10] Since NSPS OOOO required reduced emissions completion (REC) on completion flowback events, these reductions were no longer applied under the EPA Natural Gas STAR program after the effective date of the rule.

[11] SWN withdrew from the OGMP from January 1, 2018. The initiative currently has the following partner companies: BP, ENGIE E&P, Eni, Pemex, PTT, Repsol, Shell, Statoil, and Total

ONE Future Coalition

As noted earlier, our participation in scientific projects set the foundation for the ONE Future policy framework to reduce methane we helped develop. The challenges to reducing methane emissions at natural gas facilities are many. First, there are thousands of emission sources across the entire value chain. While there are cost-effective technologies to reduce methane emissions[54], the efficacy of methane abatement varies from one location to the other. Prior scientific studies have highlighted the heterogeneity, regional differences in methane emissions across the industry.[41,43,55–57] Further, multiple studies have concluded that the majority of the emissions are a result of a small fraction of the total emission sources.[45,56–60] The ONE Future Coalition believes that rather than prescribing a set of specific technologies, the policy framework should incorporate a robust, science-based numerical performance target or goal designed in a manner to provide flexibility for companies to effectively deploy capital and resources to reduce emissions in the most cost-effective manner. In addition, performance-based policies can accommodate new mitigation and methane monitoring technologies than prescriptive technology-based policies. This is particularly important in this context, because the technology for monitoring and mitigating methane leaks is improving rapidly.

SWN is a founding member of the ONE Future Coalition[16] and the architect of the ONE Future 1% approach. ONE Future is the trade name for “Our Nation’s Energy Future Coalition, Inc.” ONE Future is a unique coalition of natural oil and gas companies with operations across the entire natural gas value chain from production to distribution segments. ONE Future was formed in 2014 with the goal of achieving a total supply chain methane emission rate of less than one percent of gross production by or before 2025, a scientifically developed target.[5,15,61] ONE Future has also developed a unique private-public partnership under the EPA’s Methane Challenge[62].[62] Members may participate in the Methane Challenge program by employing EPA approved estimation methods,[63,63] implementing reduction strategies the company knows to be most effective and reporting performance in a transparent manner. In general, the reporting boundaries are those of the U.S. natural gas supply chain ranging from natural gas production through natural gas distribution, and is divided into the following segments of the industry: Production and Gathering, Processing, Transmission and Storage, and Distribution. Emissions intensity must be determined and reported at an appropriate business level or sector of the company that includes the U.S. natural gas assets covered under the industry segment(s) chosen for the ONE Future program while employing standardized methods.

Unlike the traditional command-and-control policy framework that mandates application of a specific technology or work practice, the ONE Future approach focuses on a performance goal of 1%methane emissions intensity. Each participant commits to meeting the relevant sectoral targets established in Table 1 for its industry segment and estimates emissions intensity and tracks their progress towards the goals by employing the EPA approved reporting guidelines. The flexibility of the

ONE Future framework allows each company to identify and deploy the appropriate emissions mitigation strategy for its various assets – whether employing the various technologies identified by the Natural Gas STAR program or deploying new, innovative technologies, modifying a work practice, or in some cases retiring an asset. While there have been questions about uncertainties related to methane emissions from the natural gas industry[58,64], employing EPA-approved methane estimation techniques and reporting emissions in a transparent manner enables stakeholders to evaluate the performance of the ONE Future members against the stated targets and goals (which were also developed based on EPA inventories). It should also be noted that in the absence of continuous monitoring of natural gas facilities, the abatement benefits *assumed* by the application of any methane mitigation technology or work-practice standard also relies on arguably "overly simplistic"[51] assumptions of continuous benefits realized by retrofitting the emission sources with a specific technology, or on other potentially flawed assumptions, as noted later in this paper about practices such as Leak Detection and Repair (LDAR).

Combining a performance target with a flexible pathway allows member companies to deploy their capital where it will be most effective in reducing emissions. This is important because most studies clearly show that the majority of methane emissions come from a small fraction of sources. ONE Future's approach allows companies to focus their resources on identifying and addressing those sources.

Table 1: ONE Future Segment Intensity Goals (methane emissions per gross production)[12]

	Methane Emissions Intensity	**Methane Emission Intensity Goals (percent of Gross Production)**	
Industry Segment	**2012**	**2020**	**2025**
Gas Production and Gathering	0.55%	0.46%	0.36%
Gas Processing	0.18%	0.15%	0.11%
Gas Transmission and Storage	0.44%	0.37%	0.30%
Gas Distribution	0.26%	0.24%	0.22%
Total	1.44%	1.22%	1.00%

ONE Future has also invested in methane research to better characterize methane emissions and review opportunities for further improvements. Past work included marginal abatement cost analysis.[54] Current research includes programs with National Energy Technology Laboratory (NETL)[65]

[12] The methane intensities computed using co-allocation based on energy to ensure emissions resulting from production of associated gas at oil wells, lease condensates and natural gas plant liquids (NGPL) are reasonably accounted. Without co-allocation, the 2012 methane intensity of the natural gas sector is 1.31%.

and Colorado State University.[13] Through these efforts, ONE Future promotes science-based targets and policies.

Leak Detection and Repair Programs

Based on data reported to the EPA (Subpart W) and studies addressed above, equipment leaks are one of the largest sources of methane emissions from oil and gas sites. LDAR programs are a key work practice standards aimed at reducing equipment and component leaks at oil and gas sites. In a typical LDAR program, the operator deploys a leak detection device used in a facility survey at a set frequency. These programs aim to "find and fix" the source of the leaks without quantification of the leaks.

Although LDAR programs are effective at identifying leaks and reducing methane emissions, the cost effectiveness of implementing an LDAR program is subject to debate. Recent federal rule (e.g. NSPS OOOOa) cost effectiveness evaluations have not been based on current scientific-based data nor oil and gas operations. The following sections provide an overview of regulatory based LDAR programs versus SWN's voluntary "SMART LDAR" program.

Federal Leak Detection and Repair (LDAR) Programs

The history of LDAR dates back to 1981 when it was proposed under the NSPS for Synthetic Organic Chemicals Manufacturing[66]. Under this regulation, leak surveys are performed with a non-specific instrument that can detect a clearly defined leak by following Method 21 Determination of Volatile Organic Compound Leaks (referred to as Method 21). Method 21 was incorporated into Appendix A of 40 CFR 60 in 1983. A leak was defined as a detectable volatile organic compounds (VOCs) concentration equal to or greater than 10,000 ppm. "No detectable emissions" of VOC was defined as 500 ppm or less. Method 21 was incorporated into Appendix A of 40 CFR 60 in 1983. The first regulatory application of LDAR for VOC monitoring in the oil and gas (O&G) industry was in 1985 as part of the final NSPS rules for onshore natural gas processing plants under Subpart KKK. Under these rules Method 21 was applied to identify equipment leaks at natural gas processing plants. In 1995, the EPA issued a protocol to estimate VOC emission leaks at O&G production facilities employing measurement data collected at refineries, synthetic organic chemical manufacturing industry facilities, marketing terminals, and O&G facilities. Method 21 LDAR was incorporated to National Emission Standards for Hazardous Air Pollutants (NESHAP) for Petroleum Refineries in 1995 (40 CFR 63 Subpart CC) and NESHAP Subparts HH and HHH for oil and gas production

[13] Characteristics of Gathering and Boosting Stations, DE-FE0029068

facilities and natural gas transmission and storage facilities in 1999. In 2008, EPA authorized[67] an "Alternative Work Practice" to allow the use of OGI cameras for Method 21 leak detection. Reporting regulations for GHGs from petroleum and natural gas systems (Subpart W) were promulgated[34] in 2010. These regulations established requirements for methane leak detection using Optical Gas Imaging (OGI) cameras, or Method 21 at natural gas processing plants and transmission stations. In 2016, the EPA finalized methane and VOC standards for fugitive emission components at well sites and compressor stations under NSPS OOOOa and required semi-annual monitoring and repairs at well sites and quarterly monitoring at compressor stations with "leaks" being defined as "any visible emission from a fugitive emissions component observed using optical gas imaging or an instrument reading of 500 ppm or greater using Method 21."

The EPA has documented the cost-effectiveness of LDAR programs under the EPA Natural Gas STAR program and regulatory proceedings under EPA's NSPS Subpart OOOOa. States such as Colorado, Pennsylvania, and California have also assessed the cost-effectiveness of LDAR programs. ICF International has developed updated estimates on LDAR costs employing industry provided data[54].[54]. Cost-effectiveness of LDAR programs depends on multiple factors including expected abatement volume, fixed LDAR program costs, frequency of LDAR and technology employed and repairs costs and time. Much of EPA's data related to LDAR comes from the petro-chemical industry and the abatement effectiveness of federal LDAR (assumed at 40% for annual LDAR, 60% for a semi-annual frequency and 80% for a quarterly frequency) is based on Colorado regulations which in turn are based on a draft EPA technical document[68] (1981 Refinery VOC LDAR draft). This 1981 document appears to convey that only a 42% abatement potential is possible (at petroleum refineries) for components in "gas service" for a LDAR conducted at a quarterly frequency and not the 80% effectiveness assumed in the federal regulations.

In addition, the federal NSPS Subpart OOOOa regulations assume that 1.18% of the total components are identified as leaks using the OGI methods[69] based on petro-chemical experience. Actual LDAR measurement data is limited. The ONE Future Coalition LDAR data shows leaking components to be less than 0.55% with leak volumes decreasing over time[70]. Ravikumar et al.[71] finds that OGI-based LDAR resulted in only 0.18–0.28% of total components identified as leaking.

SWN SMART LDAR overview

Since unintentional leaks of methane emissions (fugitive emissions) are one of the largest emission sources, SWN developed and implemented a voluntary LDAR program called "SWN SMART LDAR" (see SI-4 for additional details). The program was initiated in 2014 when there were no federal requiring such a program. The purpose of the SWN SMART LDAR Program is to "find and fix" methane leaks associated with SWN operations. The SMART LDAR Program includes a process

for conducting leak surveys (both Audible/Visual/Olfactory and OGI), identifying leaking components/equipment, and repairing leaking components/equipment. The program also includes recordkeeping and reporting requirements that are used to assist SWN in tracking and trending leaking components/equipment. The SWN SMART LDAR Program applies to SWN exploration, production, and midstream operations.

Today the program goes beyond the current regulatory requirements to find and fix equipment leaks in that it a) also covers certain non-fugitive equipment sources (e.g. pneumatic controllers), b) is supplemented with measurements of the emissions from equipment and fugitive emission components at select locations with Hi-Flow instruments employing manufacturer recommendations for measuring emissions. Leak rates observed beyond the limitations of the Hi-Flow device (measurements below 10 standard cubic feet per minute (scfm)) may be measured employing a bagging technique and averaging 5 measurements to arrive at the leak rate, and c) it addresses all sources, not just new sources. In addition to the find and fix LDAR, SWN develops emission factors for various equipment and fugitive emission components are developed from these measurements. The elements of the SWN SMART LDAR program includes the following (unless dictated by a more stringent requirement or schedule by regulations):

- Audio Visual and Olfactory (AVO) Leak Survey, Recordkeeping and Reporting
- Annual Instrument Leak Detection Surveys of existing wells and existing compressor stations at least annually and new wells and new compressor stations within 60-180 days of commencing operation.
- Leaking Component/Equipment Repairs: Leaking components/equipment should be repaired as soon as possible and within a target of 15 days. Leaking components or equipment deemed “delay of repair” due to the acquisition of replacement components or equipment should be repaired within 15 days of obtaining the replacement component/equipment.
- Leaking Component/Equipment Repair Re-Survey: Upon completion of leaking component or equipment repair/replacement, the component/equipment should be “re-surveyed” to confirm that the leak has been fixed.
- Leak Detection Survey Recordkeeping and Reporting: The program calls for maintenance of records of leak detection surveys including: location, date of survey, identification of leaking components or equipment, measurement data (if obtained), date of initial repair, date of final repair including re-survey, and cause of the leak. Also, SWN maintains records of components/equipment on delay of repair list

including; reason for delay of repair status anticipated date of repair, actual date of repair and re-survey.

- Training: Initial training on the SWN LDAR program is provided to SWN personnel engaged in implementing the program. Ensuing training is comprised of a review of the SWN SMART LDAR Program/Process by personnel conducting the AVO and/or instrument leak detection surveys supplemented by “hands-on” training with the optical gas imaging or infrared camera by personnel previously trained and experienced with SWN SMART LDAR Program/Process.

Results:

The EPA regulates new and modified sources of methane at oil and gas facilities. Certain states regulate methane from existing sources. Existing voluntary programs such as EPA Natural Gas Star, Methane Challenge, including the ONE Future option and API’s Environmental Partnership focuses on both new and existing facilities. Investor concerns and state initiatives are growing and leading companies are responding to methane issues. The ONE Future Coalition is the only private-public partnership that covers the entire value chain and establishes a performance-based emission reduction target. Many investors are employing it as benchmark[29] and ONE Future companies have been ranked consistently as top performers by independent analysts related to methane management.[30,31]

Studies have analyzed future methane policy frameworks for oil and gas facilities[25,51]. Munnings et al. (2017) recommends a tiered-LDAR program. Konschnick et al (2018) recommends a North American framework that integrates science and policy. For a complex sector with thousands of discrete sources and operators, the current technology-based approaches under NSPS OOOOa or state regulations fail to provide the flexibility or recognize the regional differences in emissions profiles. To fully realize the environmental benefits of natural gas, and support U.S. “energy dominance” a balanced approach, preferably a scientifically derived performance-based approach with clear, transparent and consistent reporting is needed. ONE Future is such a model and could be employed as a model for voluntary actions at oil and gas facilities. The reporting techniques have been established by the U.S. EPA and each company will transparently will report their emissions from all assets. The scientific target of 1% ensures the climatic benefit of natural gas over other fossil fuels is achieved. Further, the flexibility of employing any technology, including innovative technologies to measure and mitigate methane emissions and focusing scarce capital and resources to high emitting sources and facilities, in lieu of a “one-size” approach, makes the ONE Future design

attractive. LDAR remains a key work-practice standard to reduce fugitive emissions, however, the efficacy of methane reductions assumed by the EPA and some states is suspect.

The results of the SWN SMART LDAR program are presented in Tables 2 and 3. Over a three year period, SWN conducted over 14,000 surveys of wells and 179 surveys of gathering and boosting compressor stations (midstream facilities). In aggregate, during this period about 13% of SWN's total components and equipment emissions observed during the LDAR surveys were measured using the Bacharach HiFlow (Hi-Flow) device, which quantifies the emission rate. The leaking component and equipment fraction are relatively negligible, about 0.09% for production assets and about 0.17% for midstream assets relative to the total estimated equipment and components at our facilities (Figures S-1 and S-2). These are conservative estimates as we do not have an estimate of total equipment in the denominator (only estimated components based on EPA factors). Our LDAR survey results indicate that only about 0.25 leaks per well were observed. Similarly, about six leaks per entire midstream facility were observed during this 3 year period. In addition from the data presented below (either leak percentage or weighted average emissions per well), ensuing LDAR surveys do no result in significant drops in observed leaks from year to year.

Table 2: Summary of SWN SMART LDAR (Production)

	2014	2015	2016	2014-2016
Wells Surveyed	3,071	5,592	5,618	14,281
Component count estimates	884,349	1,478,772	1,450,553	3,813,674
Leaks observed (components and equipment)	770	1,281	1,461	3,512
Leaks per well (components and equipment)	0.25	0.23	0.26	0.25
Leaks percentage (relative to total components)	0.09%	0.09%	0.10%	0.09%
Weighted average emissions per well (thousand cubic feet (MCF))	38.12	34.15	38.94	36.85

Table 3: Summary of SWN SMART LDAR (Midstream)

	2014	2015	2016	2014-2016
Facilities Surveyed	63	58	58	179
Components and Equipment MMSCF	218,914	201,540	201,540	621,994
Leaks observed (components and equipment)	454	279	344	1,077

Leaks per facility (components and equipment)	7.21	4.81	5.93	6.02
Leaks percentage (relative to total components)	0.21%	0.14%	0.17%	0.17%
Weighted average emissions per facility (million cubic feet (MMCF))	2.75	1.16	2.03	2.00

SWN's observed component leak percent (component leaks/total components) are significantly lower than the 1.18% component leak rate used by EPA in the NSPS OOOOa cost effectiveness evaluation. The common component category identified leaking during the SWN SMART LDAR are "other" and connectors for the production segment and valves for the midstream segment. Liquid level controllers are the common pneumatic controller equipment identified as emitting during our surveys (Figures S-3 and S-4). The majority of equipment leaks associated with both SWN Production and Midstream are from intermittent (snap acting) liquid level controllers. Tables S1-S4 summarizes the average measured methane rates (using Hi-Flow) for equipment and components from SWN SMART LDAR surveys over a three year period.

Conclusion

Multiple reports from the EIA and IEA concludes that natural gas is an integral part of a low carbon transition. The opportunities created by the transition from other fossil fuels and energizing the world with low cost, scalable and flexible natural gas supplies should be embraced. The future of natural gas will depend on energy market forces and policies (e.g. growth of competing and lower or zero emitting technologies, energy storage and energy efficiency) as well as environmental policies (e.g. carbon pricing mechanisms, methane emissions). Natural gas is an integral commodity to meet the global energy needs and it has lower GHG and other emissions impact than other energy sources. However, excessive methane emissions leakage can erode its benefits over coal and oil as an energy source. The opportunities (greater gas demand due to climate and environmental concerns) and risks (e.g. upstream methane leakage) are inextricably relevant to any oil and gas firm's competitive position.

To realize the full potential of U.S. natural gas, the natural gas industry has to minimize methane emissions across the entire natural gas value chain. Continuous improvement in emissions and efficiency should be an integral part of business strategy for all companies in the natural gas industry. Methane management issues must be viewed, similar to margin improvements as an operational efficiency matter. Policies and programs to achieve a methane emissions intensity rate of less than 1% across the natural gas value chain should be implemented to ensure natural gas remains a competitive and foundational fuel in the energy transition to a lower carbon economy. And, these policies programs should be developed based on good science and sound business analysis.

Many methane measures are relatively inexpensive and can yield positive net values for certain segments of the industry where the methane captured can be monetized. Studies have shown the complexities associated with mitigating methane emissions from hundreds of thousands of discrete emission sources across the entire natural gas value chains. In addition, studies have shown that the majority of the emissions from any firm's operating assets are from a small fraction of the facilities or emission sources. Traditional technology-based policies are ill-suited as a mitigation policy for this industry due to these complexities and the fact that mitigation and monitoring technologies are advancing rapidly. Instead, a performance-based policy rooted in scientifically derived but realistic targets that provides the company the flexibility to allocate its capital and resources to the highest emitting facilities will yield substantially much more positive results than current regulatory and some voluntary measures.

Private-public partnerships in methane research and policy provide mutually beneficial opportunities for the government and industry to measure and mitigate emissions. Agencies should use data obtained from private-public partnership studies, like ONE Future and similar voluntary programs, and company specific data (e.g. SWN LDAR) to develop "science-based" methane policy and regulations. Uncertainties about emissions estimates from the natural gas industry should not be an excuse for a "do nothing" or "regulate everything" policy. Existing technologies and estimation methods are "good-enough" to initiate appropriate performance-based policies. Existing voluntary programs like ONE Future provide a platform for operators to voluntarily reduce and report their methane emissions using an EPA-approved protocol. This information also supports investors and other stakeholders in transparently evaluating the performance of these companies. Innovative methane measurement technologies and programs are better suited to performance-based programs and under voluntary policies, these technologies can emerge from a novel application to a standard application.

While LDAR is an important methane reduction practice, policy-makers are urged to revisit the cost-effectiveness analysis employed in past rulemaking. This paper reviewed the historical basis for LDAR and found that some of the key data employed in justifying the cost-effectiveness of the EPA and Colorado regulations is based on studies that are over 37 years old and from the petro-chemical industry, so potentially less relevant to natural gas industry. Furthermore, it seems likely that the data was incorrectly employed in the LDAR cost-effective analysis of the regulations. Also, SWN data indicates that a significantly lower fraction of leaking components are identified during LDAR surveys. Furthermore, ensuing surveys do not result in significant decreases in observed leaks relative to the initial survey. A comprehensive multi-year, nation-wide analysis of LDAR measured data is needed.

In summary, natural gas will very likely remain a foundational energy source in the 21st century to help meet growing global energy demand and reduce greenhouse gas emissions. Methane mitigation policies remain crucial to ensure the “green credentials” of natural gas are preserved. Efforts by ONE Future and SWN highlight how leading companies can rise up to meet this methane challenge.

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References

1. Newell, R. G. & Raimi, D. Implications of Shale Gas Development for Climate Change. *Environ. Sci. Technol.* (2014). doi:10.1021/es4046154
2. James T. Hackett et. al. Prudent Development: Realizing the Potential of North America’s Abundant Natural Gas and Oil Resources. *Harefuah* **150,** 528–531, 551 (2011).
3. - International Energy Agency, I. WEO 2012 Special Report Golden Rules for a Golden Age of Gas.
4. Shale Gas:New Opportunities, New Challenges. 1–26 (2012).
5. IEA. World Energy Outlook 2017. 782 (2017). doi:10.1787/20725302
6. EIA. Annual Energy Outlook 2017 with projections to 2050. *J. Phys. A Math. Theor.* **44,** 1–64 (2017).
7. Perry Lindstrom. Carbon Intensity of Energy Use Is Lowest in U.S. Industrial and Electric Power Sectors. *Today in Energy - U.S. Energy Information Administration (EIA)* (2017). Available at: www.eia.gov/todayinenergy/detail.php?id=31012.
8. Tollefson, J. Methane leaks erode green credentials of natural gas. *Nature* **493,** 9 (2013).
9. Shoemaker, J. K., Schrag, D. P., Molina, M. J. & Ramanathan, V. What role for short-lived climate pollutants in mitigation policy? *Science* (2013). doi:10.1126/science.1240162
10. Fevre, C. Le. *Methane Emissions : from blind spot to spotlight*. (2017).

11. M Saunois, RB Jackson, P Bousquet, B. P. and J. C. The growing role of methane in anthropogenic climate change. *Environ. Res. Lett.* **11,** (2016).
12. Howarth, R. W. A bridge to nowhere : methane emissions and the greenhouse gas footprint of natural gas. 1–14 (2014). doi:10.1002/ese3.35
13. Etminan, M., Myhre, G., Highwood, E. J. & Shine, K. P. Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophys. Res. Lett.* **43,** 12,614-12,623 (2016).
14. IEA. Energy and Climate Change. 200 (2015). doi:10.1038/479267b
15. Alvarez, R. A., Pacala, S. W., Winebrake, J. J., Chameides, W. L. & Hamburg, S. P. Greater focus needed on methane leakage from natural gas infrastructure. *Proc. Natl. Acad. Sci.* **109,** 6435–6440 (2012).
16. ONE Future Coalition. Available at: http://www.onefuture.us/. (Accessed: 1st March 2018)
17. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2015. EPA 430-38 P-17-001. Washington, DC: US Environmental Protection Agency.* (2017).
18. EIA. US Natural Gas Summary. Available at: https://www.eia.gov/dnav/ng/ng_sum_lsum_dcu_nus_a.htm.
19. Larsen, Kate; Delgado, Michael; Marsters, P. Untapped Potential Reducing Global Methane Emissions from Oil and Natural Gas Systems. (2015). doi:10.1089/big.2014.1523
20. Hendrick, M. F., Cleveland, S. & Phillips, N. G. Unleakable carbon†. *Clim. Policy* **17,** 1057–1064 (2017).
21. Abrahams, L. S., Samaras, C., Griffin, W. M. & Matthews, H. S. Life Cycle Greenhouse Gas Emissions From U . S . Liquefied Natural Gas Exports : Implications for End Uses Supporting Information. *Environ. Sci. Technol.* **49,** 1–24 (2015).
22. UN Climate Change Paris Agreement. *UNFCC* (2015). Available at: http://newsroom.unfccc.int/paris-agreement/.
23. United States' Nationally Determined Contribution. Available at: http://www4.unfccc.int/ndcregistry/PublishedDocuments/United States of America First/U.S.A. First NDC Submission.pdf.
24. EPA, U. *40 CFR Part 60 Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources; Final Rule*. *New Source Performance Standards for Oil and Natural Gas Sector: Emission Standards for New, Reconstructed, and Modified Sources; Final Rule* **81,** 35824–35939 (2016).
25. Konschnik, K. & Jordaan, S. M. Reducing fugitive methane emissions from the North American oil and gas sector: a proposed science-policy framework. *Clim. Policy* (2018). doi:10.1080/14693062.2018.1427538
26. SIERRA CLUB, ET AL., P., V., FEDERAL ENERGY REGULATORY COMMISSION, R. &

DUKE ENERGY FLORIDA, LLC, ET AL., I. *United States Court of Appeals*. (2017).

27. EDF and PRI. An investor' s guide to Methane: Engaging with oil and gas companies to manage a rising risk. *October* (2016).
28. CERES. Global Climate Disclosure Framework For Oil and Gas Companies. (2009).
29. Responsibility, I. C. on C. 2017 Proxy Resolutions and Voting Guide 2017 Proxy Resolutions and Voting Guide ICCR Member Resolutions by Company. (2017).
30. Wright, S. & Gaumond, K. THE DISCLOSURE Revisiting Rising Risk and Methane Reporting. (2018).
31. Liroff, Richard; Fugere, Danielle; Heim, S. Disclosing the Facts 2017: TRANSPARENCY AND RISK IN METHANE EMISSIONS. (2017).
32. Communication, T. N. *et al.* U . S . Climate Action Report – 2002 Under the United Nations Framework Convention on Climate Change U . S . Climate Action Report – 2002. *Environ. Prot.* (2002).
33. STATES, S. C. O. T. U. Massachusetts v. EPA, 549 U.S. 497. 1–6 (2017).
34. EPA. Mandatory Reporting of Greenhouse Gases: Petroleum and Natural Gas Systems; Final Rule. **75,** (2010).
35. Environmental Protection Agency. EPA 40 CFR Parts 60 and 63- Oil and Natural Gas Sector: New Source Performance Standards and National Emission Standards for Hazardous Air Pollutants Reviews; Final Rule. *Fed. Regist.* **77,** 49490–49600 (2012).
36. Executive Office of the President, T. The President's Climate Action Plan. 21 (2013).
37. Executive Office of the President, T. *Climate Action Plan -Strategy To Reduce Methane Emissions Executive Summary*. (2014). doi:10.1039/C3MH00098B
38. Whitehouse, T. FACT SHEET: Administration Takes Steps Forward on Climate Action Plan by Announcing Actions to Cut Methane Emissions. (2015). Available at: https://obamawhitehouse.archives.gov/the-press-office/2015/01/14/fact-sheet-administration-takes-steps-forward-climate-action-plan-anno-1. (Accessed: 28th February 2018)
39. Whitehouse, T. Reducing Methane Emissions in the Oil and Gas Sector. (2015).
40. Circuit, U. S. C. of A. for the D. of C. *WildEarth Guardians v. EPA*. **No. 13-121,** 1–13 (2014).
41. Allen, D. T. *et al.* Measurements of methane emissions at natural gas production sites in the United States. *Proc. Natl. Acad. Sci.* **110,** 17768–17773 (2013).
42. Allen, D. T. *et al.* Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers. (2015).
43. Allen, D. T. *et al.* Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Liquid Unloadings. *Environ. Sci. Technol.* **49,** 641–648 (2015).
44. Roscioli, J. R. *et al.* Measurements of methane emissions from natural gas gathering facilities and processing plants: Measurement methods. *Atmos. Meas. Tech.* **8,** 2017–2035 (2015).

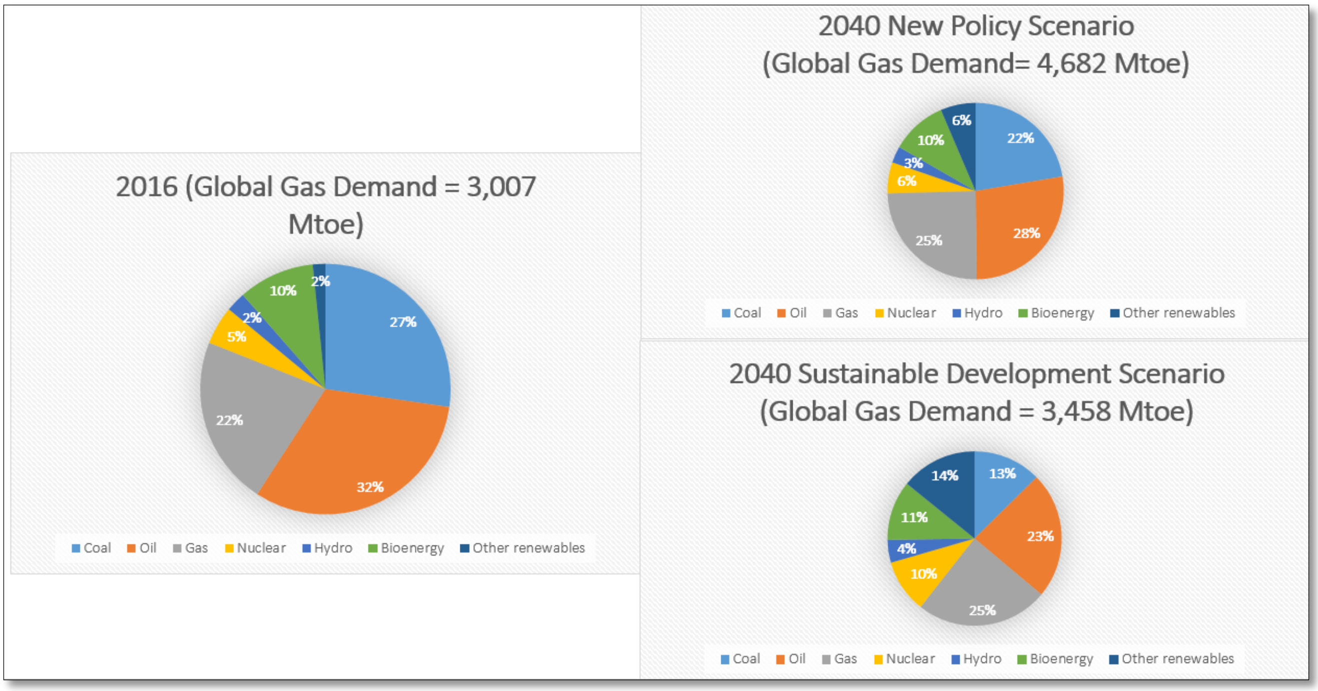
45. Mitchell, A. L. *et al.* Measurements of Methane Emissions from Natural Gas Gathering Facilities and Processing Plants-SI. *Environ. Sci. Technol.* **49,** 12602–12602 (2015).
46. Marchese, A. J. *et al.* Methane Emissions from United States Natural Gas Gathering and Processing. *Environ. Sci. Technol.* **49,** 10718–10727 (2015).
47. George, Fiji C.; Rufael, Tecle; Ryan, Vanessa; Krishna, Paul; Jersey, Gib; Sundararajan, Desikan; Lacey, P. Private-Public Partnership in Methane R&D - The Fayetteville Top-Down/Bottom-up Reconciliation Project. *Proc. 27th World Gas Conf. (in Prep.* (2018).
48. IBM. Smart sensors will detect environmental pollution at the speed of light. Available at: https://www.research.ibm.com/5-in-5/environmental-pollutants/.
49. Wethe, D. GE Drones Are Coming to Squeeze More Savings From the Oil Patch. *Bloomberg Markets* (2016). Available at: https://www.bloomberg.com/news/articles/2016-10-05/ge-drones-are-coming-to-squeeze-more-savings-from-the-oil-patch.
50. Coglianese, Cary, Jennifer Nash, and T. O. *Performance-Based Regulation: Prospects and Limitations in Health, Safety and Environmental Protection*. (2002).
51. Munnings, C. *et al. Comparing Policies to Reduce Methane Emissions in the Natural Gas Sector*. (2017).
52. Climate and Clean Air Coalition's Oil and Gas Methane Partnership (OGMP). *Oil & Gas Methane Partnership: First Year Report, Climate and Clean Air Coalition's Oil and Gas Methane Partnership (OGMP)*. (2016).
53. Climate and Clean Air Coalition's Oil and Gas Methane Partnership (OGMP). *Oil & Gas Methane Partnership: Second Year Report, Climate and Clean Air Coalition's Oil and Gas Methane Partnership (OGMP): Second-Year Report. Climate and Clean Air Coalition's Oil and Gas Methane Partnership (OGMP)*. (2017).
54. ICF International. *Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems*. (2016).
55. Allen, D. T. *et al.* Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers. 1–120 (2015).
56. Zimmerle, D. J. *et al.* Methane Emissions from the Natural Gas Transmission and Storage System in the United States. *Environ. Sci. Technol.* **49,** 9374–9383 (2015).
57. Marchese, A. J. *et al.* Methane emissions from United States natural gas gathering and processing-SI. *Environ. Sci. Technol.* (2015).
58. Brandt, A. R. et al. Methane Leaks from North American Natural Gas Systems. *Science (80-.).* **343,** 733–735 (2014).
59. Brandt, A. R., Heath, G. A. & Cooley, D. Methane Leaks from Natural Gas Systems Follow Extreme Distributions. *Environ. Sci. Technol.* **50,** 12512–12520 (2016).
60. Zavala-Araiza, D. *et al.* Reconciling divergent estimates of oil and gas methane emissions.

Proc. Natl. Acad. Sci. 201522126 (2015). doi:10.1073/pnas.1522126112

61. Environmental Defense Fund President Fred Krupp on the Benefits and Risks of Fracking ... Page 1 of 1 dea Bl. 2014 (2014).
62. EPA, U. The Methane Challenge Program. Available at: https://www.epa.gov/natural-gas-star-program/methane-challenge-program. (Accessed: 1st March 2018)
63. Natural Gas STAR Methane Challenge Program : Supplementary Technical Information for ONE Future Commitment Option. 1–39
64. Heath, G., Warner, E., Steinberg, D. & Brandt, A. Estimating U.S. Methane Emissions from the Natural Gas Supply Chain. Approaches, Uncertainties, Current Estimates, and Future Studies. (2015). doi:10.2172/1226158
65. Timothy J. Skone, J. L. *et al. INDUSTRY PARTNERSHIPS AND THEIR ROLE IN REDUCING NATURAL GAS SUPPLY CHAIN GREENHOUSE GAS EMISSIONS. National Energy TechnologyLaboratory (NETL). , DOE Contract Number DE-FE0025912*. (2018).
66. EPA, U. *40 CFR 60, Standards of Performance for New Stationary Sources; VOC Fugitive Emission Sources; Synthetic Organic Chemicals Manufacturing Industry, Federal Register, Volume 46, No. 2, January 5, 1981*. 1136–1165 (1981).
67. EPA. *40 CFR Parts 60, 63 and 65; Alternative Work Practice to Detect Leaks from Equipment, Federal Register, Volume 73, No. 246, December 22, 2008, pages 78199-78219*. (2008).
68. US EPA. EPA VOC Fugitive Emissions from Petroleum Refining Industry- Background Information for Proposed Standards, Draft EIS. EPA-450/3-81-015a. Table F-9, page F-18.
69. EPA. *Background Technical Support Document for the Proposed New Source Performance Standards 40 CFR Part 60, subpart OOOOa*. (2015).
70. Richard Hyde (ONE Future Coalition, I. . *ONE Future Comments Regarding General Operating Permit for Unconventional Natural Gas Well Site Operations (GP-5A)*. (2017).
71. Ravikumar, A. P. & Brandt, A. R. Designing better methane mitigation policies: The challenge of distributed small sources in the natural gas sector. *Environ. Res. Lett.* **12,** (2017).

Supplemental Information (SI)

S.1. Natural Gas Demand under future carbon constrained scenarios (IEA, World Energy Outlook 2017)



Global gas demand under the IEA's New Policy Scenario (NPS)[14] is projected to increase at a compound average annual growth rate (CAAGR) of 1.6% from 2016 to 2040. Under a more stringent carbon constrained scenario, the Sustainable Development Scenario (SDS)[15], the growth of natural gas is about 0.6%. Natural gas becomes the largest or one of the largest energy source to meet the global demand under the NPS and SDS highlighting the importance of natural gas as a foundational fuel in the transition to a lower carbon global economy.

S.2. Methane Intensity Leakage Calculation

The Methane intensity was computed using the ONE Future Methane Intensity Protocol[16] employing co-allocation techniques to account for associated natural gas from oil wells that are part of the US total gross natural gas production and 2017 GHGI.

[14] The ***New Policies Scenario*** (NPS) aims to provide a sense of the direction of energy supply and demand based on policies and measures that governments around the world have already put in place, including policy intentions from the Nationally Determined Contributions of the Paris Agreement
[15] The ***Sustainable Development Scenario*** (SDS) is a new scenario introduced in the WEO 2017 and incorporates an integrated strategy for achieving climate and energy security benefits.
[16] http://www.onefuture.us/wp-content/uploads/2016/08/ONE-Future-Methane-Intensity-Protocol-v-1-2016.pdf, Appendix C

Table S.2.1: Allocation of Methane Emissions from Petroleum Systems to Natural Gas (NG) systems (Source: ONE Future, 2018)

Parameter	Value	Units	Comments/Source
2015 Gas Production from oil wells	6,452,680	mmscf	EIA , Natural Gas Summary
BTU equivalent of raw gas production from oil wells	7,969,059,800	MMBtu	Used raw natural gas heating value of 1235 Btu/scf from API Compendium Table 3-8
2015 Crude Oil Production	3,434,023	k bbl	EIA, Crude Oil Production
Btus equivalent from oil wells	19,917,333,400	MM btus	Used crude oil heating value of 5.8 MMBtu/bbl from API Compendium Table 3-8
2015 Lease Condensate Production	323	mm bbl	EIA, Lease Condensate Production
Btus from Condensate production	1,873,400,000	MMBtus	Used crude oil heating value of 5.8 MMBtu/bbl from API Compendium Table 3-8
Ratio on an energy equivalent basis (Total gas from oil wells/(Total Crude-Lease Condensate+Total gas from oil wells))	30.6%		In other words, 30.6% of the emissions from oil wells need to be attributed to gas value chain, the rest resides with the oil value chain

Table S.2.2: Allocation of Methane Emissions from Natural Gas Systems (Condensate) to Petroleum systems (Source: ONE Future, 2018)

Parameter	Value	Units	Comments/Source
2015 Gross Natural Gas Withdrawls less Gas from Oil Wells	26,442,047	MMscf	EIA , Natural Gas Summary
BTU equivalent of produced gas	32,655,928,045	MMBtu	Used raw natural gas heating value of 1235 Btu/scf from API Compendium Table 3-8
2015 Lease Condensate Production	323	mm bbl	EIA, Lease Condensate Production
Btus from Condensate production	1,873,400,000	MMBtus	Used crude oil heating value of 5.8 MMBtu/bbl from API

			Compendium Table 3-8
			-
Ratio on an energy equivalent basis (Energy from condensate/(Energy from natural gas production excluding gas from oil wells))	5.43%		Assign 5.43% of emissions from Natural Gas segment to the Petroleum segment

Table S.2.3: Allocation of Methane Emissions from Natural Gas Systems (natural gas liquids (NGLs)) to Petroleum systems (Source: ONE Future, 2018)

			Source/Comment
2015 Total NG Processed	20,626,443	MMscf	EIA, Natural Gas Summary
BTU equivalent of processed gas	21,038,971,860	MMBtu	Used processed natural gas heating value of 1020 Btu/scf from API Compendium Table 3-8
2015 NGPL Equivalent	1,693,432	MMscf	
BTU equivalent of NGPL	4,260,674,912	MMBtu	Used propane gas heating value of 2516 Btu/scf from API Compendium Table 3-8
Ratio on an energy equivalent basis (Energy from NGPL/(Energy from NGPL + Energy from Processed Gas)	16.84%		Subtract 16.84% of emissions from Gas Processing due to processing liquid streams
Net Processing CH4 Emissions	444,837	tonnes CH4	
Allocated Net Processing CH4 Emissions	369,923	tonnes CH4	

Table S.2.3.: Co-Allocation of Methane Emissions[17] between Natural Gas Systems and Petroleum systems (Source: ONE Future, 2018)

	Natural Gas Systems	**Petroleum Systems**	
Emission Allocation for Production/Gathering	**Net GHGI Emissions, tonnes CH4**	**Net GHGI Emissions, tonnes CH4**	**Comments**
Vented Sources			

[17] 2015 Greenhouse Gas Inventory (US EPA, April 2017)

Gas Well Completions and Workovers with HF	25,135		Assumes 5.43% is allocated to condensate produced from gas wells (94.57% is allocated to the Natural Gas Value Chain)
Gas Well Completions and Workovers w/out HF	250		Assumes 5.43% is allocated to condensate produced from gas wells
Oil Well Completion Venting		18	Assumes 30.6% is allocated to gas produced from oil wells
Oil Well Workovers		25	Assumes 30.6% is allocated to gas produced from oil wells
Stripper Wells		-	Assumes 30.6% is allocated to gas produced from oil wells
Liquids unloading with plunger lifts	114,126		Assumes 5.43% is allocated to condensate produced from gas wells
Liquids unloading without plunger lifts	83,665		Assumes 5.43% is allocated to condensate produced from gas wells
Pneumatic Device Vents	964,893	228,331	Assumes 5.43% is allocated to condensate produced from gas wells and 30.6% is allocated to gas produced from oil wells
Chemical Injection Pumps	114,811	24,734	Assumes 5.43% is allocated to condensate produced from gas wells and 30.6% is allocated to gas produced from oil wells
Dehydrator Vents	14,154		100% is allocated to gas
Kimray Pumps	43,408		100% is allocated to gas
Tank Flashing Losses	22,177	22,820	Assumes 5.43% is allocated to condensate produced from gas wells and 30.6% is allocated to gas produced from oil wells
Malfunctioning separator dump valves	53	1,833	Assumes 5.43% is allocated to condensate produced from gas wells and 30.6% is allocated to gas produced from oil wells
Associated gas venting		13,026	Assumes 30.6% is allocated to gas produced from oil wells

Acid Gas Removal Units	-		
Well Drilling	603		Assumes 5.43% is allocated to condensate produced from gas wells
Vessel Blowdowns	380	171	Assumes 5.43% is allocated to condensate produced from gas wells and 30.6% is allocated to gas produced from oil wells
Pipeline Blowdowns	1,580		Assume 100% is associated with gas
Compressor Blowdowns	1,569	225	Assume 100% is associated with gas
Compressor Starts	4,919	504	Assume 100% is associated with gas
Pressure Relief Valve Vents	432	59	Assumes 5.43% is allocated to condensate produced from gas wells and 30.6% is allocated to gas produced from oil wells
Mishaps	855	874	Assumes 5.43% is allocated to condensate produced from gas wells and 30.6% is allocated to gas produced from oil wells
Gathering and Boosting Stations	2,163,417		Assume 100% is associated with gas
Produced water from coal bed methane - Black Warrior	8,303		Assume 100% is associated with gas
Produced water from coal bed methane - Powder River	31,220		Assume 100% is associated with gas
Offshore Platforms (GoM and Pacific)	92,475	57,472	Assumes 5.43% is allocated to condensate produced from gas wells and 30.6% is allocated to gas produced from oil wells
Fugitive Sources			
Well site fugitive emissions	166,597	34,840	Assumes 5.43% is allocated to condensate produced from gas wells. Assumes 30.6% of Petroleum System emissions are allocated to gas produced from oil wells
Centrifugal compressors	-		Assume 100% is associated with gas
Reciprocating Compressors	42,949	2,177	Assume 100% is associated with gas
Pipeline Leaks		0	Assume 100% is

	161,559		associated with gas
Combustion Sources			
Compressor Exhaust	112,764	90,197	Assume 100% is associated with gas
Heaters		10,584	Assumes 30.6% is allocated to gas produced from oil wells
Well drilling engines		257	Assumes 30.6% is allocated to gas produced from oil wells
Associated gas flaring		32,383	Assumes 30.6% is allocated to gas produced from oil wells
Flaring		-	Replaced with associated gas flaring
Sector Totals	4,172,294	520,531	
Total Tonnes CH4	**4,692,824**		

Table S.2.4.: Summary of methane emissions from Natural Gas Systems (co-allocated) (Source: ONE Future, 2018)

2015 CH4 Emissions						
	Gg CH4	Gmol CH4	10^9 SCF CH4	MMSCF CH4	MMSCF of natural gas	TCF of natural gas
Production (includes petroleum and condensate allocations)	**4,692.82**	**293.3**	**244.82**	**244,818**	**296,031**	**0.296**
Processing (adjusted for NGPL)	**369.92**	**23.1**	**19.30**	**19,298**	**22,182**	**0.022**
Transmission and Storage	**1,349.35**	**84.3**	**70.39**	**70,394**	**75,368**	**0.075**
Distribution	**439.06**	**27.4**	**22.90**	**22,905**	**24,523**	**0.025**
Total	**6,851.16**	**428.20**	**357.41**	**357,415**	**418,105**	**0.4181**

Table S.2.5.: Methane Leakage Rates from Production Segment (co-allocated) based on 2015 GHGHI (April 2017) (Source: ONE Future, 2018)

Production **Quantity**	**Value**	**Unit**	
EPA estimated leakage from production	0.296	TCF NATURAL GAS	
	4692.8	Gg CH4	Includes net Natural Gas Systems emissions + Allocation of petroleum emissions - Allocation of condensate production emissions
	0.245	TCF CH4	
Total Gross Gas Withdrawals	32.9	TCF NATURAL GAS	
CH4 Gross Withdrawals (mass basis)	521,463	Gg CH4	
CH4 Gross Withdrawals (volume basis)	27.2	TCF CH4	
Volumetric percentage leakage			
- Leakage as % of throughput of stage	0.90%	TCF gas/TCF gas	
- Leakage as % of gross withdrawals	0.90%	TCF CH4/ TCF CH4	
Mass percentage leakage			
- Leakage as % of gross CH4 withdrawals	0.90%	Gg/Gg	

Table S.2.6.: Methane Leakage Rates from Processing Segment (co-allocated) based on 2015 GHGHI (April 2017). (Source: ONE Future, 2018)

Gas processing **Quantity**	**Value**	**Unit**
EPA estimated leakage from processing	0.022	TCF NG
(Adjusted emissions from Processing attributed to NG)	369.9	Gg CH4
Gas Processed	20.6	TCF Gas
	343,981	Gg CH4
Volumetric percentage leakage		
- Leakage as % of throughput of stage	0.108%	TCF/TCF
- Leakage as % of gross withdrawals	0.067%	TCF/TCF
Mass percentage leakage		
- Leakage as % of gross CH4 withdrawals	0.071%	Gg/Gg

Table S.2.7.: Methane Leakage Rates from Transmission & Storage Segment based on 2015 GHGHI (April 2017). (Source: ONE Future, 2018)

Transmission and storage **Quantity**	**Value**	**Unit**
EPA estimated leakage from T&S	0.075	TCF NG
	1349.4	Gg CH_4
Dry Gas Production (Gas Transmitted)	27.1	TCF NG
Net Imports	0.9	TCF NG
Gas Transmitted + Net Imports	28.0	TCF NG
	501,192	Gg CH_4
Volumetric percentage leakage		
- Leakage as % of throughput of stage	0.269%	TCF/TCF
- Leakage as % of gross withdrawals	0.229%	TCF/TCF
Mass percentage leakage		
- Leakage as % of gross CH_4 withdrawals	0.259%	Gg/Gg

Table S.2.8.: Methane Leakage Rates from Distribution Segment based on 2015 GHGHI (April 2017). (Source: ONE Future, 2018)

Distribution		
Quantity	**Value**	**Unit**
EPA Natural gas system boundary		
EPA estimated leakage from distribution	0.025	TCF
	439.1	Gg CH4
Gas Distributed	15.0	TCF NG
	268,584	Gg CH4
Volume of gas delivered by LDCs to Consumers (AGA)		
Volumetric percentage leakage		
- Leakage as % of throughput of stage	0.16%	TCF/TCF
- Leakage as % of gross withdrawals	0.07%	TCF/TCF
Mass percentage leakage		
- Leakage as % of gross CH4 withdrawals	0.16%	Gg/Gg

Table S.2.9.: Total Methane Leakage Rates from Natural Gas Systems based on 2015 GHGHI (April 2017)

Sector	Mass % of Gross Prod (CH4 based)	Vol % of Gross Prod (CH4 based)	Vol % of Througput of each Segment (nat gas volume based)	Throughput Volume (tcf)	Throughput Volume (Gg CH4)	Emissions, Gg CH4	Emissions, Tcf Gas
Production & Gathering	0.90%	0.90%	0.90%	32.9	521,463	4692.8	0.296
Processing	0.07%	0.07%	0.11%	20.6	343,981	369.9	0.022
Transmission & Storage	0.26%	0.23%	0.27%	28.0	501,192	1349.4	0.075
Distribution	0.16%	0.07%	0.16%	15.0	238,704	439.1	0.025
Methane Leakage Rate =	1.39%	1.27%					

SI-3 Scientific Methane Emissions Studies Supported by SWN

1. Allen, D. T. *et al.* Measurements of methane emissions at natural gas production sites in the United States. *Proc. Natl. Acad. Sci.* **110,** 17768–17773 (2013).

2. Allen, D. T. *et al.* Methane emissions from process equipment at natural gas production sites in the United States: liquid unloadings. *Env. Sci Technol* **49,** 641–648 (2014).

3. Allen, D. T. *et al.* Methane Emissions from Process Equipment at Natural Gas Production Sites in the United States: Pneumatic Controllers. 1–120 (2015).

4. Austin L. Mitchell, Daniel S. Tkacik, Joseph R. Roscioli, Scott C. Herndon, Tara I. Yacovitch, David M. Martinez, Timothy L. Vaughn, Laurie L. Williams, Melissa R. Sullivan, Cody Floerchinger, Mark Omara, R. Subramanian, Daniel Zimmerle, Anthony J. Marche, and A. L. R. Measurements of methane emissions from natural gas gathering facilities and processing plants: Measurement methods. *Environ. Sci. Technol.* **49,** 3219–3227 (2015).

5. Mitchell, A. L. *et al.* Measurements of Methane Emissions from Natural Gas Gathering

Facilities and Processing Plants-SI. *Environ. Sci. Technol.* **49,** 12602–12602 (2015).

6. Marchese, A. J. *et al.* Methane emissions from United States natural gas gathering and processing-SI. *Environ. Sci. Technol.* (2015).

7. ICF International. *Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems*. (2016).

8. Conley, S. *et al.* Application of Gauss's theorem to quantify localized surface emissions from airborne measurements of wind and trace gases. *Atmos. Meas. Tech.* **10,** 3345–3358 (2017).

9. Zimmerle, D. *et al.* Reconciling Top-down and Bottom-up Methane Emission Estimates from Onshore Oil and Gas Development in Multiple Basins : Report on Fayetteville Shale Study. (2016).

10. Schwietzke, S. *et al.* Improved Mechanistic Understanding of Natural Gas Methane Emissions from Spatially Resolved Aircraft Measurements. *Environ. Sci. Technol.* **51,** 7286–7294 (2017).

11. Timothy L. Vaughn; Clay S. Bell; Tara I. Yacovitch; Joseph R. Roscioli;, Heath;, S. C. H. S. C. S. S. G. A. & Zimmerle, G. P. D. Temporal Variability Largely Explains Difference in Top- down and Bottom-up Estimates of Methane Emissions from a Natural Gas Production Region. *Manuscr. Prep.* (2018).

12. Daniel J. Zimmerle , Cody K. Pickering, Clay S. Bell, Garvin A. Heath, Dag Nummedal, Gabrielle Pétron, T. L. V. Gathering pipeline methane emissions in Fayetteville shale pipelines and scoping guidelines for future pipeline measurement campaigns. *Elem Sci Anth.* **5,** 70 (2017).

13. Bell, C. S. *et al.* Comparison of methane emission estimates from multiple measurement techniques at natural gas production pads. *Elem. Sci. Anthr.* **5,** (2017).

14. Tara I. Yacovitch , Conner Daube, Timothy L. Vaughn, Clay S. Bell, Joseph R. Roscioli, W. Berk Knighton, David D. Nelson, Daniel Zimmerle, Garbielle Pétron, S. C. H. Natural gas facility methane emissions: measurements by tracer flux ratio in two US natural gas producing basins. *Elem Sci Anth* **5,** 69 (2017).

15. Robertson, A. M. *et al.* Variation in Methane Emission Rates from Well Pads in Four Oil and Gas Basins with Contrasting Production Volumes and Compositions. *Environ. Sci. Technol.* **51,** 8832–8840 (2017).

16. Stefan Schwietzke, Matthew Harrison, Terri Lauderdale, Ken Branson, Stephen Conley, Fiji C. George, Doug Jordan, Gilbert R. Jersey, Changyong Zhang, Heide L. Mairs, Gabrielle Pétron, R. C. S. Aerially-guided leak detection and repair: A pilot field study for evaluating the potential of methane emission detection and cost-effectiveness. *Submitt. Manuscr.* (2018).

17. George, Fiji C.; Rufael, Tecle; Ryan, Vanessa; Krishna, Paul; Jersey, Gib; Sundararajan, Desikan; Lacey, P. Private-Public Partnership in Methane R&D - The Fayetteville Top-Down/Bottom-up Reconciliation Project. *World Gas Conf. (in Prep.* (2018).

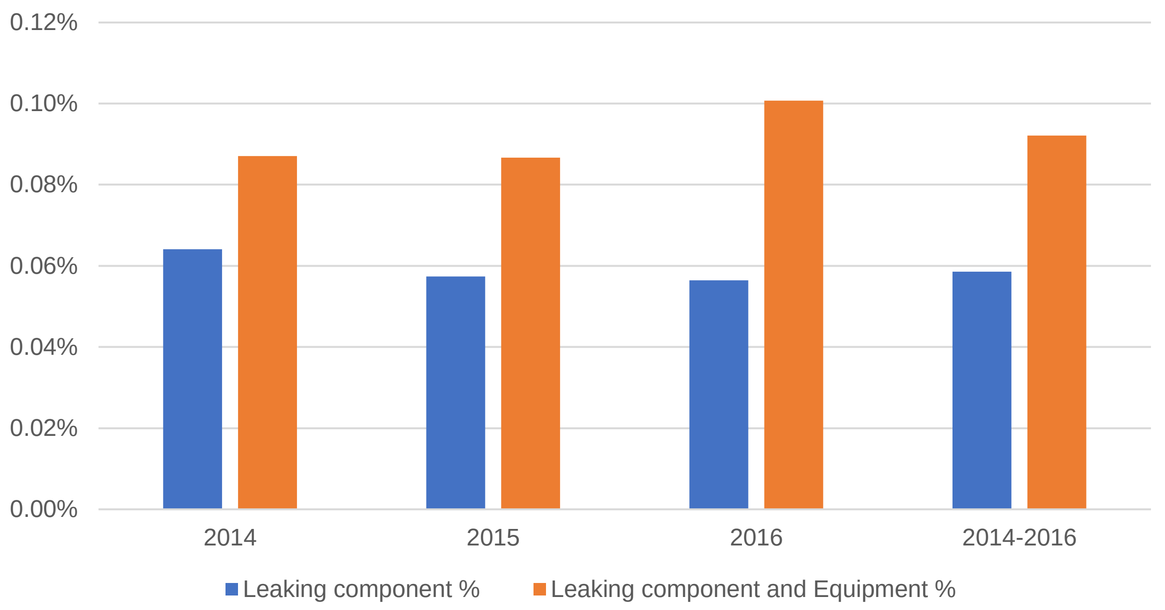
18. George, F. C. Rising to the Methane Challenge – A Synopsis of the Evolution of Corporate and National Methane Policy. *World Gas Conf. (in Prep.* (2018).

SI.4: SWN Smart LDAR

Components such as valves, flanges, connectors, open ended lines, regulators, gauges, pump seals, and "other" similar equipment in which gas is identified to be leaking based on an AVO leak survey or an instrument leak detection survey. These are traditionally considered fugitive emissions sources as the leak is not vented through a pipe or vent. “Other” includes regulators, gauges, rod packing, sight glasses, drip pots, and other items not covered by component categories.

Leaking equipment includes reciprocating compressor rod packing’s, tank thief hatches chemical injection pumps, pneumatic controllers and other similar equipment which are not operating properly or are malfunctioning (e.g. open thief hatch, stuck dump valve, leaking rod packing seals)as identified by an AVO leak survey or an instrument leak detection survey. During routine operations, these sources may release gas, by operational design and are not considered leaking equipment.

Figure S-1: Leaking component and Equipment Fraction (Production)



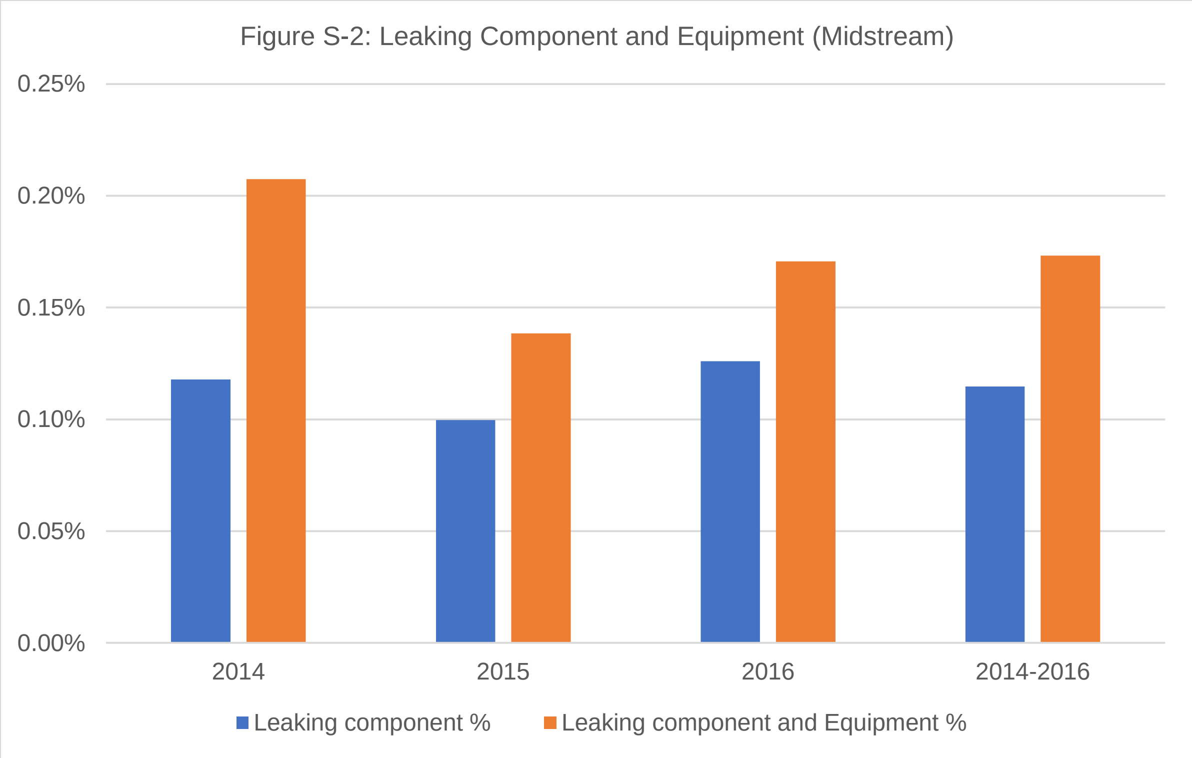


Figure S-2: Leaking Component and Equipment (Midstream)
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
2014
2015
2016
2014-2016
Leaking component %
Leaking component and Equipment %

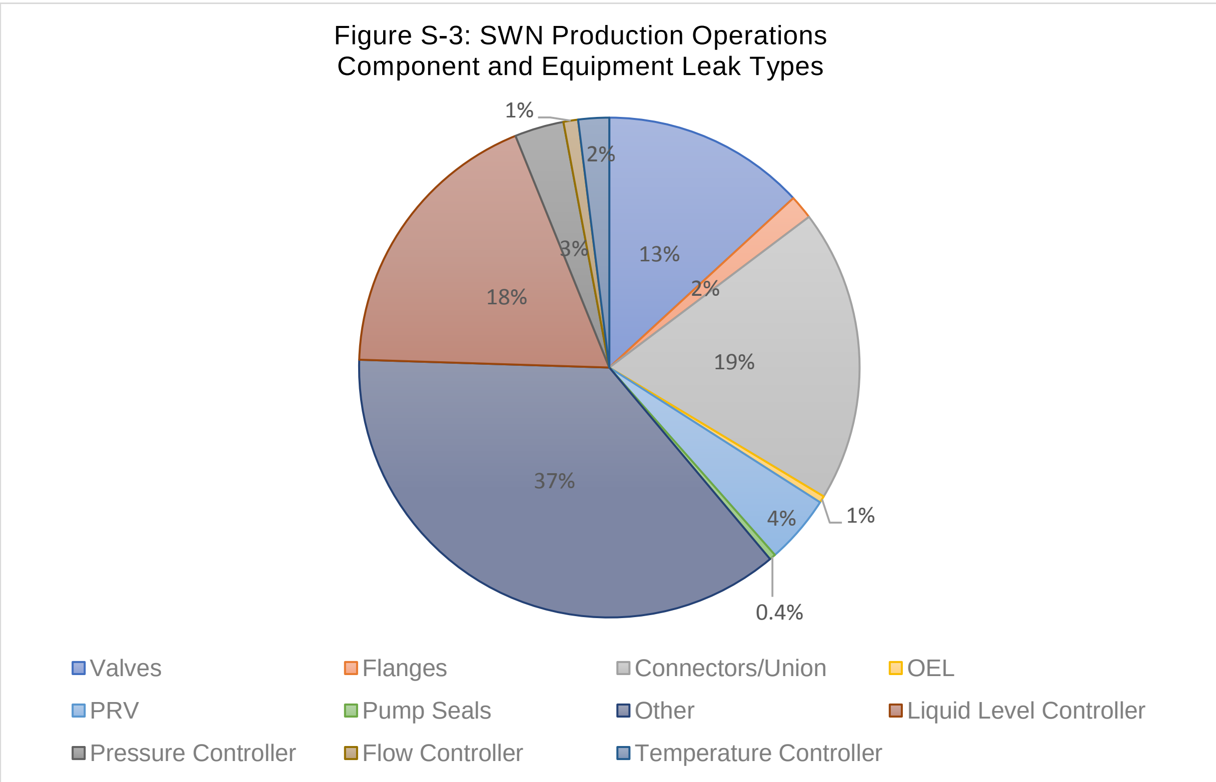


Figure S-3: SWN Production Operations
Component and Equipment Leak Types
1%
2%
13%
2%
3%
18%
19%
37%
4%
1%
0.4%
Valves
Flanges
Connectors/Union
OEL
PRV
Pump Seals
Other
Liquid Level Controller
Pressure Controller
Flow Controller
Temperature Controller

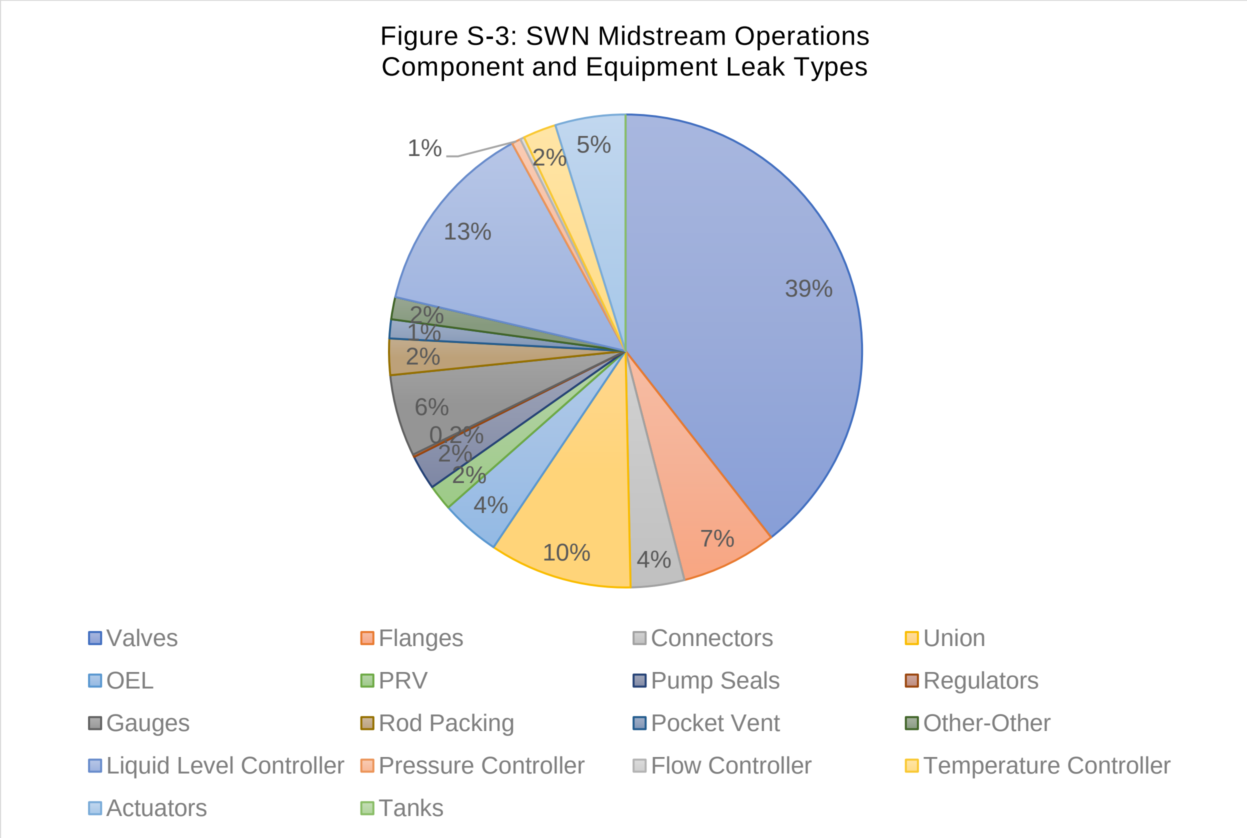


Figure S-3: SWN Midstream Operations
Component and Equipment Leak Types
39%
7%
4%
10%
4%
2%
2%
0.2%
6%
2%
1%
2%
13%
1%
2%
5%
Valves
Flanges
Connectors
Union
OEL
PRV
Pump Seals
Regulators
Gauges
Rod Packing
Pocket Vent
Other-Other
Liquid Level Controller
Pressure Controller
Flow Controller
Temperature Controller
Actuators
Tanks

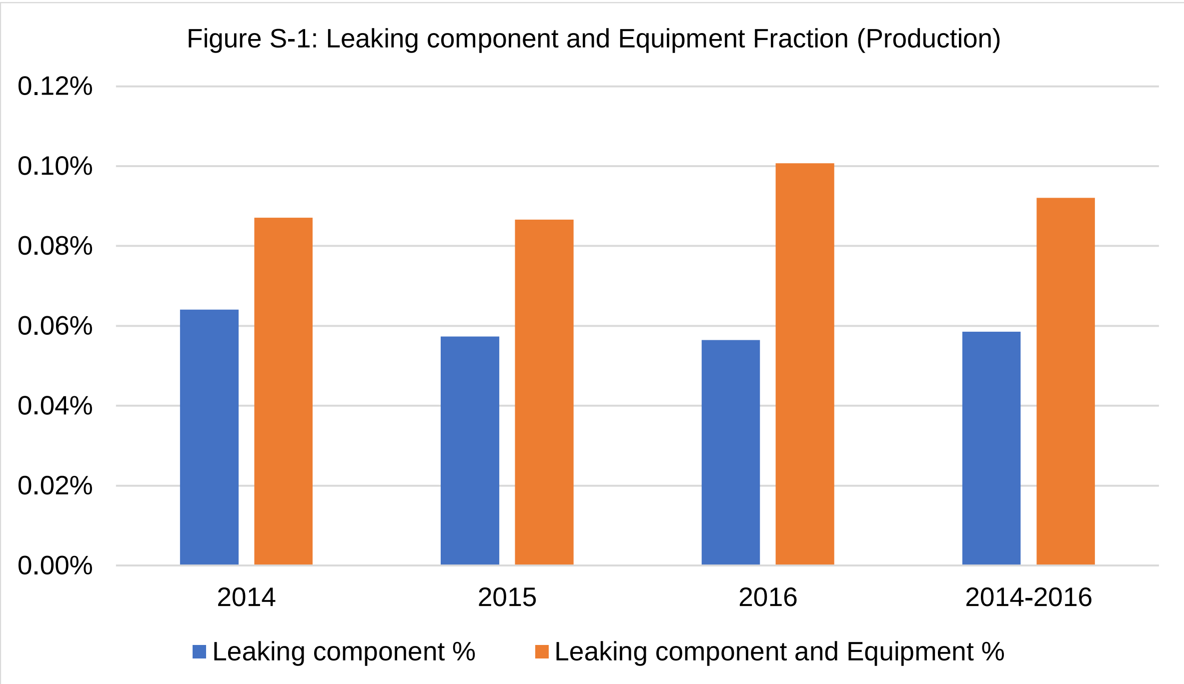


Figure S-1: Leaking component and Equipment Fraction (Production)
0.12%
0.10%
0.08%
0.06%
0.04%
0.02%
0.00%
2014
2015
2016
2014-2016
Leaking component %
Leaking component and Equipment %

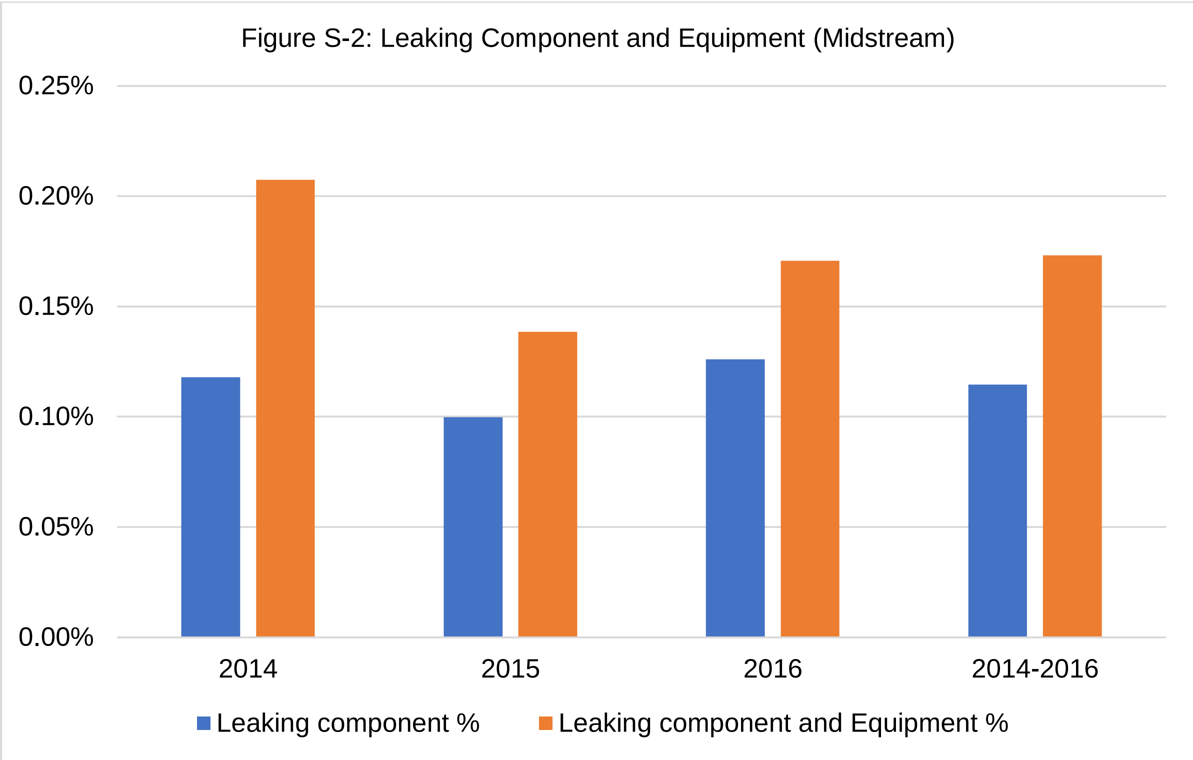


Figure S-2: Leaking Component and Equipment (Midstream)
0.25%
0.20%
0.15%
0.10%
0.05%
0.00%
2014
2015
2016
2014-2016
Leaking component %
Leaking component and Equipment %

Figure S-3: SWN Production Operations Component and Equipment Leak Types

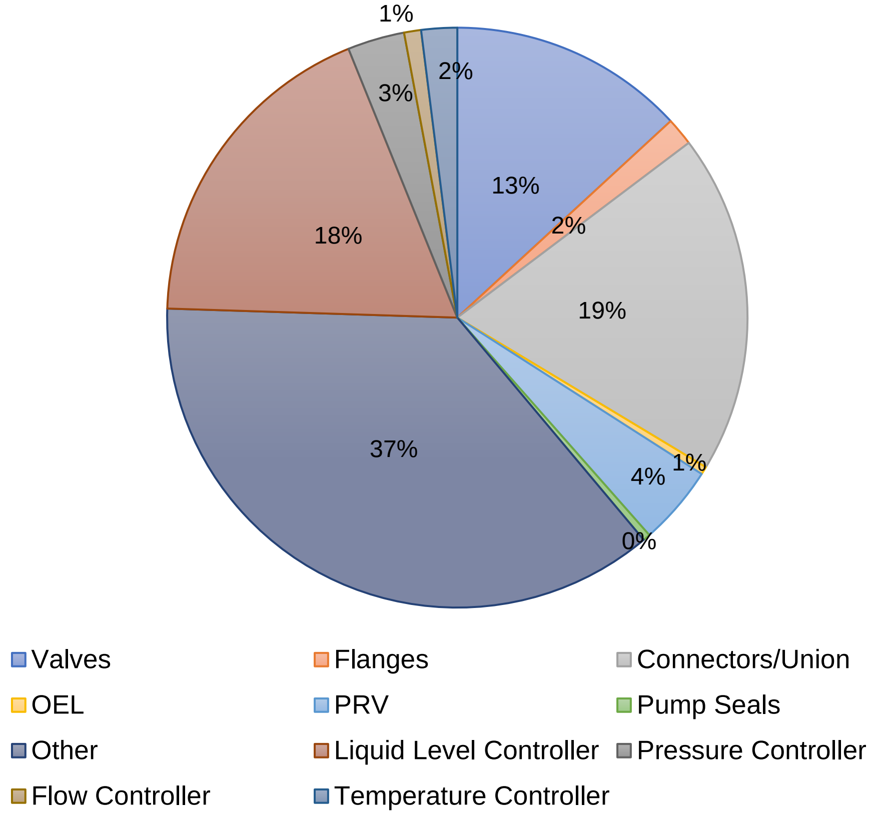


Table S1- Component: Production	2014-2016 Average HiFlow Rates (methane kg/hr)
Valves	0.24
Flanges	0.92
Connectors/Union	0.32
OEL	0.12
PRV	0.51
Pump Seals	0.03
Other*	0.36
*Other includes regulators, gauges, rod packing, sight glasses, drip pots, and other items not covered by component categories. Does not include storage tank hatches	

Table S2: Equipment: Production	2014-2016 Average HiFlow Rates (methane kg/hr)
LL Controller	0.29
Pressure	0.21
Flow	0.27
Temperature	0.16
Tanks	0.33

Table S3: Component: G&B	2014-2016 Average HiFlow Rates (methane kg/hr)
Valves	0.6
Flanges	0.3
Connectors	0.3
Union	0.4
OEL	0.5
PRV	0.8
Pump Seals	0.7
Regulators	0.3
Gauges	0.6
Rod Packing	7.3
Pocket Vent	0.2
Other-Other	0.4

Table S4: Equipment: G&B	2014-2016 Average HiFlow Rates (methane kg/hr)
LL Controller	1.3
Pressure	0.1
Flow	0.4
Temperature	0.2
Actuators	0.4