Marginal Abatement Cost for Methane Emissions Reductions

among ONE Future Members in the US Natural Gas Supply Chain

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Commissioned by:
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Executive Summary

ES.1. Purpose and Scope

The purpose of this study is to identify cost-effective emission reduction and abatement opportunities in light of the industry's current infrastructure as well as new and emerging technologies for detecting, measuring, and abating methane emissions. This study is intended to characterize the reduction effectiveness and costs for various mitigation technologies or measures, and how those technologies could be used to further reduce emissions across ONE Future member operations. The results of the study in combination with other information sources are meant to help inform ONE Future and its members in future efforts to collect additional emission data, formulate innovative emission reduction tactics and set revised targets.

ES.2. Methodology

This study consists of several major steps which characterize current emission volumes and sources and quantify abatement volumes at various cost levels. The study utilizes a series of spreadsheet models that contain historical 2023 and projected 2030 activity and emissions data for ONE Future members. The models compute the abatement volumes achievable under the costs and reduction effectiveness assumed for the mitigation measures that are most relevant to each industry segment and source. The spreadsheet models then produce marginal abatement cost (MAC) curves showing what portion of the baseline emissions in each industry segment can be abated at various cost levels.

The overall methodology used in this study is described below:

1. **Compile and organize activity and emission data:** ICF compiled or estimated activity and methane emissions data for ONE Future members for the base year 2023 and projected the same kind of data for the year 2030. The data sources, methodology, and results of these work items are presented in **Chapter 2**.
2. **Characterize costs and performance of methane mitigation technologies**: ICF collected and reconciled capital and operating cost data and performance measures of methane mitigation technologies that could best mitigate the methane emission sources with the largest current emission volumes. The work efforts related to technology costs and performance for leak detection and repair (LDAR) as well as vented and combustion related measures are discussed in more detail in the later chapters of this report.
3. **Estimate the economics of each mitigation option:** ICF created and ran models to evaluate the cost effectiveness of each mitigation technology if it were applied to specific sources in each industry segment. The results were per-unit abatement cost denominated in dollars per thousand cubic feet of abated methane or \$/Mcf CH_4. This included LDAR programs intended to detect fugitive emissions and repair or replace equipment causing those leaks. The gross cost effectiveness of the activity is computed as the present value of capital and O&M costs divided by the present value of the abated methane volumes measured in thousand standard cubic feet (Mscf). For activities in the

production segment which are capable of capturing gas, those costs can also be expressed on a net basis, represented as the gross cost minus the $/Mscf value of the recovered gas.

4. **Construct marginal abatement cost (MAC) curves:** ICF then used these abatement cost estimates -- along with the associated abatement volumes -- to construct MAC curves. Each mitigation option was sorted from the lowest per-unit cost to the highest cost in order to create the MAC curve. Each MAC curve shows the cumulative amount of methane abated (in units of annual metric tons) along the x-axis and the marginal cost in units of $/Mcf CH_4 along the y-axis.

More detail on the methodology and results of this study is included in the main report.

ES.3. Summary of Analytic Results

This study provides a MAC curve result for each industry segment/region in both 2023 and 2030 considering current ONE Future Protocol data ("Current Protocol"). The analysis also includes two cases for which baseline emission estimates were adjusted to reflect announced revisions to EPA's Greenhouse Gas Reporting Program (GHGRP) Subpart W regulation. In total, there are results provided representing four main cases:

1. Emissions from current ONE Future members in the year 2023 as estimated under the current ONE Future Protocols.
2. Projected emissions from current ONE Future members in the year 2030 estimated under the current ONE Future Protocols.
3. Emissions from current ONE Future members in the year 2023 re-calculated using a revised protocol that incorporates certain expected changes to EPA's GHGRP Subpart W rules.
4. Emissions from current ONE Future members in the year 2030 re-calculated using a revised protocol that incorporates certain expected changes to EPA's GHGRP Subpart W rules.

More detail on each of these cases and how they have been developed is discussed in both **Chapter 1** and **Chapter 3**. The key findings for all four cases are provided below.

ES.3.1. Overall Key Findings and Aggregated MAC Curves

The three exhibits found below provide MAC curve results for the four main cases analyzed in this study. Each exhibit displays a curve result for all cases with the x-axis indicating cumulative annual metric tons of methane abated and a y-axis showing the $/Mcf of CH_4 for the cumulative mitigation amount. To generate each curve, all mitigation options were sorted from the lowest per-unit cost to the highest cost. Options were included in the MAC curve only if they resulted in higher abatement volumes than were obtained by the lower-cost options already placed into the curve.

The MAC curve results provided in this section are also shown broken out by type of emission source. Exhibit 1 represents fugitive emission sources whose baseline emissions are reduced through leak detection and repair programs. Exhibit 2 contains potential abatement volumes related to process venting or methane released through incomplete fuel combustion (known as methane slip). Finally, Exhibit 3 combines results from all emission sources and all mitigation technologies.

Generally speaking, 2023 and 2030 results in the Current Protocol Cases are similar. The differences between these two cases result from changed assumptions regarding the activity levels and emission parameters expected between 2023 and 2030. These parameters were adjusted for 2030 to reflect expectations for a larger overall US natural gas market size, shifts in the regional mix of US gas supplies and consumption, declines in miles of iron and steel distribution mains and a corresponding increase in plastic miles, and reduced use of pneumatic devices which emit methane. The 2030 curves are based on the same technology performance and cost assumptions as were used for the year 2023.

A greater volume of methane reduction can be achieved in the Revised Subpart W Cases (in both the 2023 and 2030) due to the higher volume of baseline methane emissions. The larger baseline volumes usually result in a greater volume of mitigation for any given abatement effort, thus, reducing its per-unit cost.

Exhibit 1: All-Segment LDAR MAC Curves for the Four Main Study Cases

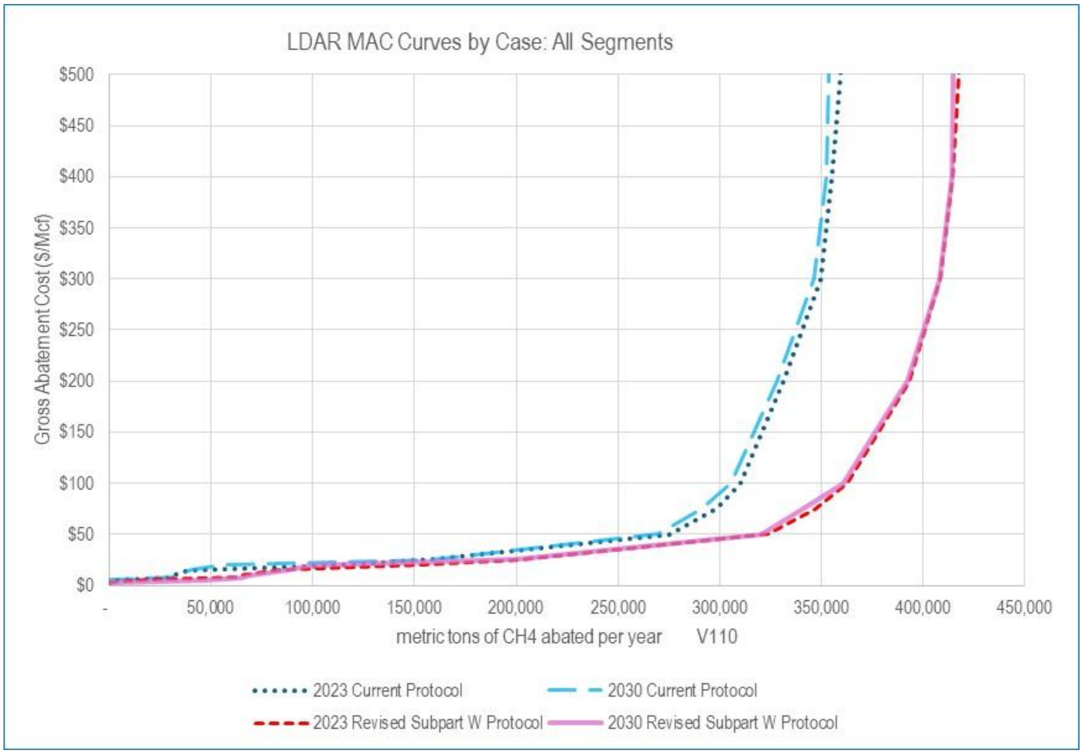

Exhibit 2: All-Segment Vented and Combustion-related MAC Curves for the Four Main Study Cases

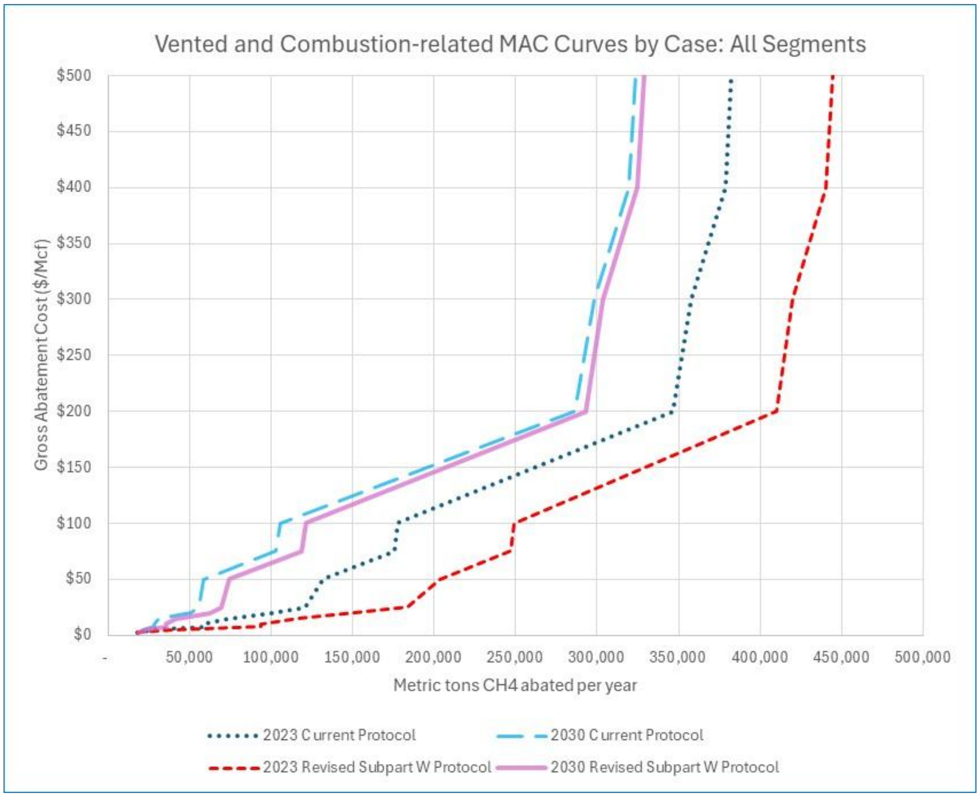

Exhibit 3: All-Segment MAC Curves for the Four Main Study Cases, All Sources

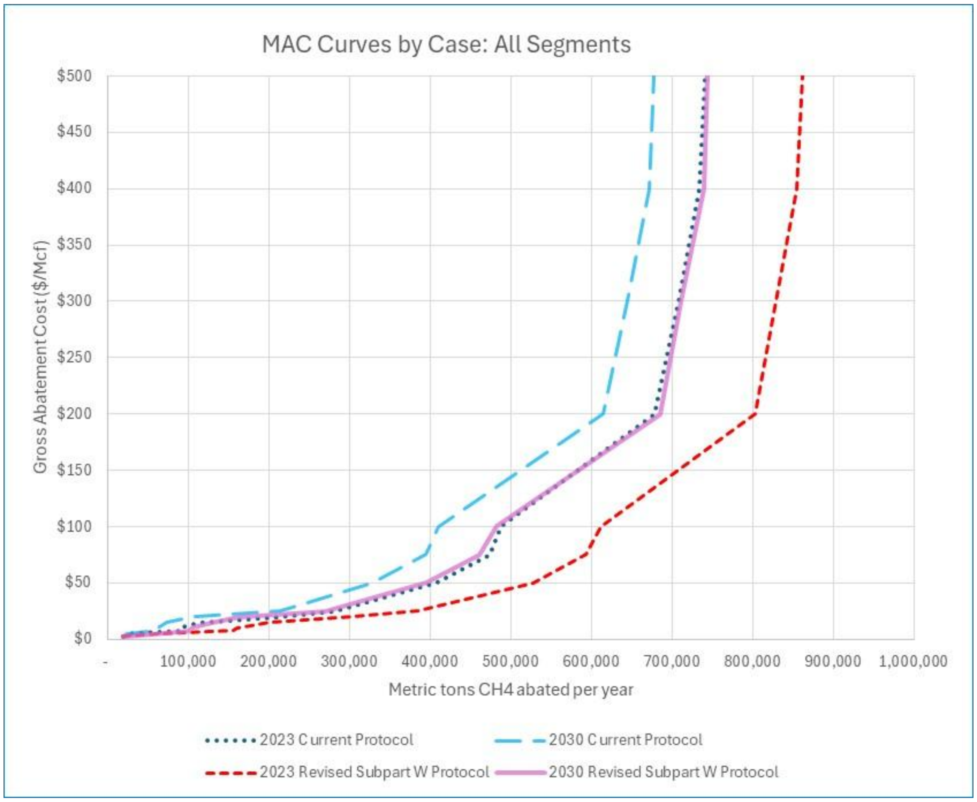

Exhibit 4 below provides MAC results for all emission source types and cases considered in this study by industry segment. The first column provides the case name. The second column indicates the marginal abatement cost ($/Mcf) for which abatement volumes are presented. The next set of columns provide the total abatement volumes achievable in that segment at each row's abatement cost level. The last column indicates the all-segment abatement achieved as a percentage of the all-segment emission baseline.

As indicated below, the cases result in overall abatement of between 76% and 79% at a $500/Mcf cost level. However, each of the Revised Subpart W Cases achieved more abatement at lower costs compared to the Current Protocol Cases. The Revised Subpart W Cases indicate 15% and 11% abatement at a cost of $10/Mcf in 2023 and 2030 respectively, compared to only 10% and 7% under the Current Protocol Cases. Additionally, the Revised Subpart W Cases have larger volumes of total abatement overall due to the larger volumes quantified and included in their baseline emissions.

It is important to remember that the MAC curves and tables presented in this report reflect current ONE Future members, who individually and collectively have already achieved substantial reductions in their methane emissions over the last several years. Therefore, the emission baseline upon which the MAC curves are developed already reflects the harvesting of "low hanging fruit" leaving less methane that could appear as potential reductions in the MAC curves. MAC curves generated for companies that have not implemented ambitious methane reduction programs like those adopted by the ONE Future companies likely would show greater potential for methane reduction at low cost levels.

Exhibit 4: MAC Curve Results by Individual Industry Segment, All Sources and Four Main Study Cases

	MAC Curve Results for All Main Cases, National Region: metric tons per year of methane abated vs. Baseline									
Case	Gross Abatement Cost ($/Mcf)	Onshore Production	Gathering	Processing	Transmission	Storage	Distribution	Other Segments	All Segments	All Segments as % of Sources Included in MAC
2023 Current Protocol	$10	30,740	12,936	11	44,870	1,545	203	431	90,735	10%
2023 Current Protocol	$100	74,246	32,075	3,653	132,713	11,319	232,747	1,160	487,913	52%
2023 Current Protocol	$500	85,669	140,698	19,600	189,970	38,313	266,197	1,341	741,787	79%
2030 Current Protocol	$10	6,831	5,386	12	46,517	1,508	216	469	60,940	7%
2030 Current Protocol	$100	23,560	21,615	3,848	126,819	9,216	224,392	1,256	410,706	46%
2030 Current Protocol	$500	37,092	139,884	20,615	186,178	35,565	256,629	1,452	677,415	77%
2023 Revised Subpart W Protocol	$10	81,606	22,400	11	54,187	1,545	203	431	160,382	15%
2023 Revised Subpart W Protocol	$100	161,546	54,225	4,764	141,511	15,037	233,324	1,160	611,568	56%
2023 Revised Subpart W Protocol	$500	177,159	155,087	19,804	200,000	41,827	266,853	1,341	862,072	79%
2030 Revised Subpart W Protocol	$10	39,337	7,490	12	56,176	1,508	216	469	105,208	11%
2030 Revised Subpart W Protocol	$100	71,527	33,219	4,984	133,851	12,112	224,994	1,256	481,943	49%
2030 Revised Subpart W Protocol	$500	88,629	143,057	20,800	194,487	38,290	257,314	1,452	744,029	76%

Note: “Other Segments” refers to offshore production, distribution storage, and LNG export.

1. Introduction, Methodology, and Data Sources

1.1 Background

ONE Future coalition was formed in 2014 and consists of natural gas companies working to voluntarily reduce methane (CH_4) emissions across the natural gas value chain. The ONE Future membership represents over 40% of the overall U.S. natural gas value chain, which is divided for reporting purposes into five segments: oil and natural gas production, natural gas gathering and boosting, natural gas processing, natural gas transmission and storage, and natural gas distribution. After 2025, ONE Future is planning to add LNG export/import facilities as a sixth segment because of the growing volumes of gas going through such facilities and the increasing interest among LNG importers to obtain LNG with documented low carbon footprints.

The ONE Future coalition members work to meet their methane reduction goals through the development and adoption of groundbreaking technologies and best practices, support for relevant scientific and engineering fields, and the setting and monitoring of methane emission targets among its members. The coalition promotes and tracks approximately 83 unique methane abatement activities across all segments and seeks to drive down emissions through continuous improvement of practices and technologies. The current emission targets (set as goals for the year 2025) are shown in Exhibit 5 along with the 2022 and 2023 emission averages reported by the ONE Future members.

Exhibit 5: Methane Targets

Segment	2025 Goal	2022 Actual	2023 Actual
Production:	0.283%	0.133%	0.067%
Gathering & Boosting:	0.080%	0.077%	0.066%
Processing:	0.111%	0.028%	0.021%
Transmission & Storage:	0.301%	0.088%	0.081%
Distribution:	0.225%	0.095%	0.097%
Overall:	1.000%	0.421%	0.331%

**Targets represent maximum methane releases stated as percents of natural gas throughputs.*
***Overall total shown here represents a simple sum.*

ONE Future is reviewing these targets in light of new technology and may update or replace them with more stringent targets or emissions reductions tactics that reflect expected technological advancements. The intent is that ONE Future member companies would meet or exceed these new targets by the year 2030 or 2035. For example, ONE Future may wish to adopt targets for the five segments that sum to 0.5% of throughput rather than the 1.0% combined target currently in place.

1.2 Purpose and Scope of This Study

One of the sources of information used to set the original targets for the year 2025 was a report written by ICF that evaluated the economics of various methane mitigation options. That report also presented marginal abatement cost (MAC) curves showing the incremental cost of abatement as those mitigation options might be applied starting first from the most cost-effective option and then moving towards less and less economic options. The values shown on the x-axis of such MAC curves are cumulative annual volumes of methane gas that could be mitigated and the values on the y-axis are the $/Mcf cost of each incremental step on the MAC curve.

The purpose of this study is to update ICF's prior MAC curve study to identify cost-effective emissions reductions and abatement opportunities in light of the industry's current infrastructure and new and emerging technologies for detecting, measuring and abating methane emissions. ONE Future will combine results of this revised MAC curves study with other information it is compiling including data on the effectiveness of measurement, monitoring, reconciliation and validation (MMRV) protocols and technologies (particularly GTI's Veritas Platform), the status and expected impacts of current and proposed regulatory requirements from PHMSA and EPA related to methane emissions, and the expected market availability of various MMRV and abatement products and services.

Another source of information to be available to ONE Future and ICF will be the ongoing and anticipated GTI work being funded through the EPA IRA-MERP program to investigate GHG mitigation options for small gas producers in the Permian, Eagle Ford and other areas. These combined information sources could be used to set ONE Future's new methane emission targets or tactics and to select science-based protocols and best practices that ONE Future will promote to increase the public's confidence in emissions inventories and GHG intensities reported by the U.S. natural gas industry.

It is expected that the science-based protocols and practices to be promoted by ONE Future will include wider adoption of measurement technologies (at various scales such as measurement of methane releases from individual pieces of equipment/ stacks/ tanks, measurements encompassing an entire facility containing multiple point sources or measurement of atmospheric methane concentrations of a large geographic area with multiple facilities). An important component of these science-based protocols and practices would include the reconciliation of measurements taken at different scales and timeframes with each other and with traditional inventory methods using activity/equipment counts and emission factors. Given the current uncertainties around methane measurement and estimation methods, such reconciliations -- done in a transparent and credible manner -- will be critical for gaining public confidence in reported methane inventories and carbon intensity calculations.

1.3 Methodology for Estimating Marginal Abatement Costs and Potential Abatement Quantities

The main analytic components of this study are in a series of spreadsheet models that contain historical 2023 and projected 2030 activity and emissions data for ONE Future members and characterizations of various methane mitigation options. These spreadsheet models compute the cost effectiveness of those mitigation options as they might be applied to various emission sources within each industry segment of the natural gas supply chain. The spreadsheet models then produce MAC curves showing what portion of the baseline emissions in each industry segment can be abated at various cost levels.

The overall methodology for creating and deploying the analytic models is summarized below. Additional methodological details and the analytic results are presented in detail in the next four chapters. These are summarized below:

1. **Compile and organize activity and emission data:** ICF compiled or estimated activity and methane emission data for ONE Future members for the base year 2023 and projected the same kind of data for the year 2030. The term “activity data” encompasses modeling parameters such as annual production or throughput, and various counts of equipment and assets (e.g., counts of wells and well pads, miles of pipeline, counts of compressors, number of customer meters, etc.) The data sources, methodology, and results of these work items are presented in **Chapter 2**.
2. **Characterize costs and performance of methane mitigations technologies:** To support its modeling efforts, ICF collected and reconciled capital and operating cost data and performance parameters of methane mitigations technologies that could best mitigate the methane emission sources with the largest current emission volumes. “Performance” usually is measured as percent reduction in baseline methane emissions that would result once that technology is implemented on a specific source category. The work efforts related to technology costs and performance are discussed in **Chapter 4** for technologies other than those related to leak detection and repair (LDAR). The LDAR technologies are separately covered in **Chapter 3**.
3. **Evaluation of LDAR technologies and programs:** LDAR programs are intended to detect fugitive emissions and repair or replace equipment causing those leaks. ICF evaluated LDAR programs by first characterizing each industry segment’s fugitive emissions in terms:
   - Total annual volume,
   - Annual count of leaks,
   - Leak size distribution in units of kilograms of methane leaked per hour, and
   - The expected average leak persistence (i.e., the expected percent of the 8,760 hours in a year that an undetected and unrepaired leak would be “on” and, thus, emitting methane).

   ICF characterized the performance of various leak detection technologies in terms of the “1-trial probability of detection” representing the expected results of leak detection survey conducted once. The probability of detection is modeled as a function of leak size using an algorithm in which 50 standardized size classes are depicted, and larger leaks have a higher probability of detection compared to smaller leaks. ICF also estimated the “N-trial probability of detection” whereby a periodic survey technology is applied through “N” surveys per year. Finally, ICF also estimated the probability of detection of “tiered” LDAR programs that combined two or more leak detection technologies that can be continuous monitoring systems or periodic surveys where “N” can range from 1 to 52 surveys per year. ICF also estimated the cost of specific leak detection programs as the sum of:

- The cost of applying the leak detection technologies,
- The cost of follow-up examinations to verify true-positive detections, and false-positive anomalies,
- The cost of repairing the detected true-positive leaks.

For each industry segment, ICF estimated the costs and emission reductions of approximately 300 combinations of one or more leak detection technologies each with a specified survey frequency. The per-unit abatement cost for each LDAR program option was computed as the annual cost of the program divided by the annual expected abated methane volume. The LDAR options were then sorted from the lowest per-unit cost to the highest cost to create the MAC curve. The efforts to evaluate LDAR technologies and programs and the resulting MAC curves are presented in more detail in **Chapter 3**.

4. **Estimate the economics of vented and combustion-related mitigation options:** ICF created and ran models to evaluate the cost effectiveness of each mitigation technology if it were applied to specific sources in each industry segment. The results were per-unit abatement cost denominated in dollars per thousand cubic feet of abated methane or \$/Mcf CH_4. These efforts and the resulting MAC curves for Vented and Combustion-related mitigation options are shown in **Chapter 4**.
5. **Construct marginal abatement cost (MAC) curves:** ICF then used these abatement cost estimates -- along with the associated abatement volumes -- to construct MAC curves. Each mitigation option was sorted from the lowest per-unit cost to the highest cost in order to create the MAC curve. Each MAC curve shows the cumulative amount of methane abated (in units of annual metric tons) along the x-axis and the marginal cost in units of \$/Mcf CH_4 along the y-axis.

1.4 Calculation of Marginal Abatement Costs

The effectiveness of each mitigation option within relevant supply chain segments was calculated as the expected annual methane emissions before the adoption of the subject activity minus the emissions expected after the subject mitigation is implemented. The cost of the mitigation option includes any upfront (capital) cost of the activity and any annual operating and maintenance (O&M) costs. Following the conventions of the original MAC study conducted by ICF, the gross cost effectiveness of the activity is computed as the present value of capital and O&M costs divided by the present value of the abated methane volumes measured in thousand standard cubic feet (Mscf). In other words, the gross cost effectiveness would be stated in \$/Mscf of methane whose release is avoided. Also, a second measure of cost effectiveness, the net cost, is computed as the gross cost in \$/Mscf minus (where appropriate) the \$/Mscf value of the recovered natural gas that can be sold. Stated algebraically, these relationships are:

$$Gross\_Cost = [PV(Capital\_Cost) + PV(OM\_Costs)] / PV(Abated\_Volume)$$
$$Net\_Cost = Gross\_Cost - NG\_Price * Percent\_Sold$$

Where:
Gross_Cost = gross cost effectiveness of a given activity measured in $/Mscf
PV(Capital_Cost) = present value of upfront costs in dollars
PV(OM_Costs) = present value of annual operating and maintenance costs in dollars
PV(Abated_Volume) = present value of abated gas volumes in Mscf. This is a function of the mitigation effectiveness and the overall emissions.
Net_Cost = net cost effectiveness of a given activity in $/Mscf
NG_Price = the natural gas price in $/Mscf (a levelized multi-year price or an annual price)
Percent_Sold = the percent of the abated gas that can be sold by the party who would be paying for the abatement activity

The industry segments that were assumed to retain a substantial portion of the value of abated natural gas were production (100% retention). The value of natural gas that was assumed for computing net costs was $2.81/MMBtu[1] for the production segment based on average Henry Hub pricing. The difference between the gross costs and net costs for technology options in the production segment would be $2.81/MMBtu for all options that capture additional gas. All other segments were assumed to be unable to realize the savings.

These two abatement cost estimates for a given mitigation option are estimated for each relevant supply chain segment (e.g., gas transmission pipelines) and for each relevant emission source category. The activity and emission parameters that can be used for these calculations (e.g., throughput capacity, throughput volume, gas composition, current emission rate, etc.) are characterized in terms a single set of “pro forma” of “typical” values meant to be average parameters for that supply chain segment, source category and “submarket”. In some cases, the submarket can be defined geographically, that is, representing facilities in one of the four regions used for this study. (See next section.) In some cases, the submarket can be defined by specific characteristics of the facilities that greatly affect the cost or performance of a mitigation technology. For example, the analysis of mitigation options for pneumatic devices is done for submarkets defined by the number of devices per facility and the facility’s access to grid electricity.

Once the economics of relevant mitigation option is estimated, the MAC curves are constructed by sorting the mitigation options from the most cost effective to the least cost effective (using either the gross or net abatement cost measure) and then summing the cumulative abatement volumes to form an upward sloping curve. Separate curves were constructed for each supply chain segment and for all ONE Future members across the entire natural gas supply chain.

An important step in constructing the MAC curves is to determine if and how the application of each activity within a relevant supply chain segment/category/submarket might impact the effectiveness of (higher cost) activities that might be applied later to the same supply chain segment/category/submarket. For example, the lowest cost activity “A” might reduce emissions

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[1] This price represents the 2026-2030 average at Henry Hub based on the EIA 2025 Annual Energy Outlook (AEO).

by 50% and the next lowest cost activity “B” might reduce emissions by 40% when applied alone. However, if activity “B” is applied after “A” has already been applied, its effectiveness might only be (1-50%) x 40% = 20%. This lower effectiveness would also mean that the cost of “B” as measured in $/Mscf of natural gas abated would be higher than if “B” were applied alone.

1.4.1 Marginal Abatement Cost Levels

The results of this study provide the volume of reductions achievable at different levels of marginal abatement costs across ONE Future member operations. The study results are provided at various marginal cost levels, with achievable reductions increasing as more expensive mitigation technologies are deployed (and thus at higher cost). For additional context, Exhibit 6 provides these cost levels expressed on a volumetric and per metric ton CH_4 basis below. The $/mt CO_2e cost shown below utilizes a GWP of 28 for methane, consistent with US EPA GHG Inventory assumptions.

Exhibit 6: Gross Abatement Cost Levels Expressed in Three Different Units

Gross Abatement Cost		
$/Mcf CH4	**$/mt CH4**	**$/mt CO2e (CH4 GWP - 28)**
$3	$130	$5
$5	$260	$9
$8	$391	$14
$10	$521	$19
$15	$781	$28
$20	$1,042	$37
$25	$1,302	$47
$50	$2,604	$93
$75	$3,906	$140
$100	$5,208	$186
$200	$10,417	$372
$300	$15,625	$558
$400	$20,833	$744
$500	$26,042	$930
$1,000	$52,083	$1,860
$2,000	$104,167	$3,720

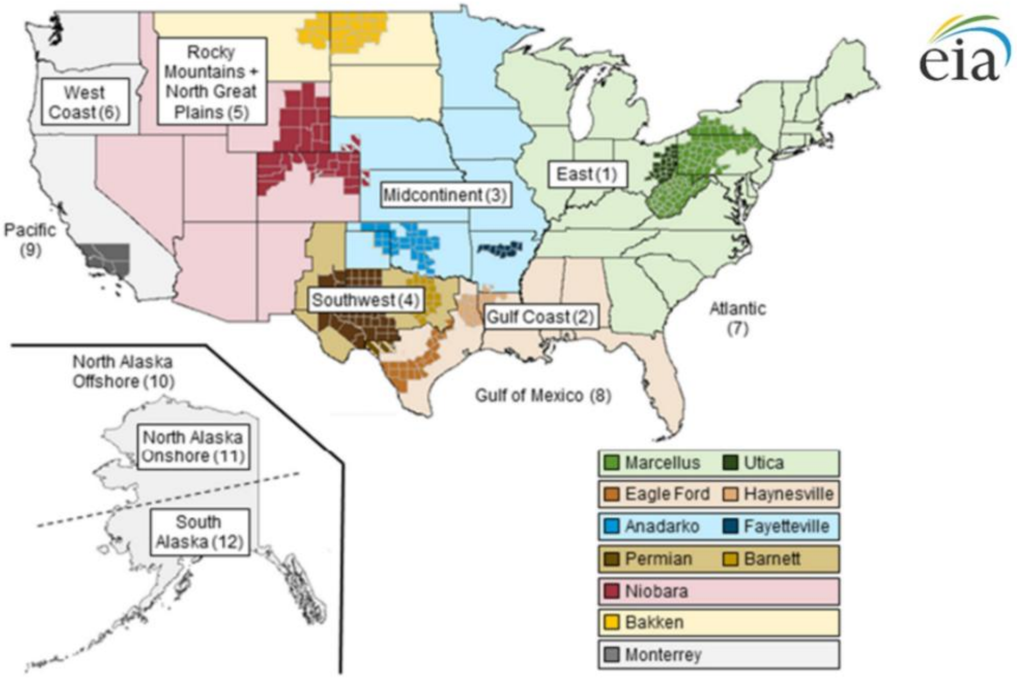
1.5 Definition of Regions

The analysis was performed on either a national or regional basis. For the transmission and storage industry segments, the pro forma characterizations were compiled nationally. This resulted in a single MAC curve for each of these two industry segments (for a given year and a given set of assumptions for baseline emissions). For the other industry segments (production, gathering, processing and distribution) regional variations are more significant and/or region-specific data are more relevant and available. For these industry segments, ICF compiled data in each of four US regions and estimated four separate regional MAC curves. In such instances, ICF also created a national curve that is the summation of the four regional curves.

The boundaries for each region were based on the EIA natural gas and oil supply modeling regions (see Exhibit 7) which are made up of aggregations of the AAPG Basins (i.e., the basin definitions used in EPA’s GHGRP Subpart W). To provide an adequate number of observations for statistical analysis and to preserve the confidentiality of company-specific data, ICF added together some of the EIA modeling regions to create the four regions used in this study:

- East
- Midcontinent
- Gulf Coast: Includes Gulf Coast + Southwest
- Rocky Mountains: Includes Rocky Mountains + North Great Plains + West Coast + Pacific
- National: Includes everything + Offshore

Exhibit 7: Map of Analytic Regions



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022)

1.6 Assumptions for Future Activity and Methane Emissions by Industry Segment

The 2023 baseline emissions used in this study are based on historical data reported by ONE Future members to ONE Future and similar data the members submit to EPA to fulfill requirements under the Greenhouse Gas Reporting Rule Subpart W. As is explained in more detail in **Chapter 2**, ICF had to fill in or disaggregate data where a particular data element needed for the modeling was not collected in these sources or when the available data did not provide the necessary level of detail. In such instances, ICF used various other data sources such as industry surveys and published studies to estimate the required parameters.

The baseline activity and emissions data for the future year 2030 analysis was estimated by ICF based on the 2023 data and expectations for future industry trends. ICF relied on the AEO Reference Case to project infrastructure development up to 2030 and the overall US natural gas supply/demand balance in that year. The activity levels of ONE Future members in 2030 were assumed to maintain the same proportions to national values as ICF estimated for the year 2023. (This process did not account for the possibility that the roster of ONE Future members will grow and that the membership could represent a larger portion of activity in a given industry segment.)

The future 2030 baseline methane emission inventories for the US and ONE Future members were estimated by ICF taking into account the factors that are expected to affect the location and volumes of methane emissions relative to activity levels. The largest of these factors include:

- The overall growth in natural gas supply/demand balances will increase production/throughput of the average pro forma facility and/or increase the number of facilities.
- The mix of gas production by region will change.
- The use of pneumatic devices will continue its historical decline reducing direct emissions from pneumatics and their contributions to fugitive emissions.
- Steel and iron distribution mains will continue to decline as a percent of mileage and plastic mains will continue their growth leading to a reduction in related fugitive emissions.

1.7 Cases Incorporating Revised Subpart W Protocols

EPA’s Greenhouse Gas Reporting Program (GHGRP) requires oil and gas operators to submit data and documentation of certain emission sources and operational characteristics to EPA annually under Subpart W. Originally released in 2009, Subpart W regulations impact oil and gas facilities that emit more than 25,000 MT CO_2e annually. At the time this study was performed, revisions to these regulations were recently approved and expected to be fully adopted by 2026.[2] Operators have the option to submit data which reflect the announced revisions in 2025 reporting, but revisions will not be fully adopted until the 2026 reporting year. Given these factors and the timing of this study, the status of these revised regulations and the relative impact on reported emissions are uncertain going forward.

Due to methodologies presented in these revisions (and the incorporation of several new sources that were not previously regulated), operators are expecting a notable increase in reported emissions. To illustrate the impact that these revisions may have on the results of this analysis, ICF has included alternative case marginal abatement results which reflect an estimation of the additional GHG impacts that are expected. The additional impacts were modeled by ICF through an analysis of data given in the EPA Regulatory Impact Assessment (RIA)[3], a review of the new regulatory language and the impact that the changes may have on existing emission factors, and data from previous GHGRP reporting years.

The Subpart W revisions are expected to impact ONE Future member emissions through several aspects:

1. Revisions to quantification methodologies for existing sources.
2. Addition of existing sources that will now be required to report to new industry segments.
3. New sources identified by the revised regulations which must now report.

There are no assumptions included in the Revised Subpart W Cases for the impact from “new” facilities which now have emissions below the reporting threshold but might be required to report under the revised regulation. This is because the data submitted by members to ONE Future and utilized in the baseline inventory (see **Chapter 2**) includes all facilities (including both those which are required to report under the previous Subpart W reporting guidelines and facilities that were not previously regulated).

Overall, ICF calculates a 16% increase to 2023 baseline methane emission volumes under the Revised Subpart W Protocol. The actual future volume may differ significantly from this estimate due to several factors, including uncertainties in the reporting of large release events (LREs). At the time of this analysis, it is unclear how LREs have been quantified and included in operator submissions under Subpart W under a different source name (such as being classified as “blowdowns”) or if they have been excluded entirely. Given this uncertainty, ICF has excluded LREs from baseline emission results in the Revised Subpart W Cases. ICF anticipates more clarity will become available as the revised regulation matures and operators are given more time to adjust their calculations to properly reflect the latest regulations.

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[2] Subpart W Rulemaking; https://www.epa.gov/ghgreporting/subpart-w-rulemaking-resources

[3] US EPA Assessment of Burden Impacts for Proposed Greenhouse Gas Reporting Rule: Revisions and Confidentiality Determinations for Petroleum and Natural Gas Systems; Docket ID. No EPA-HQ-OAR-2023-0234

2. Data Sources, Methodology and Values for 2023 Activity and Emissions Inventories

2.1 Introduction

This chapter provides a description of the sources and methodologies used to develop the activity and emissions represented in the marginal abatement cost (MAC) calculations included in this report. In order to generate a MAC curve, a baseline emissions inventory must first be developed. This inventory must quantify methane volumes from individual emission sources and identify relevant activity data needed for MAC calculations. The inventory developed in this analysis represents all ONE Future members and provides the basis for the reduction volumes, costs, and overall abatement results.

2.2 Baseline Inventory of Emissions

Exhibit 8 below summarizes the total CH_4 emissions quantified in the baseline inventory for each of the main cases considered in this study. Each emissions type is given for each case and industry segment. A comparison of 2023 and 2030 baseline volumes shows an expected overall decrease in emissions of approximately 5% across all industry segments. This result is a combination of several factors, including the expected future conversion from higher emitting to lower emitting equipment as well as regional projections of natural gas production and consumption.

Factors expected in the Revised Subpart W Cases result in a 16% increase in baseline emissions, however this increase does not include any quantification of large release events. There is uncertainty regarding the overall impact the inclusion of this source will have on total emissions, as well as the impact of revised methodologies. More information on all cases included in this analysis and shown in Exhibit 8 is given in **Chapter 3**.

Exhibit 8: Total CH_4 Emissions (mt CH_4) Considered by Emissions Type, Segment, and Case

Type	Case	Onshore Production	Gathering	Processing	Transmission	Storage	Distribution	Other Segments	Total
Fugitives	2023 Current Protocol	11,101	16,611	1,235	63,517	4,753	247,875	906	**345,998**
	2030 Current Protocol	11,737	17,789	1,312	65,849	4,640	243,629	976	**345,932**
	2023 Revised Subpart W Protocol	43,806	23,208	1,991	71,233	7,376	248,515	906	**397,034**
	2030 Revised Subpart W Protocol	46,315	24,856	2,115	73,848	7,199	244,308	976	**399,616**
Vented/ Combustion	2023 Current Protocol	96,998	161,507	28,653	294,698	40,743	1,007	4,552	**628,158**
	2030 Current Protocol	50,170	164,744	30,100	294,751	37,937	1,075	4,663	**583,441**
	2023 Revised Subpart W Protocol	158,567	187,864	33,964	297,094	42,307	11,191	4,913	**735,899**
	2030 Revised Subpart W Protocol	71,068	181,204	35,731	295,145	38,759	3,323	4,715	**629,944**
Total	2023 Current Protocol	108,099	178,117	29,888	358,215	45,497	248,882	5,458	**974,156**
	2030 Current Protocol	61,907	182,533	31,411	360,600	42,577	244,705	5,640	**929,373**
	2023 Revised Subpart W Protocol	202,373	211,072	35,955	368,326	49,683	259,706	5,819	**1,132,933**
	2030 Revised Subpart W Protocol	117,383	206,060	37,846	368,992	45,958	247,630	5,691	**1,029,560**

Note: These emission estimates are for the current ONE Future member companies and assume that membership stays the same through 2030.

2.3 Key Data Sources for Inventories

In order to develop the baseline inventory used in this analysis, ICF primarily utilized member data submitted to ONE Future under the current protocol. Data submitted to this protocol includes individual member submissions representing company-specific operations and allows for the identification of emissions from unique facilities and sources. The inventory represents emissions from thousands of facilities throughout the entire natural gas supply chain. Facilities consist of onshore and offshore wellhead natural gas production equipment, gathering and boosting compressor stations and pipelines, gas processing facilities, large-diameter transmission pipeline and compressor stations, underground storage and LNG facilities, and gas local distribution companies.

The emission volumes quantified by ONE Future members are based on engineering calculations representing company specific operating conditions or more frequently general quantification methodologies provided by EPA. Data represents calendar year 2023 operations, and the total methane emissions in the inventory developed in this analysis align with the methane volumes used to generate the leakage rates reported in ONE Future's 2024 annual report.[4]

Certain data utilized in the MAC calculations in this analysis is not collected from members under the ONE Future protocol. Some examples of the additional data needed include pneumatic device counts by bleed rate, the count of certain types of compressors, and the specific source of blowdown volumes (e.g., pipelines, compressors) and number of blowdown events. In these cases, ICF incorporated data submitted to EPA's Greenhouse Gas Reporting Program (GHGRP) to supplement the ONE Future inventory. This regulation (more specifically, Subpart W) requires oil and gas operators to provide activity and emissions data for facilities which emit greater than 25,000 mt CO_2e per year. More detail on how the Subpart W data is incorporated into the inventory is provided in the next section.

2.4 Data Processing Steps to Estimate 2023 Inventories

For the development of the inventory for 2023, ICF reformatted the ONE Future member submitted data to align each emission source with a representative activity (equipment counts, throughput, etc.). The representative activity is based on the MAC calculations and differs for certain sources. Some emission sources also require further detail and disaggregation to properly apply mitigation measures. For example, compressors may represent a single piece of equipment but generate several sources of emissions including seal venting, fugitives, blowdowns, and methane slip from compressor starts. These specific emission sources are mitigated using different technologies and, therefore, vary in cost and reduction effectiveness.

To supplement the ONE Future inventory with additional Subpart W data, ICF first aligned facilities within the ONE Future member data that report to Subpart W. For these facilities, ICF utilized reported data directly in the inventory as needed. To disaggregate emission data for facilities which do not report to Subpart W, ICF utilized the proportion of data in each disaggregation from facilities with reported data. If activity must also be derived for sources at

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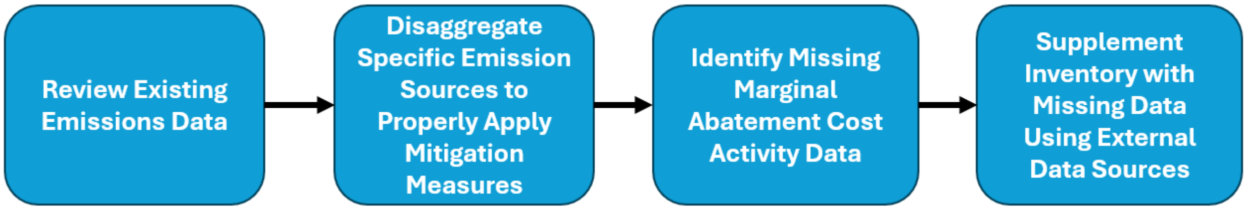
[4] ONE Future 2024 Annual Report; https://onefuture.us/annual-report/

facilities which do not report to Subpart W, ICF generated a composite emission factor from EPA reported data generated from reporting facilities. This composite factor is used to quantify activity from the total emissions.

The end result of these processing steps is a disaggregated composite inventory containing appropriate activity and emissions which can be properly applied in the MAC calculations.

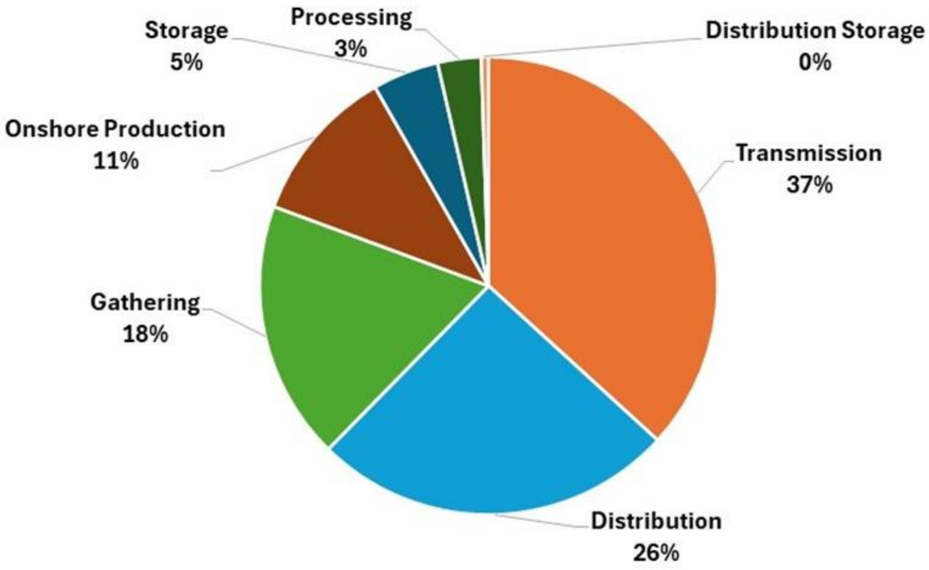
Exhibit 9: Flow Chart of Processing Steps to Estimate Inventories



2.5 Methane Emission Sources by Industry Segment

Methane emissions are quantified by individual emission source for all facilities in the baseline inventory. The proportion of total emissions by industry segment is provided in Exhibit 10 below. Gas transmission is the industry segment representing the largest volume of methane emissions reported across member operations (358 kt CH_4). Gas production (108 kt CH_4), gathering and boosting (178 kt CH_4), and gas distribution (249 kt CH_4) are also segments which generate large volumes of emissions relative to member operations. The results shown below exclude a small quantity of emissions in offshore production and LNG import/export operations.

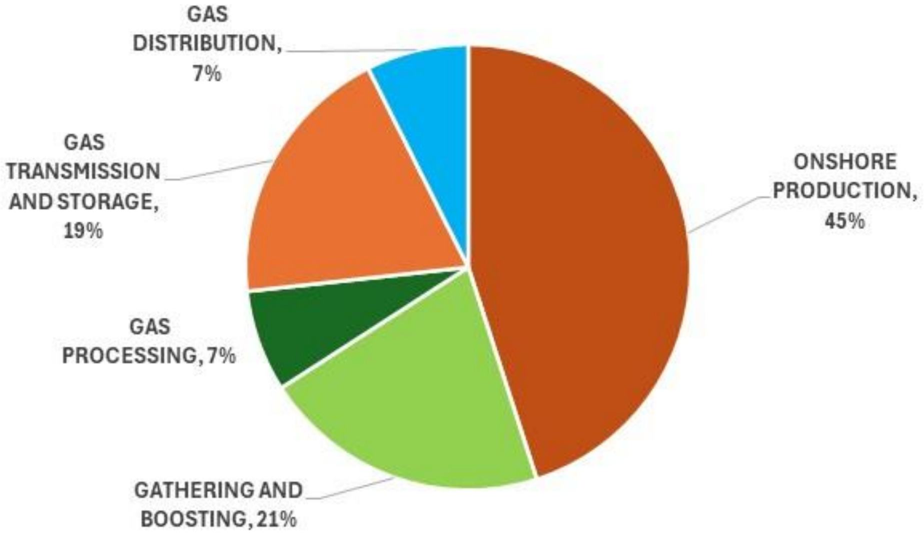
Exhibit 10: Proportion of Methane Emissions from ONE Future Members



Source: ONE Future Protocol Member Data

Comparing the proportion of emissions from ONE Future Members with the national average indicates that ONE Future Members have a large fraction of their emissions in the transmission and distribution segments. This differs from the national average breakdown (shown below in Exhibit 11) which indicates the largest methane emissions overall can be found in the upstream sectors of production and gathering and boosting.

Exhibit 11: Proportion of Methane Emissions (National Average)



Source: ICF analysis of 2024 US EPA GHG Inventory data

Comparing the volume of emissions from ONE Future members with national oil and gas industry averages shows some notable differences on a CH_4 leakage rate basis. Exhibit 12 below provides a breakdown of CH_4 leakage rates for each oil and gas industry segment on a national average basis and for ONE Future members only. Both nationally and for ONE Future members, the natural gas production segment has the highest methane leakage rate. However, production emissions for ONE Future members show CH_4 leakage rates which are significantly less than the national average. Even when comparing recalculated ONE Future member leakage rates which reflect expected Subpart W revisions (the last column of Exhibit 12), the national average rates are still higher than ONE Future averages across all industry segments.

Exhibit 12: Comparison of National CH_4 Leakage Rates (%) with ONE Future Members

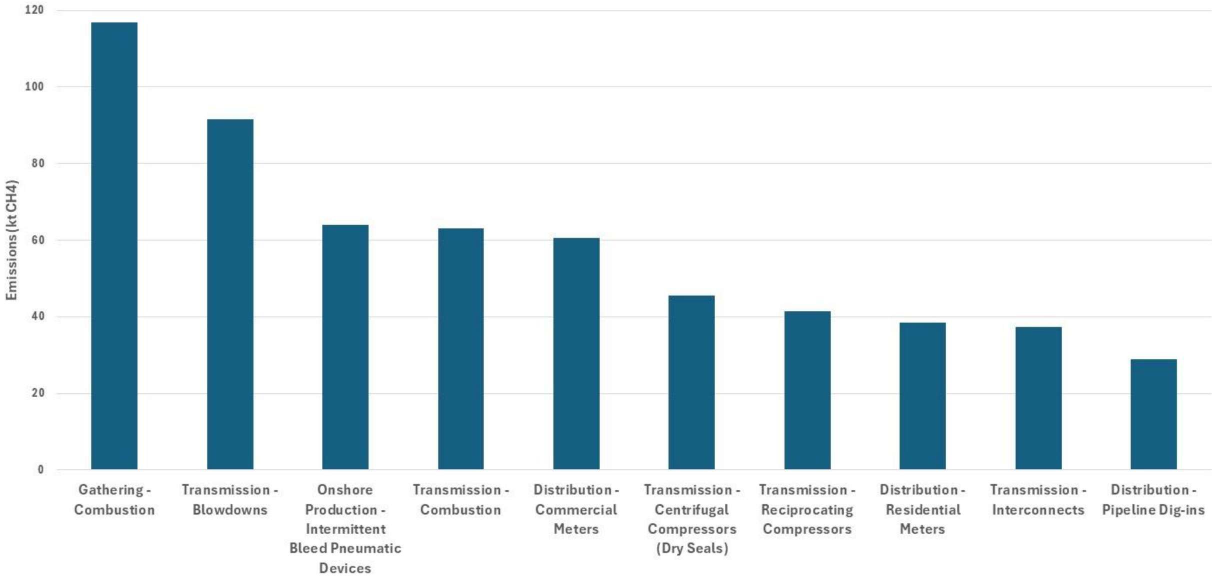
Segment	***2022 National***	***ONE Future 2023***	***ONE Future 2023 Subpart W Revisions***
OG PRODUCTION	0.557%	0.067%	0.234%
GATHERING AND BOOSTING	0.258%	0.066%	0.150%
GAS PROCESSING	0.131%	0.021%	0.048%
GAS TRANSMISSION AND STORAGE	0.216%	0.081%	0.173%
GAS DISTRIBUTION	0.208%	0.091%	0.097%

Note: 2022 National Leakage Rate based on ICF analysis of 2024 EPA National GHG Inventory and EIA data

2.6 Major Methane Emission Sources by Industry Segments

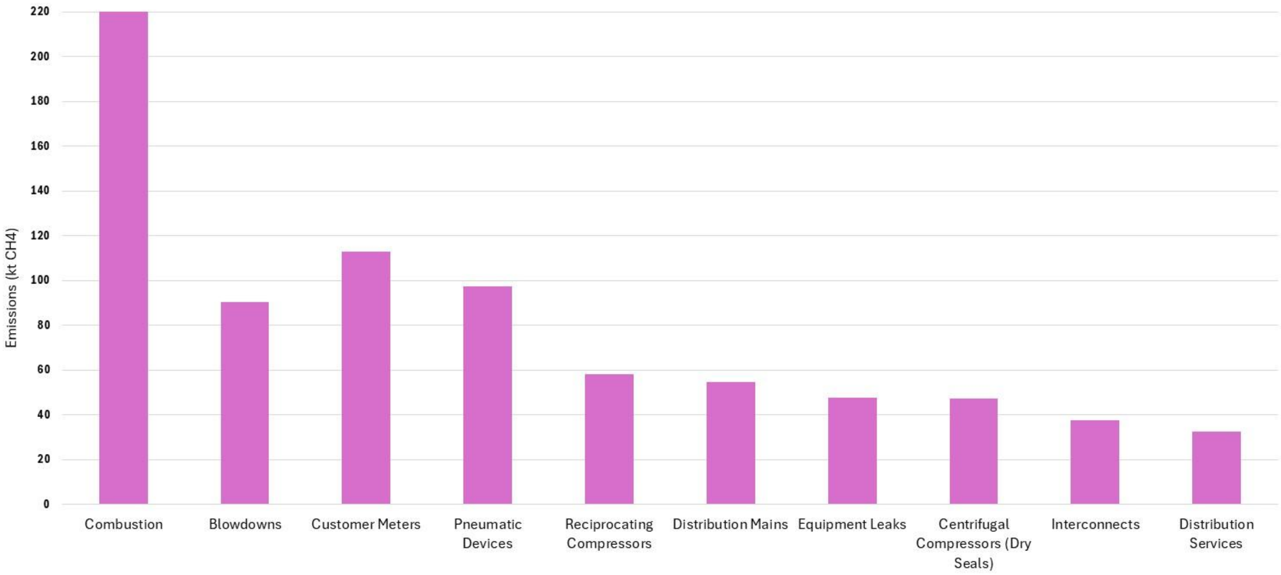
The ten largest sources of methane in the baseline inventory are shown in Exhibit 13 below. The largest overall source of emissions is methane slip generated from the combustion of fuel from compressor engines and turbines. Specifically, the gathering and boosting and gas transmission segments generate high volumes of methane slip. Another significant source of methane emissions are blowdowns, which represent the gas volumes “blown down” from compressors, pipelines, scrubbers and other equipment for maintenance, testing, and safety activities. This activity results in natural gas from these equipment sources emitting directly into the atmosphere.

Exhibit 13: Largest CH_4 Emission Sources by Industry Segment, ONE Future Member Operations



Another way of comparing the largest methane emission sources is to aggregate each kind of emission source across all industry segments. After combining by emission source across all segments in the gas supply chain, the resulting ten highest emitting sources are shown in Exhibit 14 below. These results illustrate the significance of methane slip emitted from engines and turbines, which in total generate nearly double the amount of methane emissions than the second largest source (blowdowns). Local distribution company (LDC) customer meters and pneumatic devices also represent significant sources of methane across ONE Future member operations. Collectively, the methane emissions from these sources represent over 85% of all methane emissions in the baseline inventory.

Exhibit 14: Largest Generalized CH_4 Emission Sources, ONE Future Member Operations



3. Development of MAC Curves for LDAR Programs

3.1 Introduction

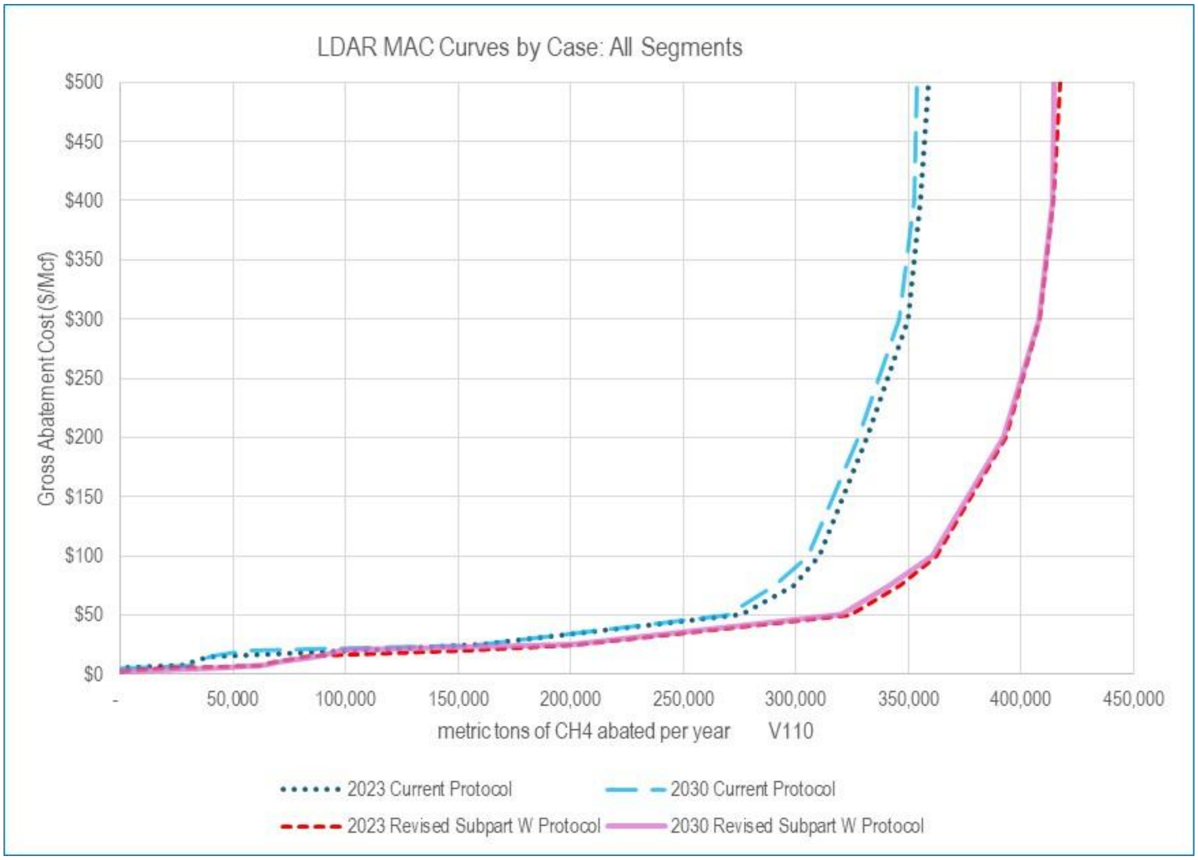
This chapter discusses the data sources, methodology and results of ICF's efforts to estimate MAC curves related to leak detection and repair programs within each natural gas industry segment. LDAR MAC curves are presented in this chapter starting from emission baselines based on the Study's four "main cases" that were discussed in previous chapters:

1. Emissions from current ONE Future members in the year 2023 as estimated under the current ONE Future Protocols.
2. Projected emissions from current ONE Future members in the year 2030 estimated under the current ONE Future Protocols.
3. Emissions from current ONE Future members in the year 2023 re-calculated using a revised protocol that incorporates certain expected changes to EPA's GHGRP Subpart W rules.
4. Emissions from current ONE Future members in the year 2030 re-calculated using a revised protocol that incorporates certain expected changes to EPA's GHGRP Subpart W rules.

As was discussed in the previous chapter, the Subpart W changes will permit new estimation methods, incorporate updated emission factors, and add new sources including Large Release Events. Overall, these changes are expected to increase reported emissions including fugitive emissions that can be mitigated by LDAR programs.

A summary chart of final LDAR MAC curves results is shown in Exhibit 15 for the Study's four main cases. The quantity of potential mitigation under the Revised Subpart W Protocol is larger in both 2023 and 2030 relative to the Current Protocol because the baseline quantities of emissions are roughly 16% larger. The mitigation volumes that are achievable at $500 per Mcf of methane are about 83% to 82% of the baseline methane volumes in the 2023 and 2030 cases based on the Current Protocol. For the two cases reflecting the Revised Subpart W Protocol, mitigation at $500/Mcf represents 84% to 83% of baseline volumes. The somewhat improved economics (as a percent of the baseline) under the Revised Subpart W Protocol cases reflect the fact that those cases assume a greater number of leaks and larger average leaks sizes compared to the cases whose assumptions are based on leak volumes calculated under current protocols. Since more methane is found for any given LDAR program in the Revised Subpart W Protocol Cases, the $/Mcf cost goes down.

Exhibit 15: All-Segment LDAR MAC Curves for the Four Main Study Cases



3.1.1 The Definition and Purpose of LDAR

Unintentional releases of methane and other hydrocarbons into the atmosphere from facilities along the oil and gas supply chain are referred to as “fugitive emissions” or “leaks.” A leak detection and repair (LDAR) program finds leaking equipment so that fugitive emissions can be reduced through repairs. The first element of LDAR is the design and implementation of a monitoring program that applies one or more leak detection technologies (often applied at specified time intervals) to determine whether and where leaks may be occurring and -- sometimes -- to estimate the volume of natural gas lost. The second element of an LDAR program is the timely repair or replacement of leaking equipment after leaks are detected. An optional third element of an LDAR program (not evaluated in this study) is enhanced maintenance practices to find any fouled, misadjusted, worn, or damaged components so that they can be cleaned, re-set, refurbished, or replaced before leaks occur.

Beyond the societal benefits of reduced GHG emissions, an LDAR program can be of value to companies in the natural gas supply chain through:

- Higher revenues (going primarily to producers) stemming from reduced natural gas losses.
- Improved ability to meet mandated methane/hydrocarbon emissions standards or avoid emission fees.

- Enhanced ability to reach corporate ESG goals and demonstrate success to stakeholders.
- Effective LDAR programs can reduce hazards and improve worker safety.
- Easier compilation of high-quality data to help comply with mandatory emissions reporting requirements.
- Stronger supporting data for certified gas sales or compliance with domestic and international carbon intensity standards for natural gas and LNG sales.

3.1.2 Scope of Analysis

In this report, ICF presents marginal abatement cost (MAC) curves for hypothetical LDAR programs that could be applied to “typical” or “pro forma” facilities representing average characteristics of ONE Future members within each industry segment (i.e., production, gathering, processing, transmission, storage and distribution). ICF generated these curves using a model that relies primarily on activity and methane emission data reported by ONE Future members. ICF also projected emission and activity data to the year 2030 and used those data to estimate MAC curves for that future year.

Because much of the data underlying the MAC curves is difficult to reliably and comprehensively obtain, ICF also created cases employing differing assumptions. Some of the most uncertain model input parameters changed for these cases included fugitive emission volumes; leak counts and size distributions; and the performance characteristics of various leak detection technologies. One set of cases were created for the year 2023 and 2030 by increasing the assumed fugitive leak volumes in line with expected reporting changes under GHGRP Subpart W. Under the revised protocol assumptions fugitive emissions increased by 15.4% in 2023 and 16.2% in 2030. These are the third and fourth of the Study’s four “main cases,” which are applied to both LDAR and Vented and Combustion-related mitigation options.

Another set of “sensitivity cases” were created for the year 2023 to test how the MAC curve results would be affected if the assumed leak size corresponding to a 90% probability of detection for each technology were doubled (labeled the “Worse Performance Case”) versus the base case or if they were cut in half (labeled “Better Performance Case”) versus the base case. Because these sensitivity cases only apply to leak detection, their MAC curves are presented only in this LDAR chapter.

In the transmission and storage industry segments, the pro forma characterizations were compiled nationally, which resulted in a single MAC curve for each of these industry segments (for a given year and a given set of assumptions for baseline emissions and technology performance). For the other industry segments, where regional variations are more significant and region-specific data are more relevant and available, ICF compiled pro forma characterizations for an average facility in each of four US regions and estimated four separate regional MAC curves. In such instances where the analysis was conducted regionally, ICF also created a national curve that is the summation of the four regional curves.

3.1.3 Summary of Methodology

The methodology for creating the LDAR MAC curves is described below in 18 steps:

1. **Fugitive Emissions Data**: ICF compiled 2023 fugitive activity and emissions data for the ONE Future companies using the data sources and processing procedures described in **Chapter 2**.
2. **Facility Characteristics**: ICF compiled or estimated modeling parameters that represent an average facility in each industry segment and (where needed) each region. These modeling parameters included annual production or throughput, annual fugitive emissions by type, and various counts of equipment and assets (e.g., counts of wells and well pads, miles of pipeline, counts of compressors, number of customer meters, etc.). The "baseline" values to be used in the modeling for annual fugitive methane emissions (in units of metric tons of methane per year per facility) were derived from the statistical average of data reported to ONE Future with an upward adjustment ranging from 3% to 31% for each segment and averaging 24% across all segments. These adjustments are intended to account for the belief that (a) the emission factors applied to activity counts to estimate annual fugitive emission volumes and (b) that commonly used alternative estimation methods based on measurement surveys miss some of the smallest leak sizes and result in an undercount of leak occurrences and total leak volumes.
3. **Leak Counts and Sizes**: Starting with leak size distributions presented in various published leak detection studies, ICF broke out the fugitive emission target for pro forma facilities in each industry segment/region into annual counts of leaks by leak size class. The annual leaks are distributed across 50 leak size classes which are denominated in units of kilograms of methane per hour (CH_4 kg/h). The leak size distributions for all industry segments are assumed to follow a "power law distribution" that is characterized by a small number of large leaks, a greater number of mid-size leaks and a large number of small leaks.
4. **Selection of Detection Technologies**: To evaluate the performance and economics of different options for an LDAR program, ICF selected up to five monitoring technologies to be evaluated for each industry segment. Some of these are continuous monitoring technologies and the others are periodic leak detection surveys. For the periodic surveys, ICF selected up to five possible survey frequencies (ranging from zero to 52 surveys per year) to be evaluated during development of the MAC curves.
5. **Detection Performance**: The performance of each monitoring technology is modeled starting with a "1-trial probability of detection (PoD) curve" that shows the probabilities of detecting leaks of specific sizes assuming the survey or measurement is conducted just once per year. The modeling is done for the same 50 standard leak size classes discussed earlier with regard to the number of leaks expected from an average facility in each industry segment. A minimum detection size is also specified for each monitoring technology. The 1-trial probability of detecting large (fully continuous) leaks of 100 CH4 kg/h or larger will typically be near 100% and the 1-trial PoD for the smallest detectable leaks can be below 10%. Leaks that are smaller than the minimum detection threshold are modeled as having PoDs of 0%.
6. **Persistence of Leaks**: Fugitive leaks (as well as emissions from venting and combustion) along the natural gas supply chain are typically not continuous. In other words, they persist for a number of hours, come to an end, and then may reappear to begin a new "on-off" cycle. Therefore, the PoD values that apply to fully continuous leaks

are adjusted for periodic surveys based on the assumed “leak persistence factor” for each industry segment. This persistence factor (defined as the average percent of hours in a year a given leak will be “on”) is assumed to be 50% for the production and gathering segments and 75% for all other industry segments. The correct values for persistence factors are very uncertain and, so, they are among the variables that can be changed to create “sensitivity analysis” MAC curves for the year 2023.

7. **Annual Volume per Leak**: The annual emission from a modeled leak is calculated as the average hourly flow rate of its size class times its duration (the number of hours it is expected to flow in a year). This duration is a function of the leak’s persistence factor and whether and when it is detected and repaired.
8. **Probability of Detection**: In addition to adjusting the 1-trial PoD of a given monitoring technology and leak size to account for the average persistence factor expected in each industry segment, ICF also recalculates the PoD for each LDAR program option based on the number of times a periodic survey is assumed to be performed each year. For example, a hand-held survey option using an optical gas imaging (OGI) camera might be evaluated at frequencies of zero, once, three times, six times and 12 times per year. As the number of surveys trials (N) goes up, the N-trial PoD increases. (See below for the mathematical algorithms used in the LDAR MAC modeling.)
9. **PoD for Tiered Programs**: The modeling framework ICF employed to calculate the LDAR MAC curves also takes into account so called “tiered” LDAR program options that combine two or more monitoring technologies. When two monitoring technologies are employed in the same LDAR program, the combined PoD is not a simple addition of the PoDs of each option evaluated separately. Instead, the PoD of a second technology will be reduced to the degree the first option has already found a set of leaks and the second technology can only contribute additional finds among the remaining undetected leaks. The same consideration (i.e., that each subsequent detection technology added to the program has a smaller set of remaining leaks to work on) holds when there is a combination of three, four or five technologies employed in an LDAR program.
10. **Specification of LDAR Programs**: To create the MAC curve, several possible LDAR program options (that is, specific combinations of one to three monitoring technologies, each with a specific survey frequency) had to be evaluated. With up to five technologies (from which up to three can be applied in a program) and up to five survey frequencies that can be evaluated, there are hypothetically thousands of different LDAR program options that could be modeled for each industry segment/region. But since not every technology and survey frequency option makes sense in practice, the number of practical options modeled by ICF are approximately 300 per industry segment/region.
11. **LDAR Program Benefits**: ICF evaluated each practical LDAR program case in terms of the portion of fugitive leaks it is expected to detect and the degree by which it is expected to reduce the duration of leaks. The benefit of LDAR program was estimated as the difference between the baseline annual leak volume with no LDAR program versus the expected annual emissions after an LDAR program is implemented.
12. **LDAR Program Costs**: ICF computed the annual costs of each LDAR program option as the sum of the monitoring costs, plus the cost of follow-up inspections (to detect the exact location of true-positive leaks and distinguish false-positive leaks), plus the cost of repairing the detected true-positive leaks. ICF divided the total annual cost of a given

LDAR program option by the annual volume of methane that is expected to be detected and mitigated to produce the gross abatement cost in units of dollars per metric tons of methane abated ($/MT of CH4). This abatement cost is then converted to $/Mcf of CH4 for most of the tables and charts shown in this report.[5]

13. **LDAR MAC Curve Format**: ICF produced the MAC curve for LDAR programs in each industry segment/region with an x-axis indicating cumulative annual metric tons of methane abated and a y-axis showing the $/Mcf of CH_4 for each cumulative mitigation amount. To do this, ICF first sorted the approximately 500 LDAR program options starting from the lowest per-unit abatement cost and going up to the option with the highest per-unit abatement cost. The first point in the MAC curve was given a y-axis value equal to the $/Mcf of CH_4 abatement cost of the LDAR program with lowest cost. That first point of the curve had an x-axis value equal to the tons mitigated by the lowest cost case for the pro forma (average) facility times the number of ONE Future facilities in the subject industry segment/region.
14. **Construction of LDAR MAC Curves**: If the mitigation volume of the second most cost-effective option was greater than the mitigation volume achieved by the lowest cost case, then that second-place option was used to create the second point of the MAC curve. If the second most cost-effective LDAR program option resulted in a lower mitigation methane volume than the first, then the third (or later) most cost-effective LDAR program case was used -- provided it has greater mitigation volume. Stated in other words, the MAC curve was created using the LDAR program options sorted by cost effectiveness but skipping over options that had less mitigation volume than the lower-cost options already put into the curves. The y-axis value of each point on the MAC curve is the $/Mcf of CH_4 abatement cost of each marginal case and the x-axis value is the mitigation volume expected for an average or pro-forma facility times the number of facilities in the subject industry segment/region.
15. **Aggregated LDAR MAC Curves**: Where the MAC analysis is performed regionally, ICF added together the four MAC curves defined by segment/regions to create a national LDAR MAC curve for an industry segment. Likewise, ICF aggregated the national MAC curves by industry segment to create an LDAR MAC curve for all segments combined.
16. **LDAR MAC Curves for 2030**: ICF repeated steps 2 to 12 to create LDAR MAC curves for the future year 2030. The 2030 curves are based on the same performance and cost assumptions for monitoring technologies as were used for the year 2023. However, the activity and fugitive emission parameters used in the modeling were altered to reflect expectations for a larger overall US natural gas market size, changes in the regional mix of US gas supplies, declines in miles of iron and steel distribution mains and a corresponding increase in plastic miles, and reduced use of high-emitting pneumatic devices.
17. **LDAR MAC Curves under Revised Subpart W**. Another set of 2023 and 2030 MAC curves were created to investigate the potential impacts on reported fugitive leak

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[5] The “gross” abatement cost is computed simply as the annual LDAR program costs divided by annual methane volume that is abated. If the industry segment conducting the LDAR program can retain the value of the recovered gas, then “net” abatement cost is also computed by adjusting downward the program costs by the value of the recovered gas.

volumes that might occur due to new GHGRP Subpart W regulations. These Subpart W changes include new emission factors and expanded methodological options for reporters to estimate their emissions. As was stated above, these changes are modeled in the alternative cases as increasing 2023 fugitive emissions by 15.4% and those of 2030 by 16.2%.

18. **Sensitivity Cases for Technology Performance**: To produce the "sensitivity cases" related to uncertainties in the performance of leak detection technologies, ICF again repeated steps 2 to 12 but with different parameters that are used to generate the PoD curves. For the "Worse Performance Case," ICF doubled the leak sizes corresponding to a 90% (Q90) and 0.1% (Qmin) probability of detection for each technology as compared to the base case values. For the "Better Performance Case" the Q90 and Qmin values were set to one-half the base case values. Thus, the Q90 and Qmin values were tested over a range that varied by a factor of four. For example, the Q90 values for satellite leak detection technology are 50, 100 and 200 kg/h of methane for the Better, Base and Worse cases respectively.

3.2 Baseline Fugitive Emissions for 2023 and 2030

ICF compiled 2023 fugitive activity and emissions data for the ONE Future companies using the data sources and processing procedures described in **Chapter 2**. These fugitive emissions data are shown in the top part of Exhibit 16. The bottom portion of the Exhibit 16 contains the same data for the year 2030. As was explained in **Chapter 2**, the 2030 emission estimates are based on the 2025 EIA Annual Energy Outlook Reference Case energy supply and demand balances and incorporate ICF's expectations for shifts in certain supply chain infrastructure such as reduced use of high-bleed pneumatic devices and an increase in the use of plastic distribution mains and services and a reduction in the use of mains and services made from steel and other metals.

To conduct the analysis of the economics of various LDAR program options, ICF compiled or estimated modeling parameters that represent an average facility in each industry segment and (where needed) each region. These modeling parameters included annual production or throughput, annual fugitive emissions by type, and various counts of equipment and assets (e.g., counts of wells and well pads, miles of pipeline, counts of compressors, number of customer meters, etc.).

The "baseline" values to be used in the modeling for annual fugitive methane emissions (in units of metric tons of methane per year per facility) were derived from the statistical average of data in Exhibit 16 with a upward adjustments averaging 24% across all segments. The upward adjustments were calculated as the difference in emissions detectable by the best widely used (e.g., handheld devise) methods versus the power law distributions used to model the underlying "actual" emission. These adjustments account for the belief that estimation methods miss some of the smallest leak sizes and result in an undercount of leak occurrences and total leak volumes.

Exhibit 16: Reported 2023 and Estimated 2030 Current Protocol Fugitive Emissions

			East	Midcontinent	Gulf Coast	Rocky Mountain	National Total
Year	**Case**	**Segment**	**Emissions (mt CH4)**	**Emissions (mt CH4)**	**Emissions (mt CH4)**	**Emissions (mt CH4)**	**Emissions (mt CH4)**
2023	Base Case	Onshore Production	1,115	1,108	8,908	1,676	12,807
2023	Base Case	Offshore Production					442
2023	Base Case	Gathering	4,461	3,840	7,483	1,886	17,669
2023	Base Case	Processing	170	105	1,300	109	1,683
2023	Base Case	Transmission					63,517
2023	Base Case	Storage					4,753
2023	Base Case	Distribution	141,711	37,895	31,887	36,381	247,875
2023	Base Case	Distribution Storage	656	9	7	55	726
2023	Base Case	LNG Import Export					52
2030	Base Case	Onshore Production	1,408	1,089	9,300	1,648	13,445
2030	Base Case	Offshore Production					485
2030	Base Case	Gathering	5,634	3,774	7,812	1,854	19,074
2030	Base Case	Processing	214	103	1,358	107	1,782
2030	Base Case	Transmission					65,849
2030	Base Case	Storage					4,640
2030	Base Case	Distribution	138,742	38,112	30,295	36,481	243,629
2030	Base Case	Distribution Storage	712	9	7	56	784
2030	Base Case	LNG Import Export					52

Notes: These emission values are the unadjusted values derived from emissions reported by ONE Future members and the projection of those values to 2030. To produce the fugitive emissions "baseline" values used to model LDAR economics, the values in this table are increased by an average of 24% (ranging from 3% to 31% by segment) to correct for what is believed to be an under-reporting of emissions from small leaks. Rows with no regional values and shaded in gray indicate industry segments in which the modeling was done on a national (rather than regional) basis.

Exhibit 17: Estimated Baseline Fugitive Emissions after Expected Subpart W Revisions

			East	Midcontinent	Gulf Coast	Rocky Mountain	National Total
Year	Case	Segment	Emissions (mt CH4)	Emissions (mt CH4)	Emissions (mt CH4)	Emissions (mt CH4)	Emissions (mt CH4)
2023	Subpart W Rev.	Onshore Production	4,374	4,140	35,251	6,547	50,312
2023	Subpart W Rev.	Offshore Production					442
2023	Subpart W Rev.	Gathering	6,239	5,371	10,460	2,619	24,688
2023	Subpart W Rev.	Processing	274	169	2,096	175	2,714
2023	Subpart W Rev.	Transmission					71,233
2023	Subpart W Rev.	Storage					7,376
2023	Subpart W Rev.	Distribution	141,936	38,148	31,928	36,504	248,515
2023	Subpart W Rev.	Distribution Storage	656	9	7	55	726
2023	Subpart W Rev.	LNG Import Export	52	0	0	0	52
2030	Subpart W Rev.	Onshore Production	5,524	4,069	36,801	6,439	52,833
2030	Subpart W Rev.	Offshore Production					485
2030	Subpart W Rev.	Gathering	7,879	5,278	10,920	2,576	26,653
2030	Subpart W Rev.	Processing	345	166	2,189	172	2,872
2030	Subpart W Rev.	Transmission					73,848
2030	Subpart W Rev.	Storage					7,199
2030	Subpart W Rev.	Distribution	138,986	38,379	30,335	36,607	244,308
2030	Subpart W Rev.	Distribution Storage	712	9	7	56	784
2030	Subpart W Rev.	LNG Import Export					52

Notes: These emission values are estimated by adjusting the "baseline" values shown in the previous exhibit to account for expected changes in the Subpart W reporting rule. These changes involve revised emission factors and the introduction of new sources. To produce the fugitive emissions for the "Subpart W Revisions Case" modeling, the values in this table are increased by an average of 24% (ranging from 3% to 31% by segment) to correct for what is believed to be an under-reporting of emissions from small leaks. Rows with no regional values and shaded in gray indicate industry segments in which the modeling was done on a national (rather than regional) basis.

3.3 The Distribution of Leak Sizes

ICF broke out the fugitive emission target for pro forma facilities in each industry segment/region into annual counts of leaks by leak size class. There are 50 leak size classes which are denominated in units of kilograms of methane per hour (CH_4 kg/h). The annual emissions from the leaks are calculated as their hourly emission rate times the number of hours the leak is expected to last over one year. This is a function of the persistence factor (i.e., the fraction of the hours the leak is "on") and how long the leak will survive until it is detected and repaired. The benefit of LDAR programs comes from finding leaks sooner and reducing the time they are leaking.

The modeling of the leak sizes begins with a "basic distribution pattern" that ICF derived from various published leak detection studies.[6] These basic patterns were assumed to follow a "power law distribution" that is characterized by a small number of large leaks, a greater number

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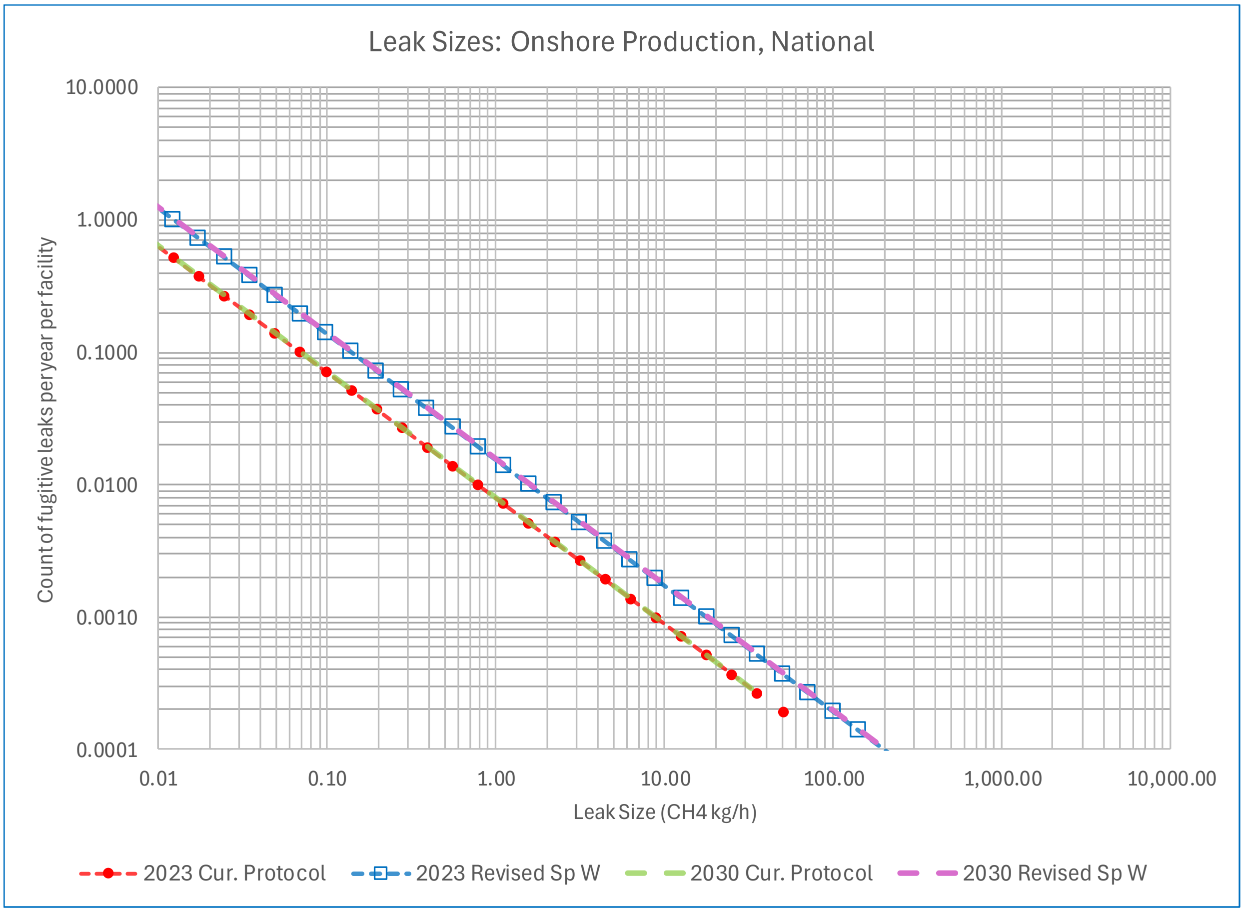
[6] The basic leak size distribution for production, gathering, processing and transmission was derived from the Appalachian Methane Initiative 2024 Champaign as published March 4, 2025. See AMI+2024+Campaign+Final+Report.pdf The source used for the distribution segment was Zachary D. Weller et al. at https://pubs.acs.org/doi/10.1021/acs.est.0c00437?goto=supporting-info.

of mid-size leaks and a large number of small leaks. The power law distribution forms a straight line when the number of leaks is plotted along the y-axis on a logarithmic scale and the size of the leak is plotted on the x-axis on a logarithmic scale.

The leak counts in the “basic distribution pattern” are adjusted in the LDAR MAC curve model so that the number of leaks and the unmitigated fugitive emission volumes match the per-facility targets for the industry segment, case (Current Protocol Case or Revised Subpart W Case) and year (2023 or 2030). This is done by first sequentially removing the largest leaks from the basic distribution pattern until the truncated distribution matches the target average leak size for the case. The target average leak size for a case is computed as the segment’s target emissions in kilograms per year divided by the target leak count divided by the number of facilities divided by the number of hours an unmitigated leak is “on” in a year. Then in the second step, the count of leaks in all size classes is scaled by a single factor that causes the sum of all sizes classes to exactly match the target leak volume.

This calibration of the leak size distribution is conducted for the Current Protocol Cases and then again for the Revised Subpart W Cases. An example is shown for the national average Onshore Production segment in Exhibit 18. Because of the larger target leak volumes in the Revised Subpart W Cases (see Exhibit 17 versus Exhibit 16) their leak size distributions contain a larger number of leaks and bigger average leak sizes as compared to the Current Protocol Cases.

Exhibit 18: Leak Size Distribution for Current Protocol Case versus Revised Subpart W Case: Onshore Production



Average Leak Statistics by Case	2023 Cur. Protocol	2023 Revised Sp W	2030 Cur. Protocol	2030 Revised Sp W	*Onshore Production 'facilities' are defined as Well Pads*
Leaks per year per facility	2.5	5.0	2.6	5.1	
Avr. Leak Size (kg/hr)	0.08	0.16	0.08	0.16	
Emissions per facility (kg/year)	880	3,456	902	3,542	

V110

small leak adjustment factor 1.139

3.4 Performance of Leak Detection Technologies

To evaluate the performance and economics of different options for an LDAR program, ICF selected up to five monitoring technologies to be evaluated for each industry segment and category. Some of these are continuous monitoring technologies and the others are periodic leak detection surveys. For the periodic surveys, ICF selected up to five possible survey frequencies (ranging from zero to 52 surveys per year) to be evaluated during development of the MAC curves. Each of approximately 300 practical options are evaluated and then sorted from the lowest to highest $/Mcf of methane abatement cost to create the MAC curve.

3.4.1 Probability of Detection for N=1

The probability of finding a leak with a single survey (N=1) of a specific technology is modeled using the equation shown below.[7] The coefficients for this equation are fitted in the LDAR MAC curve model so that the resulting PoD curve for a given technology passes through the two benchmark points that are used to describe the performance of the technology (when the leak is assumed to be "on" and the persistence factor is held at one). The first benchmark point is the leak rate (called Q90) that corresponds to a 90% probability of detection. Therefore, leak sizes of Q90 or greater will have PoDs of 90% to 100%. The second benchmark point (called Qmin) is where the PoD value comes close to zero (equals 0.1% to be exact). Leak sizes below Qmin are essentially undetectable with a given technology.

$$PoD_{k,t,N=1} = exp\left(-(C1_t \times {Q_k}^{C2_t})^{C3_t}\right) \times Persistence\_Factor$$

Where:

$PoD_{k,t,N=1}$ *is probability of detection of leaks size class "k" using technology "t" for a single trial (N=1)*

Q_k *is the average emission rate of leaks in size class "k" measured in kg/h of methane*

$C1_t$, $C2_t$ *and* $C3_t$ *are coefficients of the PoD equation for technology "t"*

Persistence_Factor is the fraction of the hours in a year an undetected leak will be "on"

The "base case" or "Middle Case" parameters for the performance of various leak detection technologies are shown in Exhibit 19. The exhibit shows the Q90 and Qmin values assumed for each technology and the three equation coefficients that were fitted so that the PoD curve for each technology passes through the quantity Q90 at a 90% probability and through the quantity Qmin at a 0.1% probability. In addition to these "Middle Case" leak detection performance parameters, the model also contains a "Better Performance Case" option in which the Q90 and Qmin values are cut in half and a "Worse Performance Case" option in which the Q90 and Qmin values are set to twice the "Middle Case" values. The "Better Performance Case" and "Worse Performance Case" parameters are used in sensitivity analyses that are shown later in section 3.9 of this chapter.

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[7] The formulation of this equation was adapted (in a simplified form) from Bradley Conrad et al., 2023. (PDF) Robust probabilities of detection and quantification uncertainty for aerial methane detection: Examples for three airborne technologies

Exhibit 19: Leak Detection Performance Parameters: Middle Case

				Parameters for PoD Equation		
Short Name	Leak Detection Technology	Qmin (kg/h)	Q90 (kg/h)	Q Exponent (C2)	Outer Exponent (C3)	Q Intercept (C1)
NOM/AVO	Normal Operations Monitoring or Audio, Visual, Olfactory	10.0	91.0	1.250	-1.515	0.016
Patrol-p/l	Mobile Patrols of P/L Rights of Way	5.0	25.0	1.225	-2.121	0.056
Walking ALD-p/l	Walking Survey w/ALD Instrument	0.020	1.0	0.614	-1.740	3.644
Aerial-p/l	Mobile Aircraft (LiDAR) Linear	0.53	4.0	1.244	-1.669	0.687
Aerial	Mobile Aircraft (LiDAR)	0.53	4.0	1.244	-1.669	0.687
AMLD	AMLD Mobile Ground Vehicle (LiDAR)	0.020	1.0	0.775	-1.380	5.106
Satellite-p/l	Satellite SWIR Linear	12.50	100.0	1.250	-1.609	0.013
Satellite	Satellite Short Wave Infrared (SWIR)	12.50	100.0	1.250	-1.609	0.013
CM Tower-p/l	Stationary CM: Laser Spect. Tower Linear	0.429	3.0	0.874	-2.460	0.956
CM Tower	Stationary CM: Laser Spectroscopy Tower	0.429	3.0	0.874	-2.460	0.956
CM Tower LDC	Stationary CM: LST in urban area	0.429	3.0	0.874	-2.460	0.956
CM Tower Single	Stationary CM: LST 1 facility only	0.429	3.0	0.874	-2.460	0.956
Handheld	Handheld Survey (e.g., OGI camera)	0.010	0.5	0.569	-1.880	4.909

Notes: These are the “Middle Case” leak detection performance parameters. The LDAR MAC curve model also contains a “better performance case” option in which the Q90 and Qmin values are cut in half and a “worse performance case” option in which the Q90 and Qmin values are set to twice the “Middle Case” values. The term “linear” and “p/l” is used in this table to describe the application of the technology to survey for leaks along linear infrastructure (i.e., gathering lines, transmission pipelines or distribution mains). The cost of linear surveys are usually represented in the LDAR MAC curve model in units of $/mile.

The performance parameters for leak detection technologies displayed in Exhibit 20 come from ICF’s compilation of performance data from vendors, third party verifiers, and ONE Future members who have researched, tested or deployed each technology. The parameters shown in Exhibit 20 and the corresponding “Better Performance Case” and “Worse Performance Case” values should be understood to be approximations suitable for the MAC curve analysis. But the model’s range of performance parameters should not be expected to encompass “real world” results under all circumstances.

The accuracy of leak detection and quantification of any specific technology can depend on many factors such as gas composition, leak velocity, gas temperature, ambient temperature and humidity, presence of background methane, wind speed, distance between the detection device and the leak, survey protocol (e.g., number of passes, detector spacing, dwell time, post-survey data processing) and the training and experience of survey technicians. For example, Exhibit 20 shows how one technology (continuous monitoring using laser spectroscopy towers) was estimated to perform under varying wind conditions in a controlled release study. The bottom of the exhibit also shows the performance parameters applied in the MAC curve model – which are typically chosen to be more conservative than the results of the controlled release studies.

Exhibit 20: Performance Parameters for Continuous Monitoring Towers

Leak Rates Corresponding to 90% and 0.1% Probability of Detection: CM Towers

Estimates from Controlled Release Study			
Wind Speed in meters per second	Q90 (CH4 kg/h)	Qmin (CH4 kg/h)	Ratio Q90:Qmin
1 m/s wind speed	0.41	0.063	6.6
3 m/s wind speed	1.23	0.188	6.6
5 m/s wind speed	2.05	0.313	6.6

Adapted from Longpath Technology's application to EPA quoting Gas Mapping LiDAR Study (Clay Bell, et al. "Performance of Continuous Emission Monitoring Solutions under a Single-Blind Controlled Testing Protocol," Environ. Sci. Technol. 2023, 57, 5794-5805). The study itself did not identify specific technology vendors.

Modeling Assumptions for This Study			
Modeling Sensitivity Case	Q90 (CH4 kg/h)	Qmin (CH4 kg/h)	Ratio Q90:Qmin
Modeling Worse Case	6.0	0.857	7.0
Modeling Middle Case	3.0	0.429	7.0
Modeling Better Case	1.5	0.214	7.0

3.4.2 Adjustment of the PoD for Leak Persistence

As was mentioned earlier in this chapter, fugitive leaks along the natural gas supply chain are often not continuous but rather persist for a number of hours, come to an end, and then may reappear to begin a new “on-off” cycle. For example, a study by Cusworth et al. calculated an average persistence factor of 26% for 1,100 Permian Basin sources.[8] The study covered 55,000 square kilometers of area with thousands of upstream and midstream elements employing an aerial survey technology with an instrument detection limit of 10–20 CH_4 kg/h. This study included methane emissions from both normal operations as well as fugitive emissions. The average persistence value of 26% means that at any one time 74% of sources would be “off” while 26% would be “on.” This intermittency is caused by periodic maintenance activities and equipment blowdowns, changing weather conditions, cycling process conditions such as liquid levels in tanks and separators, and occasional equipment failures such malfunctioning pneumatic devices, stuck thief hatches, etc.

To deal with this persistence issue, the MAC curve model’s N=1 PoD equation applies an assumed “leak persistence factor” for each industry segment. This persistence factor is as the average percent of hours in a year that leaks will be “on.” So, if a leak is not detected and repaired, it will emit for 8,760 hours per year times the persistence factor. In the Base Case and the Subpart W Revision cases, the persistence factor is assumed to be 50% for the production

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[8] Daniel H. Cusworth et al. 2021, Intermittency of Large Methane Emitters in the Permian Basin | Environmental Science & Technology Letters

and gathering segments and 75% for all other industry segments. An upstream persistence factor above the 26% calculated in the Cusworth study has been selected under the belief that fugitive emissions might be more consistent than those associated with normal operations, which are associated with cyclic maintenance work schedules and product/byproduct logistics. Also, higher assumed values for the LDAR model's persistence factors may be justified because they represent persistence of all leak sizes before any mitigation while the Cusworth study covered relatively large leaks, some of which presumably would have been detected and fixed during the periods between surveys. The correct values for persistence factors are very uncertain and, so, they are among the variables that can be changed to create "sensitivity analysis" MAC curves.

3.4.3 How PoD Changes as Number of Annual Surveys is Increased

LDAR "programs" are created and evaluated is this analysis by combining one or more detection technologies that would be applied once or several times per year. The number of annual surveys or "trials" is represented by the letter "N." The probability of detection for N=x trials per year is calculated in the model using the equation shown below.

$$PoD_{k,t,N=x} = \left(\sum_{i=1}^{x} 1 - (1 - PoD_{k,t,N=1})^{i} \right) / x$$

Where:

$PoD_{k,t,N=x}$ *is the probability of detection of leaks in size class "k" using technology "t" for "x" trials in a year*

$PoD_{k,t,N=1}$ *is probability of detection of leaks in size class "k" using technology "t" for a single trial (N=1) – this was calculated by the previous equation*

"x" is number of surveys conducted each year

"i" is how many surveys any particular leak might be subject to (1 time for leaks starting in the last survey period up to x times for leaks that begin in the first survey period)

The equation differs from the standard method of estimating the chance of one success after N trials by introducing a summation from "i" equals one to "x" (where "x" represents the number of trials per year specified for a given detection technology included in an LDAR program) and then dividing the result of that summation by "x." This is done because a leak can begin at any time in a year and, therefore, the number of chances a regularly scheduled survey program will have to detect it is itself a stochastic variable. For example, if leak detection surveys are scheduled to occur at the end of each month, a leak that begins in January will have 12 chances of being detected during the annual LDAR program. If a leak begins in February, it will have 11 chances of being detected and a leak that begins in December will have just one chance. Therefore, the N=x PoD equation is computing the weighted average probability given that leaks can begin at any time in the year and will be subject to something between 1 and x surveys.

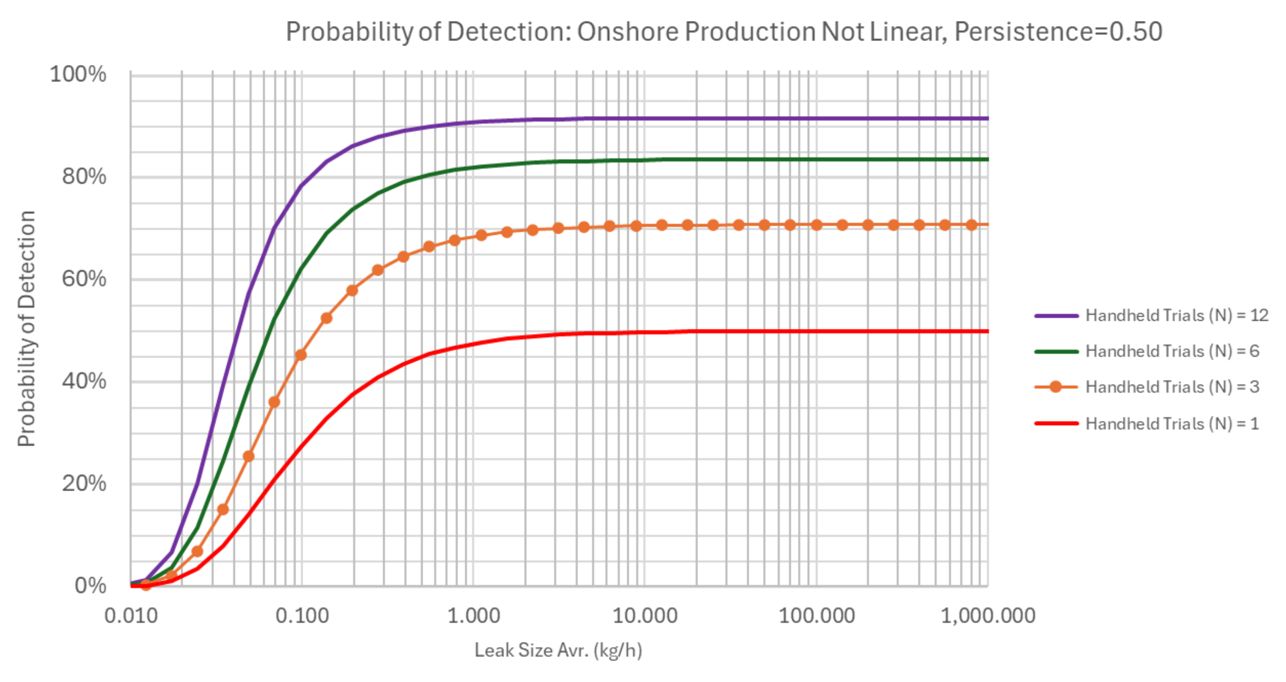
An example of the resulting PoD curves is shown in Exhibit 21 for handheld devices applied to the onshore production sector in which leaks have a persistence factor of 50%. The red line at the bottom represents the N=1 probability curve, which is built up from the assumption that leaks of size 0.50 kg/h have a 90% chance of being found if they exist when the survey is being made. (See the technology performance parameters shown in Exhibit 19.) Since there is a 50%

persistence factor, leaks of size 0.50 kg/h on the x-axis have y-axis values of 45% (the assumed 90% PoD benchmark point times the 50% persistence factor).

As you move from right to left on the x-axis (that is, leaks become smaller and smaller), the probability of leak detection goes down. The Qmin for handheld device is assumed to be 0.010 kg/h. This is the point (times the 50% persistence factor) where the red line comes close to zero percent.

The orange, green and purple lines above the red line represent N=3 to N=12 surveys per year. As the number of surveys increase, so does the probability of detection. However, the rate of increase (measured as the incremental detections for each one extra survey) goes down as N goes up because each extra survey has a smaller population of remaining leaks that it can find.

Exhibit 21: PoD Example: Handheld Device for Onshore Production (persistence factor is 50%)



3.4.4 Calculation of PoD When More than One Detection Technology is Included in a “Tiered” Program

The process of estimating the LDAR MAC curves includes so called “tiered” LDAR program options that combine two or more monitoring technologies. For tiered LDAR programs, individual PoD’s are first computed separately for each technology using the equations described above. The resulting technology-specific probabilities are then combined into a program probability by multiplying together each technology’s probability of failure (that is, one minus the PoD) and subtracting that product from one, as shown in the equation below.

$$PoD_{k,p} = 1 - \left(\prod_{t=1}^{c} \left(1 - PoD_{k,t,N=x}\right) \right)$$

Where:

$PoD_{k,p}$ *is the probability for program "p" of detecting leaks in size class "k"*

$PoD_{k,t,N=x}$ *is the probability for detecting leaks in size class "k" when technology "t" is applied by itself for N=x times per year*

"c" is the number of leak detection technologies being included in the program

The combined probability for a tiered program is not a simple addition of the PoDs of each technology. This is because the PoD of a second technology will be reduced to the degree the first technology has already found a set of leaks and the second technology can only contribute additional detections among the remaining undetected leaks. The same consideration (i.e., that each subsequent detection technology added to the program has a smaller set of remaining leaks to work on) holds when there is a combination of two or three technologies employed in an LDAR program.

3.5 Cost of LDAR Program Options in the MAC Model

The LDAR MAC model computes the annual cost of each LDAR program option as the sum of the monitoring costs, plus the cost of follow-up inspections (to detect the exact location of true-positive leaks and distinguish false-positive leaks), plus the cost of repairing the detected true-positive leaks. To compute the per-unit cost of methane abatement, the total cost of a given LDAR program option (in units of dollars per year per facility) is divided by the volume of methane (in units of metric tons) that is detected and mitigated. This results in the gross abatement cost in units of dollars per metric tons of methane abated (\$/MT of CH_4). This abatement cost is then converted to \$/Mcf of CH_4 for most of the tables and charts shown in this report.[9]

3.5.1 Leak Detection Survey Costs

Leak detection costs are computed in the MAC curve model using the cost coefficients that are shown in Exhibit 22. Note that there are direct costs for the survey service itself plus a general and administrative (G&A) cost factor of 15% that is applied to the direct cost. This G&A factor represents the asset owner's cost of procuring and supervising the survey work. These cost coefficients were developed by ICF based on information provided by ONE Future members. The coefficients are presented on a per-unit basis under the assumption that a number of facilities are being surveyed under a service contract between the asset owner and a technology provider. If a survey contract were to cover only one or a small number of

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[9] The "gross" abatement cost is computed simply as the annual LDAR program costs divided by annual methane volume that is abated. If the industry segment conducting the LDAR program can retain the value of the recovered gas, then a "net" abatement cost is also computed by adjusting downward the program costs by the value of the recovered gas.

facilities/sources, then the per unit costs could be much higher than shown here. This is particularly true for technologies such as aerial surveys that have high mobilization costs.

In cases where the detection survey is to be conducted along linear assets such as gathering lines, gas transmission pipelines or distribution mains, the cost coefficients are typically in units of dollars per mile for a single survey. Where the survey covers a large area (e.g., satellite or aerial surveys of production and gathering assets), the cost coefficients are usually specified in dollars per square mile for a single survey.

The cost of surveys using handheld devices such as optical gas imaging cameras are represented as a fixed cost per facility plus a variable cost per source in the facility. For example, a handheld survey of an onshore production pad is modeled as having direct costs $500 plus $1/source times 200 sources/pad = $700. Adding the 15% G&A cost factor brings the total cost to $805 per pad.

The technology used to represent advanced continuous monitoring is a rotating laser spectroscopy unit mounted on a tower surrounded by fixed mirrors attached to poles, buildings or other infrastructure which are located up to three kilometers or more away from the tower. The laser is periodically directed at each mirror and the laser beam that bounces off the mirrors and returns to the spectroscopy unit is analyzed to determine what gases are contained in the air along the pathway. The system compares the gas compositions estimated along each radial pathway over time and factors in wind direction and speed to determine the rate of methane release from different areas within the survey area.

The survey area covered by a single tower is modeled as nine square miles in production areas and 2.25 square miles in populated areas, where the laser pathways are more likely to be interrupted by buildings. If applied to linear infrastructure, a single tower is assumed to be able to monitor about six miles of pipeline. The assumed cost of each CM tower leased from a service provider (including installation, maintenance, monitoring and data processing) is estimated to be $54,000 per year in production areas and $82,000 per year in populated areas.[10] The cost shown in Exhibit 22 for CM towers are based on these costs and survey areas translated into unit costs. For example, a CM tower costing $54,000 per year and covering six miles of pipeline translates into $6,000 per year per mile. Note that even though such towers can provide several readings in a day under favorable weather conditions, they are probabilistically modeled as providing N=365 surveys per year.

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[10] The higher cost assumed for populated areas is made up by 25% higher construction cost plus $15,000 per year for land rental (the average rent paid in the US for cell phone towers).

Exhibit 22: Cost Coefficients for Leak Detection Technologies

		Direct Costs						
Short Name	Leak Detection Technology	$ per linear mile per survey	$ per linear mile per YEAR	$ per square mile per survey	$ per square foot of facility per YEAR	Fixed Cost per Facility per Survey	Variable Cost per Source Inside Facility per Survey	**General & Administrative Cost Factor (% of direct costs)**
NOM/AVO	Normal Operations Monitoring or Audio, Visual, Olfactory					$1	$0.01	15%
Patrol-p/l	Mobile Patrols of P/L Rights of Way	$130						15%
Walking ALD-p/l	Walking Survey w/ALD Instrument	$160						15%
Aerial-p/l	Mobile Aircraft (LiDAR) Linear	$195						15%
Aerial	Mobile Aircraft (LiDAR)			$3,500				15%
AMLD	AMLD Mobile Ground Vehicle (LiDAR)	$200						15%
Satellite-p/l	Satellite SWIR Linear	$775						15%
Satellite	Satellite Short Wave Infrared (SWIR)			$1,550				15%
CM Tower-p/l	Stationary CM: Laser Spect. Tower Linear		$9,000					15%
CM Tower	Stationary CM: Laser Spectroscopy Tower				$0.032			15%
CM Tower LDC	Stationary CM: LST in urban area				$0.001			15%
CM Tower Single	Stationary CM: LST 1 facility only					$148 ($54k/year for 1 tower)		15%
Handheld	Handheld Survey (e.g., OGI camera)					$500	$1.00	15%

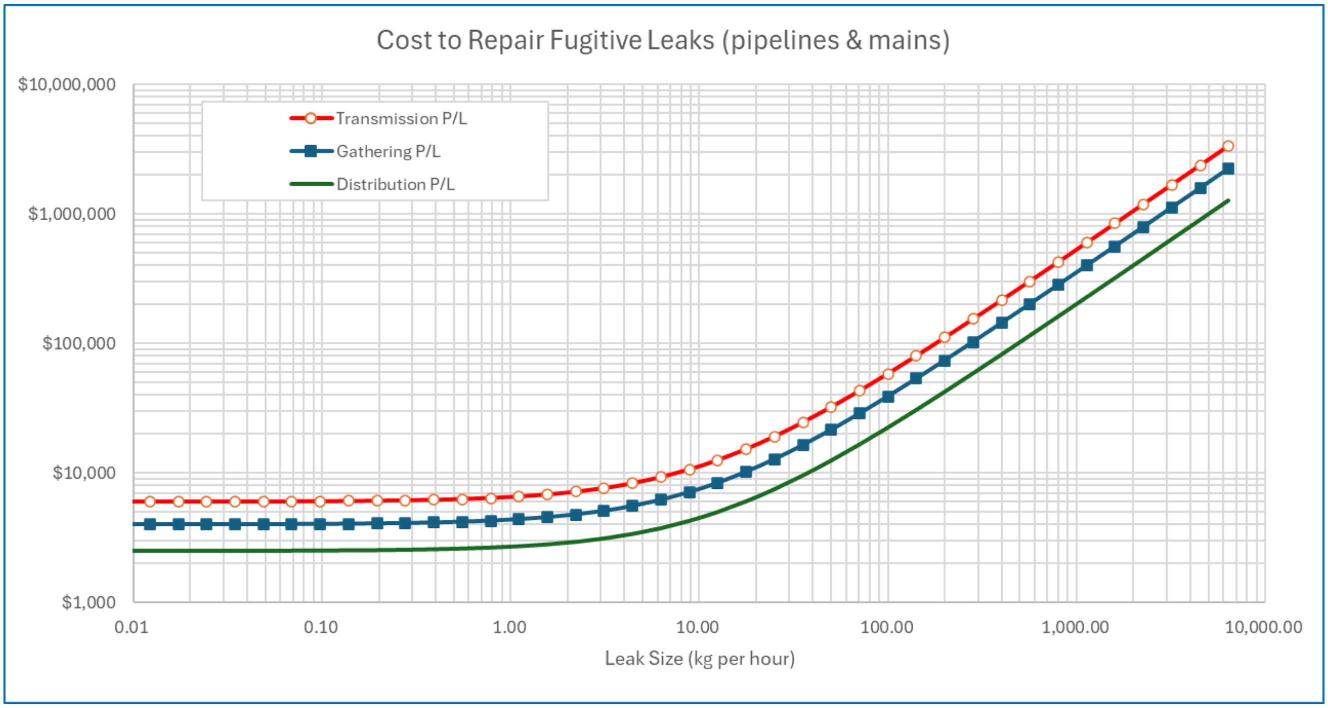
Note: These costs are presented in this table on a per-unit basis under the assumption that a number of facilities are being surveyed under a service contract with a technology provider. If a survey contract were to cover only one or a small number of facilities/assets, then the per unit costs could be much higher than shown here. This is particularly true for technologies such as aerial surveys that have high mobilization costs.

3.5.2 Follow-up Inspection and Repair Costs

As was stated above, the cost of each LDAR program option is the sum of the monitoring costs, plus the cost of follow-up inspections (to detect the exact location of true-positive leaks and distinguish false-positive leaks), plus the cost of repairing the detected true-positive leaks. The follow-up inspections are assumed to cost $360 (the cost of survey using a handheld device such as OGI camera or “sniffer”) and to occur for all true-positive leaks plus for a number of false-positive leaks assumed to be equal to 25% of the true-positive leak count. Stated in other words, follow-up inspection costs are computed as $360 x 125% x number of true-positive leaks.

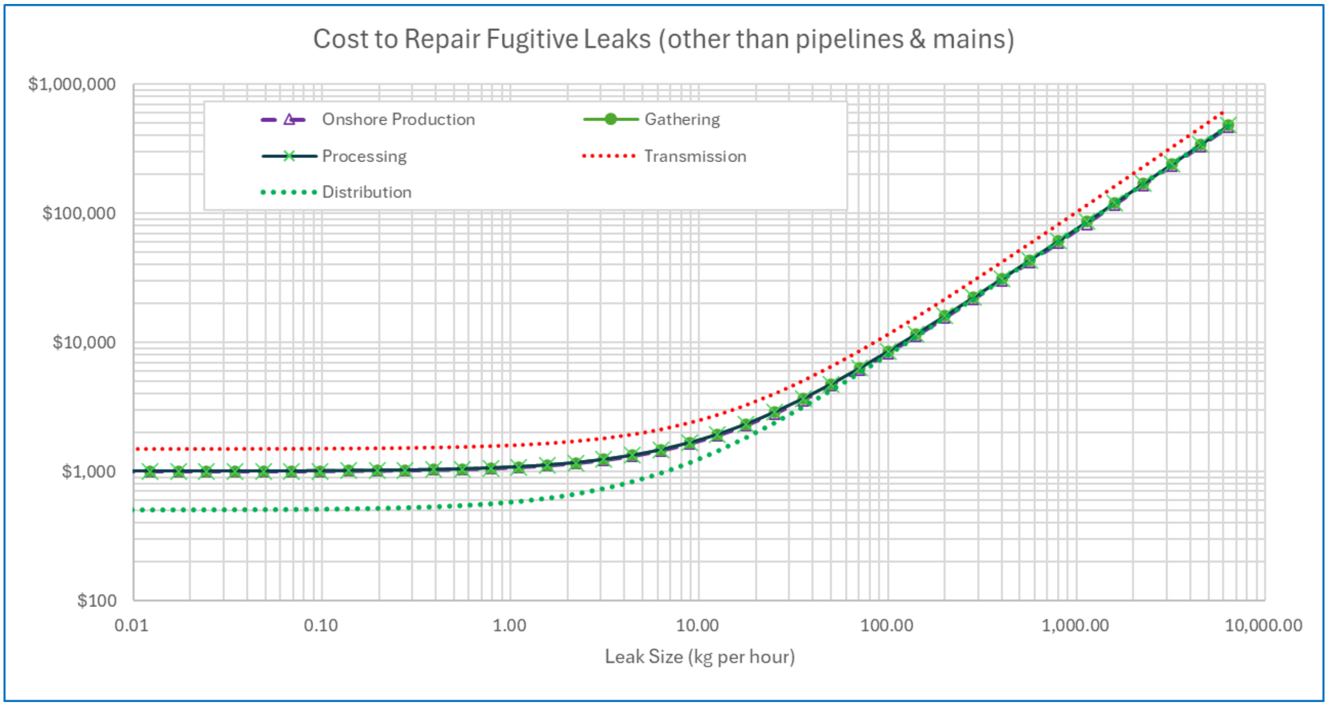
The cost to repair leaks varies widely (from under $500 to over $1,000,000 per leak) in the MAC curve model. The repair costs are calculated as a function of industry segment and the size of the leaks. These repair costs are shown graphically in Exhibit 23 for pipelines and mains and in Exhibit 24 for other kinds of equipment and facilities.

Exhibit 23: Leak Repair Costs: Pipelines and Mains



Note: These are costs per each true-positive leak and include labor, equipment and materials and general and administrative expenses including any costs related to excavation and surface remediation.

Exhibit 24: Leak Repair Costs: Facilities Other Than Pipelines and Mains



The cost estimates were developed by ICF from industry association comments related to PHMSA draft rule[11], consultant reports related to PHMSA draft rules[12], third-part studies[13], and ONE Members' confidential survey responses. As is the case with cost algorithms for leak detection technologies, these values should be understood to represent approximations suitable for industry-wide modeling and do not represent what real-world costs would be in any given case.

3.6 Creation of the MAC Curves

In creating the MAC curve, ICF evaluated several possible LDAR program options made up of one to three monitoring technologies, each of which had up to five different survey frequencies. Since not every combination of technology and survey frequency makes sense in practice, the number of practical options modeled by ICF come out to be approximately 300 per industry segment/region.

ICF evaluated each practical LDAR program case in terms of the number and size distribution of fugitive leaks it is expected to detect. The benefit of each practical LDAR program was estimated as the difference between the baseline annual leak volume with no LDAR program versus the expected annual emissions after an LDAR program is implemented. To compute the per-unit cost effectiveness, ICF divided the total cost of a given LDAR program option by the volume of methane that is detected and mitigated to produce the gross abatement cost in units of dollars per metric tons of methane abated ($/MT of CH_4) and in units of $/Mcf of CH_4 – the convention used for most of the tables and charts shown in this report.

ICF produced the MAC curve for LDAR programs in each industry segment/region with an x-axis indicating cumulative annual metric tons of methane abated and a y-axis showing the $/Mcf of CH_4 for each cumulative mitigation amount. To do this, ICF sorted the approximately 500 LDAR program options starting from the lowest per-unit abatement cost and going up to the option with the highest per-unit abatement cost. Options were put into a MAC curve only if they resulted in higher abatement volumes than were obtained by the lower-cost options already placed into the curve.

3.7 2023 and 2030 LDAR MAC Curves for Emissions Estimated under Current Protocol

Exhibit 25 shows the LDAR MAC curve analysis for the year 2023 wherein the fugitive emissions were based on ONE Future's Current Protocol and the performance parameters of detection technologies are the "Middle Case." Exhibit 26 shows the same data for the year 2030. The 2030 curves are based on the same performance and cost assumptions for monitoring technologies and repairs as were used for the year 2023. However, the activity and fugitive emission parameters used in the modeling were altered to reflect expectations for a

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[11] "Comments on Pipeline Safety: Gas Pipeline Leak Detection And Repair," from API and other gas industry associations at https://www.api.org/~/media/files/news/2023/08/16/industry-ldar-nprm-comments

[12] Highwood Emissions Management, "PHMSA Methane Detection Requirements Analysis: Evaluation of PHMSA's proposed monitoring technology requirements," Technical Report for API, August 2023.

[13] See Carbon Limits study for CATF at Carbon Limits LDAR

larger overall US natural gas market size, changes in the regional mix of US gas supplies, declines in miles of iron and steel distribution mains and a corresponding increase in plastic miles, reduced use of pneumatic devices, etc.

The baseline emissions for these cases are shown by sector in the last row of Exhibit 25 and Exhibit 26. The last column of the exhibits shows the all-segment abatement volume from LDAR programs as a percent of the baseline emissions. For 2023, potential abatement at $500/Mcf is estimated to be 82.9% of the baseline fugitive emission volume. In 2030, potential abatement at $500/Mcf is estimated to be 81.8% of the baseline fugitive emission volume.

Exhibit 25: LDAR MAC Curves by Segment: 2023 Current Protocol

2023 LDAR MAC Curve for Cur. Protocol, Mid P Scenario, National Region: metric tons per year of methane abated vs. baseline									*V110*
Gross Abatement Cost ($/Mcf)	Onshore Production	Gathering	Processing	Transmission	Storage	Distribution	Other Segments	All Segments	*All Segments as % of Baseline*
$3	-	-	-	-	-	-	318	318	*0.1%*
$5	-	-	-	-	-	-	318	318	*0.1%*
$8	-	-	-	29,445	-	-	366	29,811	*6.9%*
$10	-	-	-	30,951	-	-	431	31,382	*7.2%*
$15	-	-	-	38,498	-	-	467	38,964	*9.0%*
$20	6,417	-	-	42,531	3,237	57,703	490	110,378	*25.5%*
$25	6,417	-	-	45,788	3,908	102,688	490	159,290	*36.8%*
$50	8,025	8,223	1,335	48,246	4,329	204,493	1,064	275,716	*63.7%*
$75	8,593	12,731	1,374	48,596	4,424	221,863	1,148	298,729	*69.0%*
$100	8,593	13,835	1,469	48,596	4,424	232,184	1,148	310,249	*71.6%*
$200	9,027	16,125	1,485	53,163	4,481	246,194	1,155	331,631	*76.6%*
$300	9,179	16,345	1,492	57,912	4,481	259,255	1,156	349,819	*80.8%*
$400	9,601	16,510	1,492	59,689	4,481	262,498	1,156	355,427	*82.1%*
$500	10,330	16,628	1,492	59,689	4,481	265,394	1,158	359,172	*82.9%*
$1,000	11,409	16,852	1,492	60,714	4,481	268,627	1,158	364,733	*84.2%*
$2,000	11,576	16,922	1,492	61,005	4,481	269,229	1,158	365,864	*84.5%*
Baseline MT/y	**14,587**	**18,284**	**1,961**	**66,369**	**5,162**	**325,313**	**1,429**	**433,105**	***100.0%***

Note: "Other Segments" include offshore production, distribution storage and LNG export.

Exhibit 26: LDAR MAC Curves by Segment: 2030 Current Protocol

2030 LDAR MAC Curve for Cur. Protocol, Mid P Scenario, National Region: metric tons per year of methane abated vs. baseline									*V110*
Gross Abatement Cost ($/Mcf)	Onshore Production	Gathering	Processing	Transmission	Storage	Distribution	Other Segments	All Segments	*All Segments as % of Baseline*
$3	-	-	-	-	-	-	349	349	*0.1%*
$5	-	-	-	-	-	-	349	349	*0.1%*
$8	-	-	-	30,525	-	-	400	30,926	*7.2%*
$10	-	-	-	32,087	-	-	469	32,556	*7.5%*
$15	-	-	-	39,911	-	-	530	40,440	*9.4%*
$20	6,699	-	-	45,195	3,160	-	533	55,587	*12.9%*
$25	6,699	1,897	-	47,468	3,814	97,306	533	157,717	*36.5%*
$50	8,378	9,237	1,475	50,017	4,226	194,963	1,153	269,450	*62.3%*
$75	8,971	14,316	1,512	50,380	4,318	210,312	1,244	291,053	*67.3%*
$100	8,971	15,050	1,590	50,380	4,318	223,793	1,244	305,346	*70.6%*
$200	9,583	17,524	1,606	55,115	4,374	238,410	1,252	327,864	*75.8%*
$300	9,583	17,684	1,616	60,038	4,374	251,671	1,252	346,218	*80.1%*
$400	10,116	17,892	1,617	61,881	4,374	255,189	1,254	352,322	*81.5%*
$500	10,881	18,000	1,617	61,881	4,374	255,771	1,254	353,778	*81.8%*
$1,000	11,984	18,244	1,617	62,943	4,374	261,089	1,254	361,504	*83.6%*
$2,000	12,154	18,294	1,617	63,244	4,374	262,185	1,254	363,122	*84.0%*
Baseline MT/y	**15,314**	**19,737**	**2,075**	**68,806**	**5,039**	**319,741**	**1,547**	**432,259**	***100.0%***

Note: "Other Segments" include offshore production, distribution storage and LNG export.

3.8 2023 and 2030 LDAR MAC Curves for Emissions Estimated under Revised Subpart W

Exhibit 27 contains the LDAR MAC curve results for the year 2023 when the fugitive emissions are recalculated using a revised protocol that incorporates certain expected changes to EPA's GHGRP Subpart W rules. Exhibit 28 contains the same data for the year 2030 when that year's fugitive emissions are recalculated using the same revised protocol. Only the baseline emissions are changed relative to the Current Protocol Cases as the detection costs, repair costs and "Middle Case" performance parameters of detection technologies remain the same.

The quantity of potential mitigation under the Revised Subpart W Protocol is larger in both 2023 and 2030 relative to the Current Protocol because the baseline quantities of emissions are as larger. For the two cases reflecting the Revised Subpart W Protocol, mitigation at $500/Mcf represents 84.2% (2023) and 83.3% (2030) of baseline volumes. The portion of baseline emission that can be mitigated for $500/Mcf under Revised Subpart W Protocol is 1.3 to 1.5 percentage points higher compared to the Current Protocol Cases. This reflects the fact that the Revised Subpart W Protocol Cases assume a greater number of leaks and larger average leaks sizes compared to cases whose assumptions are based on leak volumes calculated under current protocols. In the Revised Subpart W Protocol Cases more methane is found for any given LDAR program and, thus, the $/Mcf cost goes down relative to the Current Protocol Cases.

Exhibit 27: LDAR MAC Curves by Segment: 2023 Revised Subpart W Protocol

2023 LDAR MAC Curve for Revised Sp W, Mid P Scenario, National Region: metric tons per year of methane abated vs. baseline									*V110*
Gross Abatement Cost ($/Mcf)	Onshore Production	Gathering	Processing	Transmission	Storage	Distribution	Other Segments	All Segments	*All Segments as % of Baseline*
$3	-	-	-	-	-	-	318	318	*0.1%*
$5	-	-	-	17,964	-	-	318	18,282	*3.7%*
$8	25,801	-	-	35,936	-	-	366	62,104	*12.5%*
$10	25,801	-	-	40,268	-	-	431	66,500	*13.4%*
$15	28,322	364	-	48,534	6,298	-	467	83,986	*16.9%*
$20	31,994	2,174	1,464	51,951	6,486	57,795	490	152,353	*30.7%*
$25	34,177	2,889	1,785	51,999	7,013	102,851	490	201,204	*40.6%*
$50	35,848	18,031	2,356	54,472	7,142	204,992	1,064	323,904	*65.3%*
$75	38,726	20,033	2,539	54,829	7,142	222,410	1,148	346,826	*69.9%*
$100	42,361	21,670	2,563	54,829	7,207	232,761	1,148	362,538	*73.1%*
$200	47,238	22,967	2,588	65,436	7,207	246,808	1,155	393,399	*79.3%*
$300	48,811	23,418	2,590	65,436	7,207	259,910	1,156	408,527	*82.4%*
$400	49,090	23,703	2,590	67,432	7,207	263,166	1,156	414,342	*83.5%*
$500	49,246	23,796	2,590	67,432	7,207	266,067	1,158	417,496	*84.2%*
$1,000	49,246	23,861	2,590	68,574	7,207	269,312	1,158	421,947	*85.1%*
$2,000	49,309	23,959	2,590	69,177	7,207	269,916	1,158	423,314	*85.3%*
Baseline MT/y	**57,305**	**25,546**	**3,162**	**74,431**	**8,010**	**326,153**	**1,429**	**496,036**	***100.0%***

Note: "Other Segments" include offshore production, distribution storage and LNG export.

Exhibit 28: LDAR MAC Curves by Segment: 2030 Revised Subpart W Protocol

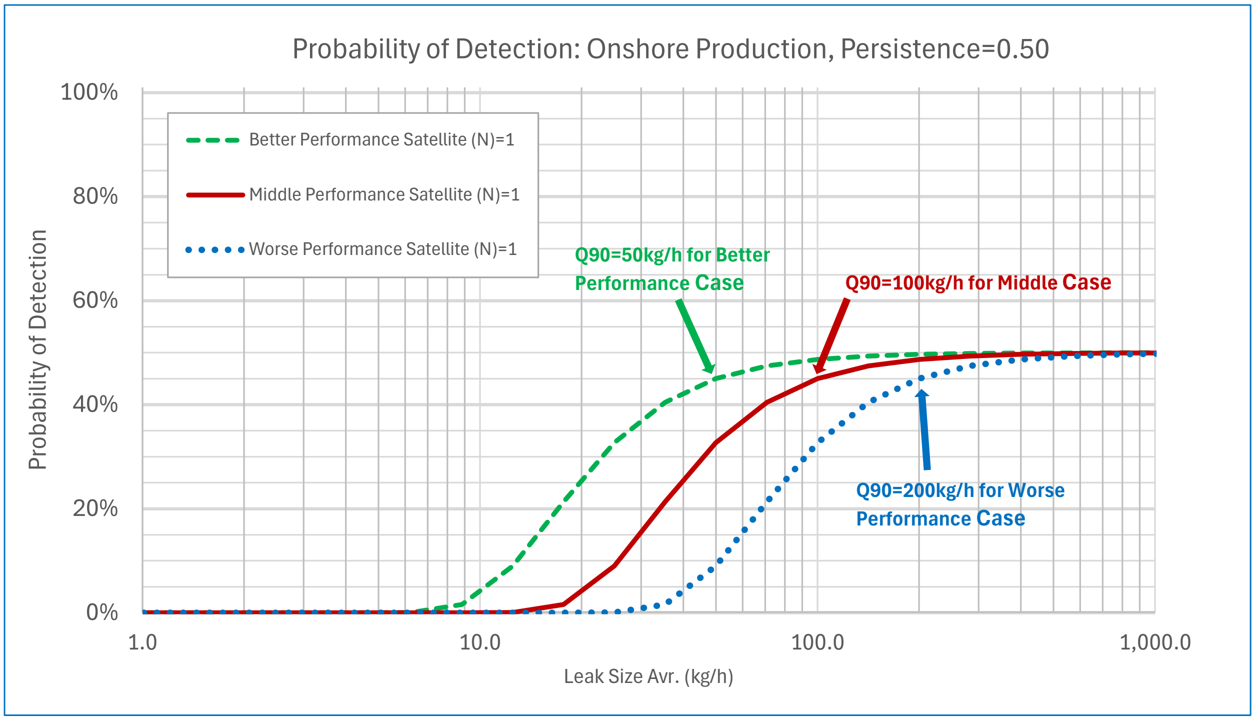
2030 LDAR MAC Curve for Revised Sp W, Mid P Scenario, National Region: metric tons per year of methane abated vs. baseline									*V110*
Gross Abatement Cost ($/Mcf)	Onshore Production	Gathering	Processing	Transmission	Storage	Distribution	Other Segments	All Segments	*All Segments as % of Baseline*
$3	-	-	-	-	-	-	349	349	*0.1%*
$5	26,936	-	-	18,623	-	-	349	45,908	*9.2%*
$8	26,936	-	-	37,255	-	-	400	64,592	*13.0%*
$10	26,936	-	-	41,746	-	-	469	69,151	*13.9%*
$15	29,568	460	-	50,316	6,148	-	530	87,021	*17.5%*
$20	33,401	3,382	1,528	53,858	6,331	-	533	99,033	*19.9%*
$25	35,680	3,654	1,863	53,908	6,846	97,477	533	199,960	*40.1%*
$50	37,425	20,318	2,542	56,471	6,971	195,483	1,153	320,363	*64.3%*
$75	40,892	21,769	2,695	56,841	6,971	210,870	1,244	341,282	*68.5%*
$100	45,042	23,473	2,723	56,841	7,007	224,394	1,244	360,723	*72.4%*
$200	49,642	24,940	2,747	67,838	7,034	239,053	1,252	392,506	*78.8%*
$300	51,244	25,383	2,749	67,838	7,034	252,359	1,252	407,859	*81.9%*
$400	51,518	25,623	2,749	69,907	7,034	255,891	1,254	413,976	*83.1%*
$500	51,671	25,720	2,749	69,907	7,034	256,474	1,254	414,810	*83.3%*
$1,000	51,671	25,790	2,749	71,091	7,034	261,807	1,254	421,397	*84.6%*
$2,000	51,743	25,891	2,749	71,717	7,034	262,907	1,254	423,295	*85.0%*
Baseline MT/y	**60,176**	**27,579**	**3,346**	**77,163**	**7,818**	**320,631**	**1,547**	**498,262**	***100.0%***

Note: "Other Segments" include offshore production, distribution storage and LNG export.

3.9 Sensitivity Analyses on Performance Parameters of Leak Detection Technologies

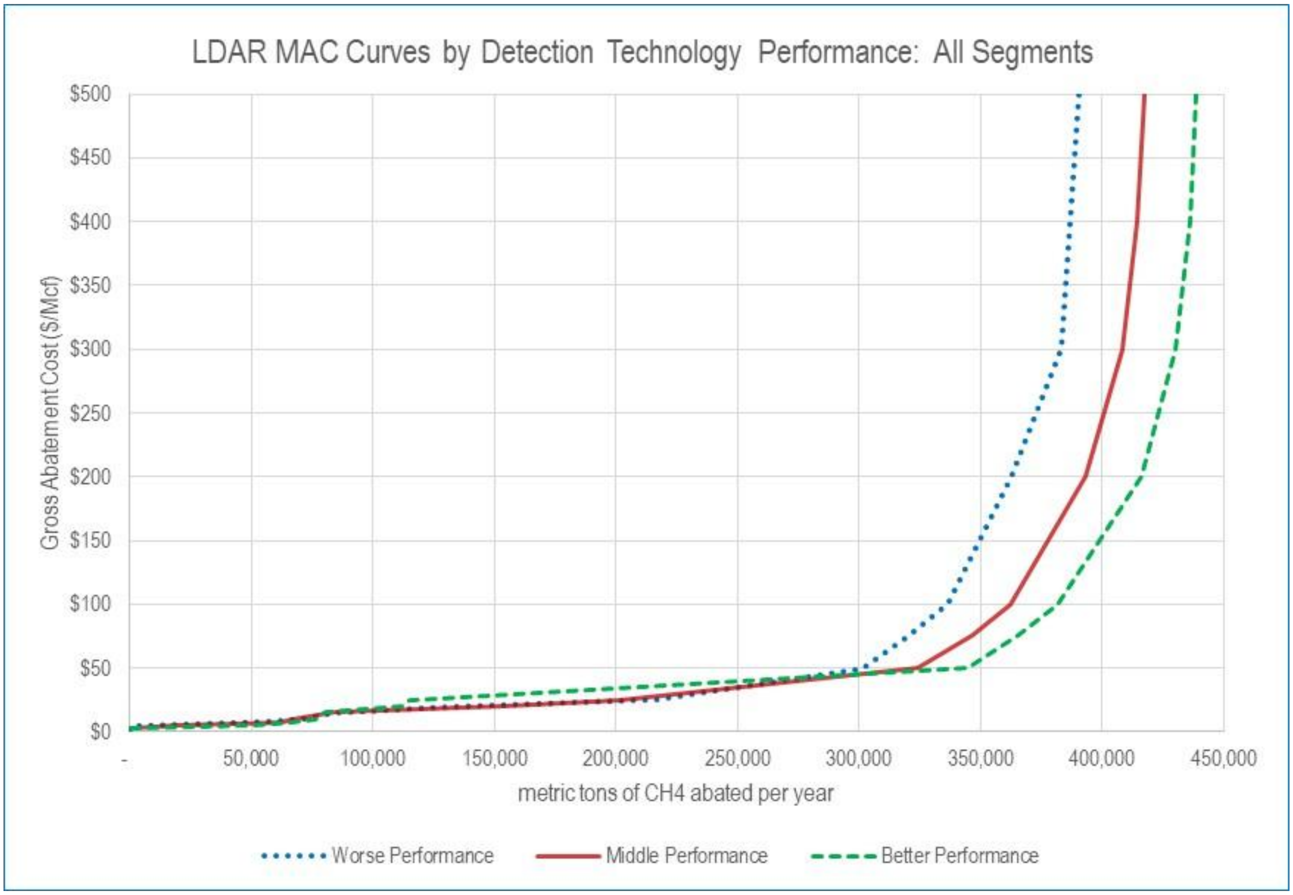
The LDAR MAC curve results shown above were generated using the “Middle Case” parameters for the performance of various leak detection technologies. The model also contains a “Better Performance Case” option in which the benchmark parameters (Q90 and Qmin) are cut in half and a “Worse Performance Case” option in which the benchmarks are set to twice the “Middle Case” values. The effect these changes have on the PoD curves is illustrated in Exhibit 29 which depicts the N=1 probability of detection for various leak sizes when applying short wave infrared satellite surveys to the onshore production segment. The Q90 parameter values are 50 kg/h for the Better Performance Case, 100 kg/h for the Middle Case and 200 kg/h for the Worse Case. (Those are the x-axis points where the y-axis values for the respective curves equal 90% benchmark x 0.50 persistence factor = 45% PoD.)

Exhibit 29: Example PoD Curves under the Three Performance Levels Assumed for Leak Detection Technologies



The MAC curve results for the sensitivity cases are shown in Exhibit 31 for all gas supply chain sectors combined. The sensitivity cases were performed for the year 2023 under the Revised Subpart W Protocol. As would be expected, an assumption of better performance for all leak detection technologies produces MAC curves in which larger abatement volumes are possible at a given abatement cost level. For example at $500/Mcf, 88.4% of the baseline emissions can be abated in the Better Performance Case, as compared to 84.2% in the Middle Case and 78.7% in the Worse Performance Case.

Exhibit 30: LDAR MAC Curves for Sensitivity Cases: 2023 Revised Subpart W Protocol



4. Methane Mitigation Technologies and Costs Related to Venting and Combustion Sources

4.1 Data Collection and Analysis

Data Collection Factors

- Capital Costs
- Installation Costs
- O&M costs
- Lifetime
- Effectiveness
- Sector Applicability

In order to estimate the marginal abatement costs for various mitigation technologies, data was collected on key inputs utilizing literature reviews (i.e. EPA, IEA, etc.), sourcing product prices from company websites and vendors, and seeking feedback from ONE Future Membership. This analysis focused on the largest sources of emissions as represented by One Future member reporting.

Recognizing the different needs across facilities, as well as variable applications of several of these mitigation technologies, each technology was evaluated using representative assumptions on various parameters such as size of the unit, volume of gas, or other factors. Therefore, research was conducted to make assumptions that represent average or industry-standard cases in the oil and gas industry for each technology and industry segment. Cost data from the data collection was aggregated into modeled capital costs, installation costs, and operating costs (including labor, maintenance, and operations) per year. Certain technologies had differing applicability across sectors (onshore production, offshore production, gathering, processing, transmission, storage, distribution, and LNG import export).

4.2 Summary of Methodology

The methodology for creating MAC curves for vented and combustion-related methane emissions included the following steps:

1. **Vented Emissions Data**: ICF compiled 2023 activity and emissions data for the ONE Future companies using the data sources and processing procedures described in **Chapter 2**.
2. **Evaluated Mitigation Technology Costs:** ICF determined capital and installation costs, O&M costs, lifetime, effectiveness and sector applicability. As part of this analysis ICF determined the drivers for the costs and whether the cost was driven by equipment counts (e.g. rod packing), facilities (e.g. instrument air for pneumatics), or number of events that were mitigated (e.g. blowdowns). Based on the key drivers for the technologies, appropriate cost coefficients were estimated and used to model the MAC curves.
    a. **Mitigation technologies whose costs were driven by equipment counts**: This was a straightforward calculation where costs were associated with each equipment count and the associated emissions

   b. **Mitigation technologies whose costs were driven by facility counts**: In these instances, ICF compiled or estimated modeling parameters that represent an average facility or broke facilities into a few categorical buckets. For example, for pneumatics, ICF separated out facilities with less than 5 pneumatic devices, 5-10 pneumatic devices, 10-15 pneumatic devices and above 15 pneumatic devices. ICF relied first on data reported to One Future and supplemented it with outside sources where needed. For production and gathering and boosting, data is oftentimes reported at the basin level and, therefore, other sources helped disaggregate those data using counts of wells or pads.
   c. **Mitigation technologies whose costs were driven by other factors**. For some technologies data on emissions were based on other factors other than equipment counts. An example of this was blowdowns for pipelines in the distribution segment. Companies can mitigate blowdowns by purchasing or renting equipment. ICF built up the costs as if the company purchased the equipment and used it across their facilities.
3. **Annual Volume of Emissions**: The annual emissions reported by One Future members were used to evaluate the various mitigation options as defined in Step 2. The potential abatement volumes were calculated as the baseline emission volumes times each technology's mitigation effectiveness.
4. **MAC Curve Format**: As with the LDAR analysis, ICF produced the MAC curve for vented and combustion-related emissions in each industry segment/region with an x-axis indicating cumulative annual metric tons of methane abated and a y-axis showing the \$/Mcf of CH_4 for each cumulative mitigation amount. To do this, ICF stacked each mitigation solution with mitigation solutions with the lowest per-unit abatement cost and going up to the option with the highest per-unit abatement cost. The first point in the MAC curve was given a y-axis value equal to the \$/Mcf of CH_4 abatement cost of the LDAR program with lowest cost. That first point of the curve had an x-axis value equal to the tons mitigated by the lowest cost case for the pro forma (average) facility times the number of ONE Future facilities in the subject industry segment/region.
5. **Construction of LDAR MAC Curves**: If the mitigation volume of the second most cost-effective option was greater than the mitigation volume achieved by the lowest cost case, then that second-place option was used to create the second point of the MAC curve. If the second most cost-effective LDAR program option resulted in a lower mitigation methane volume than the first, then the third (or later) most cost-effective was used -- provided it had greater mitigation volume.

4.3 Mitigation Technologies and Costs

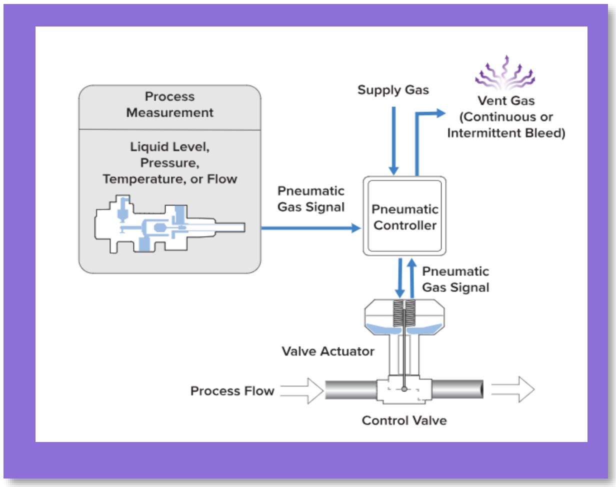
Below are various mitigation categories evaluated as part of this work and their associated mitigation activities/technologies. A cost breakdown table is provided for each mitigation measure.

Pneumatic Devices

Emission Descriptions: Pneumatic devices are used to operate valves and other control variables. They can be powered multiple ways, but many are powered by directing natural gas to operate the device. These controllers are designed to continuously emit natural gas or only emit natural gas when operated.

Emission Mitigation Activities:

1) Installation of instrument air (with and without existing grid power)
2) Pneumatic controllers/actuators: replacing existing gas driven pneumatic controllers/actuators with electric, solar, and implemented plans to design all new wellpads without any gas driven pneumatic controllers/actuators
3) Nitrogen (compressed cylinders, bulk nitrogen trucks, and MicroBulk)



Source: EPA Natural Gas STAR

Instrument air	
EPA Natural Gas Star Program [1]	$60,000 per facility. • Companies reported $79,000 for an air compression system in one facility, • $52,000 for compressed air to drive pneumatic devices in 10 facilities, • $227,000 for converted pneumatic controllers to compressed air, • $72,000 instrument air at 3 production satellites and one tank
IEA Methane Abatement Model [2]	$75,600 Capital Cost, In challenging settings capital cost can be $378,000
Carbon Limits Zero emission technologies for pneumatic controllers in the USA [3, 4]	Costs vary based on whether or not they have electricity at the site, new build/retrofit, and the number of devices. $2,698 for a continuous controller and valve $2,471 for an intermittent controller and valve $22,000 for a 5 HP compressor package $32,000 for a 10 HP compressor package $48,000 for a 15 HP compressor package $70,000 for a 20 HP compressor package Compressor package that includes compressors, dryers, air receiver tanks
One Future Member	Air System installation at existing T&S facility – Budget $750k Equipment & Installation + $600k electrical upgrade
One Future Member	Existing Air System upgrade/expansion at existing T&S facility – Budget $350k Equipment & Installation

One Future Member	Air System installation at existing G&B facility – Budget $1.1 million Equipment & Installation + $500k electrical upgrade
EQT[5]	**Compressed air** Pros: • Inert air • Removal of freezing issues with sufficient air dryer design • Minimal maintenance costs Cons: • High initial capital cost ($60k-110k, depending on power supply needs) • Single failure point with loss of compression Hazards associated with introducing oxygen into part of the process stream
Installation Cost/Operating Costs	
EPA Natural Gas Star Program [6]	Electricity Cost: $13,140 Compressor Maintenance: $1,736 Air dryer membrane replacement: $2,894 Total: $17,770
IEA Methane Abatement Model [7]	$22,050 annual operating costs
*Carbon Limits Zero emission technologies for pneumatic controllers in the USA [8]	Installation cost is 100% of equipment costs for a retrofit and 50% of equipment cost for a new install
Frequency/Lifetime	10 years
IEA Methane Abatement Model [9]	100%
Effectiveness	100%

*Source provides additional information into cost buildup

Electric Controllers	
Carbon Limits Zero emission technologies for pneumatic controllers in the USA [10]	$2,000 per unit
IEA Methane Abatement Model [11]	$3,780 to replace Pneumatic chemical injection pumps with Electric Pumps
Carbon Limits[12]	$4,000 per unit for electric controllers
One Future Member	Budget $50k per controller w/ installation at existing facility
Installation Cost	
Carbon Limits[13]	20% of equipment costs for labor.
Frequency/Lifetime	10 years
IEA Methane Abatement Model [14]	100%
Effectiveness	100%

Nitrogen (compressed cylinders, bulk nitrogen trucks, and MicroBulk)	
EQT[15]	Pros: • Inert gas • Removal of freezing issues • Less nitrogen replenishment for smaller pads • Low initial capital cost <$20,000 • Little to no maintenance Cons: • Hazardous in confined space • Monthly operating expense – up to $1,500/month (depending on nitrogen consumption) • Regular nitrogen replenishment required • Continuous low rate nitrogen flash loss when using liquid nitrogen in addition to vent loss
Frequency/Lifetime	10 years
Effectiveness	100%

4.3.1 Applying Costs to Pneumatics Mitigation Strategies - Example

Pneumatic controllers/actuators use natural gas to operate mechanical processes in equipment throughout the onshore production, gathering, processing, transmission, storage and distribution segments of the natural gas value chain. Nearly 70% of One Future member pneumatic emissions come from the onshore production sector, with Gathering and Transmission sectors taking roughly equal shares of the remaining 30%. Processing and Storage together account for less than 3%. Exhibit 31 illustrates the derived emission factor from reporting for each pneumatic device type across the One Future Membership.

Exhibit 31: Emission Factor by Type and Sector (scf/h)

	Low Bleed Pneumatic Devices	Intermittent Bleed Pneumatic Devices	High Bleed Pneumatic Devices
Onshore Production	1.1	5.6	0.0
Gathering	1.1	8.5	33.4
Processing	-	2.1	16.1
Transmission	1.3	2.2	16.9
Storage	1.3	2.3	16.8
Distribution Storage	-	2.0	-

When determining the costs of pneumatic devices, ICF modeled and took into consideration the following factors:

- Pneumatic devices in onshore production, gathering, transmission, processing, storage, and distribution sectors.
- Given that leading emissions mitigation strategies for pneumatic controllers involve a degree of electrification, markets with and without existing grid connection were considered. Constraints with grid connections were also considered.

- Facility size also factors into mitigation cost and effectiveness, facilities ranging in size from 1 to over 15 controllers were considered in increments of 5.
- Limitations related to grid connection and instrument air device application in the transmission sector.

ICF utilized assumptions from the Clean Air Task Force – Zero Emission Technologies a cost tool developed by Carbon Limits for CATF supplementing information from ONE Future members and the data specified above to estimate costs for individual technologies.

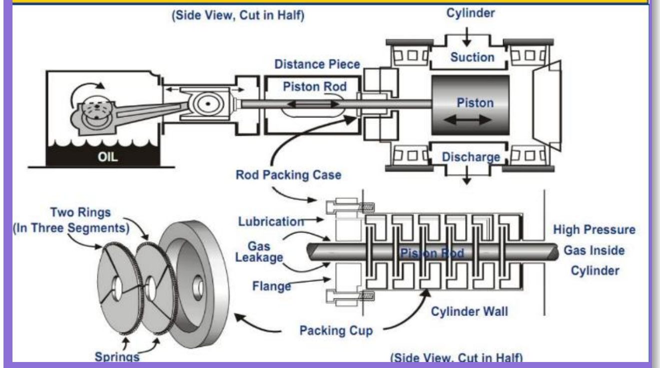
Reciprocating Compressors

Emission Descriptions: Rod packing systems leak depending on various operating parameters such as cylinder pressure, fitting and alignment of the packing parts, and amount of wear on the rings and rod shaft.

Emission Mitigation Activities:

1) Perform rod packing maintenance and replacement for all reciprocating compressor units regardless of whether they are subject to regulatory requirements.
2) Perform rod packing replacement on reciprocating compressors equal to or more frequently than required by regulation

Exhibit 1: Typical Compressor Rod Packing System



Source: EPA Natural Gas STAR

Rod Packing Replacement on compressors not subject to regulation	
Capital Cost	
SoCalGas[16]	$8,000 ($128,000 for 16 rod packing replacements)
EPA Natural Gas STAR Program[17,18]	Rods ($9,450) + Rings - ($1,620) = $11,070 price range for standard rods: $2,430 to $4,725 price range for special coated rods: $12,150 to $13,500 price range for rings: $ 1,350 to $ 1,700 price range for rings with cups and case: $ 2,025 to $ 3,375
World Standard Compressor [19]	Rod and Ring - $3000 per rod multiplied by 4
Northern Natural Gas	$3,000 per rod multiplied by 4 = 12,000
IEA Methane Abatement Model [20]	$8,316
One Future Member	Approximately $10-15K depending on compressor size
Installation Cost	
World Standard Compressor [21]	Labor (overtime) = $2000/day
EPA Natural Gas STAR Program[22,23]	Installation costs comparable to capital costs
Modeled Capital Cost	$10,600
Modeled Installation Cost	$10,600

Modeled Operating Costs	$0
Frequency/Lifetime	3 years
IEA Methane Abatement Model [24]	50%
Effectiveness	33%

Rod Packing Replacement more frequently than required by regulation	
Capital Cost	
SoCalGas[25]	$8,000 ($128,000 for 16 rod packing replacements)
EPA Natural Gas STAR Program[26,27]	Rods ($9,450) + Rings - ($1,620) = $11,070 price range for standard rods: $2,430 to $4,725 price range for special coated rods: $12,150 to $13,500 price range for rings: $ 1,350 to $ 1,700 price range for rings with cups and case: $ 2,025 to $ 3,375
World Standard Compressor [28]	Rod and Ring - $3000 per rod multiplied by 4
Northern Natural Gas	$3,000 per rod multiplied by 4 = 12,000
IEA Methane Abatement Model [29]	$8,316
One Future Member	Approximately $10-15K depending on compressor size
Installation Cost	
World Standard Compressor [30]	Labor (overtime) = $2000/day
EPA Natural Gas STAR Program[31,32]	Installation costs comparable to capital costs
Modeled Capital Cost	$24,500
Modeled Installation Cost	$24,500
Modeled Operating Costs	$0
Frequency/Lifetime	2 years
Effectiveness	33%

Centrifugal Compressor (Dry Seal)

Emission Descriptions:
Dry seals are mechanical face seals that utilize high-pressure gas between stationary and rotating pieces of the compressor, but some gas will leak through this interface.

Emission Mitigation Activities:

1) Capture and recompression of dry seal vented gas and compressor process vented gas

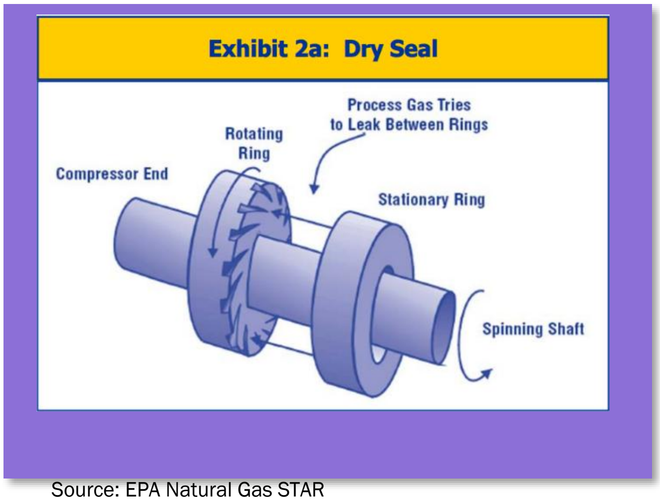


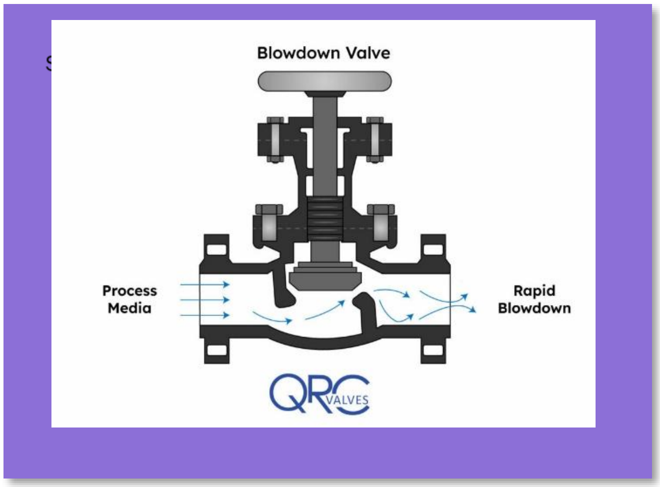
Exhibit 2a: Dry Seal

Source: EPA Natural Gas STAR

Capture and recompression of dry seal emissions	
DCP Operating Company[33]	$575,000 – DCP installed a dry seal recompression system on two turbines at the Kersey/Mewbourne plan
One Future Member	Dry Gas Seal Recompression – 2 Turbine Units at an existing T&S facility - ~ $2.4 million – Equipment, installation including electrical work
One Future Member	Dry Gas Seal Recompression – 1 Turbine Unit at an existing T&S facility - ~ $1.4 million – Equipment, installation including electrical work
One Future Member	Approximately $1.5 Million, including installation and commissioning cost.
See Vapor Recovery Unit Costs under Combustion Section for more	
Frequency/Lifetime	15
Effectiveness	95%

Blowdowns

Emission Descriptions:
When pipelines or equipment are taken out of service for operational or maintenance purposes, the pipeline/equipment is commonly depressurized to the atmosphere.



Source: QRC Valves

Emission Mitigation Activities:

1) Best Management practices for blowdowns
    a. Implement best management and operational practices by minimizing the frequency of blowdowns to the extent possible through scheduling and grouping of maintenance activities.
    b. Best management and operational practices to minimize pipeline segment length and gas volume needing to be blown down during planned events
    c. Implementation of emergency shutdown system procedures to more effectively isolate the station and close station block valves. This helps to manage and reduce the amount of gas blown down from the station if an emergency shutdown of the station occurs. During testing of the system, the blowdown valves/vents are capped to prevent blowdown to atmosphere.

2) Portable Compression
    a. During gathering and transmission pipeline planned events, reduce the operating pressure on segment(s) of gathering and transmission pipelines as much as possible using portable compression and/or existing compression and route the gas downstream of the isolated segment being blown down
    b. Cross compression for transmission/large pipes (major projects); piloting for distribution pipe
    c. Utilize vapor recovery units (VRUs), ECDs, or flares to combust or capture 90%+ of compressor or pipeline blowdowns

3) Utilizing hot taps/Stopple® fittings during pipeline maintenance not requiring pipeline blowdowns to atmosphere
4) Installation of "line break" valves to prevent a significant loss of gas to the atmosphere
5) Use of pipeline wrap or steel sleeves during pipeline maintenance to reduce or eliminate pipeline blowdowns to atmosphere
6) Route to Flare
    a. ESD blowdown to flare

7) Use of YALE Enclosures for ESD Testing to prevent full station blowdowns

Best Management practices for blowdowns	
IEA Methane Abatement Model [34]	$37,800 to redesign blowdown systems and alter ESD practices.
PG&E[35]	$2,763,223 to reduce blowdowns across their system
Environmental Defense Fund: Pipeline Blowdown Emissions and Mitigation Options[36]	$2,122 total labor costs per event – interstate $1,471 total labor costs per event – intrastate $1,000 annual maintenance cost Capital Costs $50,000
Frequency/Lifetime	the blowdown and maintenance will be done an average of 4 times per month, flaring equipment life is 7 years[37]
IEA Methane Abatement Model [38]	95%
Effectiveness	95%

Portable Compression	
EPA Natural Gas Star Program[39]	Purchasing a permanent portable recompression unit: $518,131 to $777,197 for a 300 PSIG portable compressor $1 million to $1.6 million for a 600 PSIG portable compressor $3 million to $6 million for a 1,000 PSIG portable compressor Cost to rent units varies between $20,000-$70,000
EPA Natural Gas Star Program[40]	$98,757 to pump down before maintenance
Methane to Markets EPA[41]	The below costs are for permanent recompression: Capital cost: $3 million to 6 million for a 69.05 atm high flow portable compressor O&M: $5,000 to $30,000 Labor and Transportation Costs: $5,000 to $20,000
Environmental Defense Fund: Pipeline Blowdown Emissions and Mitigation Options[42]	$500,000 to $1.6 million for 8,500 scfm compressor $10,000 maintenance costs
New Mexico Gas Company[43]	$710,000 $31,047,288 - total distribution O&M for future test year ending 12/31/23 (as filed), labor included: $0 $8,463,460 - total transmission O&M for future test year ending 12/31/23 (as filed), labor included: $384,588
One Future Member	Currently, for pipeline retirements over 500-ft for 2” main or over 100’ for 4” main, we utilize cross compression units that can be purchased for approximately $50,000 each. There are also crew costs associated with this cross-compression technology, but they do not represent a significant increase from a scenario where gas would be directly vented to the atmosphere. For larger, higher pressure mains, we subcontract with a company that uses larger cross compression equipment that can cost between $20,000 and $30,000 per instance, dependent upon the project size and pressure.

ONE Future Company	Zevac Mini – CapEx around \$50k - small and very mobile, but extremely low flow, existing air compressor on crew truck is too small to operate the unit well, so you would likely need to pair with a larger air compressor. Zevac – Unit CapEx around \$250k but after you add a large air compressor and truck, it's closer to \$700k – similar size/access needs as a crew truck with mini excavator, low to medium flows. GoFlow – CapEx around \$250k - trailer fits in a typical parking space, low flowrates, stand-alone unit that runs on the pipeline gas being evacuated. GoFlow Max – CapEx around \$800k – similar footprint to Zevac set-up below, medium flowrates, stand-alone unit that runs on pipeline gas being evacuated. Typical transmission scale compression – never priced one, but I would expect it to be in the \$5MM+ range, access and space needs are for a Class 8 truck, extremely high flowrates, runs on pipeline gas being evacuated, all units will lose performance as the suction pressure decreases, but this is magnified for units like this.
Frequency/Lifetime	10 years, 15 years[44]
Environmental Defense Fund: Pipeline Blowdown Emissions and Mitigation Options[45]	80%
Effectiveness	80%

Utilizing hot taps/Stopple® fittings	
PHMSA blowdown analysis [46]	Capital costs for the required stopples and fittings could be as high as \$90,000 or more depending on the size of the pipeline, and much of this equipment can often only be used once. Installation could take 50 man-hours or more and requires specialized skills (i.e. welders). \$3,059 total labor costs per event – interstate \$3,059 total labor costs per event – intrastate \$0 annual maintenance costs
Made in China[47]	\$5,500 to \$6,500 per fitting
EPA Natural Gas Star Program[48]	\$17,287 - \$30,122 for taps less then 12" and \$130,963 - \$261,927 for taps bigger then 12" \$724-\$7,235 equipment O&M costs/year for taps less then 12" \$0 equipment O&M costs/year for taps bigger then 12" Annual hot tap equipment cost for hypothetical scenario is \$23,704 /machine, 2 machines needed to total \$47, 409 Annual hot tap O&M cost for hypothetical scenario is \$3,979 /machine, 2 machines needed to total \$7,959 Typically, a visit to a residential customer would take 15 to 30 minutes, and a visit to a commercial or industrial customer would take approximately 1 hour. According to the Bureau of Labor Statistics, an employee would be paid approximately \$9.75 per hour for this work.
Frequency/Lifetime	1

Effectiveness	75%

Line Break Valves	
PHMSA [49]	Costs can be around 1 million per automatic shut off valves
JME Ellsworth[50]	$7,115 for a flanged stainless steel ball valve
Frequency/Lifetime	
Effectiveness[51]	LBV system could reduce the accident consequences by more than 60%

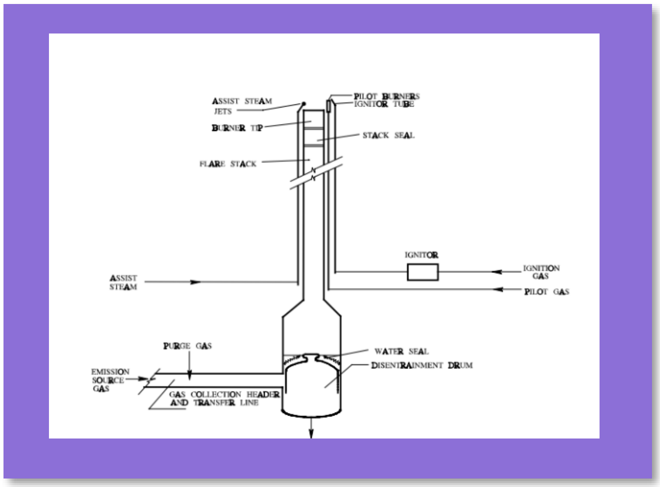
Pipeline wraps or steel sleeves	
Maddock Industries[52]	$211 to $1,090 depending on the size of the steel pipe sleeve $211 for WS-10-36-S-12 $1,090 for WS-12-37-S-12 $503 for WS-16-37-S-12
EPA Natural Gas Star Program[53]	$1,087 for a composite wrap kit and $2,320 for labor
RELI Engineering[54]	$400 to $910 for galvanized carbon steel pipeline sleeves
Frequency/Lifetime	the manufacturer estimates will last at least 50 years[55]
Effectiveness[56]	80%

Route blowdowns to flare including ESD	
ProFlex [57]	$20 per linear foot includes labor costs.
IEA Methane Abatement Model [58]	$3,780 capital with a project lifespan of 10 years
EPA Natural Gas Star Program [59]	$3,000 for the flare and $1,800 for a year for pilot fuel gas
EPA Natural Gas Star Program[60]	$21,000 per flare
Environmental Defense Fund: Pipeline Blowdown Emissions and Mitigation Options[61]	$10,000 to $50,000 for a flare sized to handle a 12-to-36-inch transmission pipeline. Annual maintenance costs of ~1,000. Reduction of emissions up to 95%.
Frequency/Lifetime	
IEA Methane Abatement Model [62]	90%
Effectiveness	90%

Yale Enclosures	
EPA Natural Gas Star Program[63]	$785 to $1,600 depending on the size not including installation costs Operation costs = $0
YAGI Pipe and Steel[64]	$2,275 for Yale 12" Fig 500 Quick Closure
Frequency/Lifetime	

Effectiveness[65]	Permanent Total Enclosures (PTEs) have a capture efficiency of 100%

Combustion



Source: EPA Natural Gas STAR

Emission Descriptions: Combustion is a source of emissions throughout the natural gas supply chain. Flares, reciprocating engines, and compressor drivers represent common emission points that can be mitigated.

Emission Mitigation Activities:

1) Locating production sites:
    a. Best management and operational practices integrated across construction and production sites with the goal of minimizing venting and flaring
    b. Company requirement to have adequate takeaway capacity at wellpads to prevent venting or flaring of associated (or stranded) gas. All natural gas produced is sent directly to pipeline.
2) Equipment Maintenance:
    a. Perform regular preventative maintenance and burner tip maintenance on combustion units and flares (tuning of the unit)
    b. Perform periodic maintenance on flare burner and blower (air-assisted) to improve flare efficiency and minimize methane slip due to combustion
3) Vapor Recovery Unit
    a. Vapor recovery unit on flare header to recover vent gas from process with the flare only used as backup in the event the VRU goes down
    b. Utilize vapor recovery units (VRUs), ECDs, or flares to combust or capture 90%+ of compressor or pipeline blowdowns
4) Improve Combustion Efficiency
    a. Performing annual methane slip stack testing of reciprocating engines and comparing to gas engine rating pro (GERP) curves to improve combustion efficiency and minimize methane slip
    b. Reduce "methane slip" through combustion efficiency improvements
    c. Replacement of reciprocating engines with newer more efficient reciprocating engines resulting in lower methane slip from combustion
5) Electrify Equipment
    a. Replacement of natural gas-fired compressor drivers with electric motor driven compressor drivers

Adequate Takeaway Capacity	
IEA Methane Abatement Model [66]	$2,383,920 to improve flaring for stranded gas venting and $7,560 in annual operating costs with a lifespan of 10 years.
IEA Methane Abatement Model [67]	$630,000 to improve well completions $126,000 in annual operating costs with a lifespan of 15 years.
IEA Methane Abatement Model [68]	$63,000 to improve flaring for well completion with $7,560 in annual operating costs with a lifespan of 10 years.
Frequency/Lifetime	10-15 years
IEA Methane Abatement Model [69]	98%
Effectiveness	98%

Burner Tip Maintenance	
Industrial Access[70]	$600,000 for a replacement burner tip $25,000 for a drone inspection
Acuren[71]	$100,000 to $1 million depending on flare size to replace the burner tip.
Frequency/Lifetime	
Effectiveness	98%

Vapor Recovery Unit	
IEA Methane Abatement Model [72]	$82,942 to install a vapor recovery unit with $17,324 in annual operating costs for a 10 year lifespan. Could be as much as $207,356 in challenging settings.
EPA Star Natural Gas Program[73]	Vapor recovery unit sizes and costs 25 Mcf/day - $20,421 capital costs - $7,367 O&M 50 Mcf/day - $26,327 capital costs - $8,419 O&M 100 Mcf/day - $31,728 capital costs - $10,103 O&M 200 Mcf/day - $42,529 capital costs - $11,787 O&M 500 Mcf/day - $59,405 capital costs - $16,839 O&M
PHMSA blowdown analysis [74]	8,500 scfm compressor powered by a 750 kW natural gas engine; such a system could cost $500,000 to $1.6 million, and annual maintenance costs could be $10,000
One Future Member	Station Vent Gas Recovery & Recompression – 2 Turbine Units at an existing T&S facility - ~ $3.3 million – Equipment, installation including electrical work
One Future Member	Station Vent Gas Recovery & Recompression – 11 Recip Units at an existing T&S facility - ~ $6.5 million – Equipment, installation including electrical work
One Future Member	Station Vent Gas Recovery & Recompression – 5 Recip Units at an existing T&S facility - ~ $3.9 million – Equipment, installation including electrical work
One Future Member	Station Vent Gas Recovery & Recompression – 2 Turbine Units at an existing T&S facility - ~ $2.0 million – Equipment, installation including electrical work
Frequency/Lifetime	10 years

IEA Methane Abatement Model [75]	98%
Effectiveness	98%

Improve Combustion Efficiency	
Cost-Effective Reciprocating Engine Emissions Control and Monitoring[76]	$405,000 for retrofitting a 2,500 hp engine in 2003.
REMEDY Projects[77]	$1,000,000 for flare efficiency improvements.
One Future Member	Engine Uprate at existing T&S facility – 1 Recip Unit - $2.5 Million Equipment & Installation
Frequency/Lifetime	
Effectiveness	98%

Purchase New / More Efficient Equipment	
LCG Consulting Energy Online[78]	$130 million for 12 natural gas fired reciprocating engines – that makes each engine $10,833,333.3
EPA Combined Heat and Power Partnership[79]	$2,900 to $1,433 per kw for a more efficient gas spark ignition engine in 2013. $500 to $231 per kw for labor/materials for a typical gas engine generator in grid interconnected CHP applications
One Future Member	Engine Replacement or Engine “Swing” at existing G&B facility – 5 Recip Units - ~ $2.6 Million Equipment & Installation
Frequency/Lifetime	
Effectiveness	98%

Electrify Equipment	
IEA Methane Abatement Model [80]	$31,500 to replace with electric controls with $252 in annual operating costs for a lifespan of 15 years.
Northwest Compressor Station Analysis[81]	$3,000 per horsepower Annual operator labor = $12,000, supervisor labor = $1,875, maintenance labor = $12,500 Annual operating materials = $23,789, maintenance materials = $5,000, catalyst maintenance/replacement = $138,250, testing and QA/QC = $20,000, electricity = $2,500
EPA Star Natural Gas Program[82]	$6,050,000 to install electric compressors. Assuming 50% efficiency for the four 1,750 hp electric compressors and 8,760 hours of operation per year at a price of $0.075 per kw-hr, electricity costs would be $6,800,000 per year.
Frequency/Lifetime	20 years[83]
IEA Methane Abatement Model [84]	100%
Effectiveness	100%

Pipeline Mains and Services

Emission Descriptions: Pipelines may leak gas due to a variety of causes which include corrosion, earth movements, and other damage.

Emission Mitigation Activities:

1) Pipeline Replacement Programs:
    a. Capital based allocation largely based on leakage rate and type pipe in the system.
    b. Installation of cathodically protected pipe
    c. MSRP Replacement program for older metallic services under a 20-year program in one of the states with cost ~13 million a year

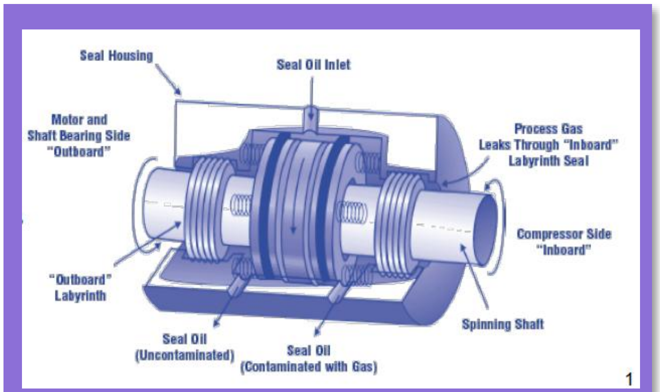
Pipeline Replacement Programs	
Global Energy Monitor	**Distribution:** Range from $.5 million to $1 million per mile
Hanging H Co. [85]	**Transmission:** 2017-2020 costs average $8.45 million per mile
Installation Cost	
Global Energy Monitor: Labor Costs	Can vary between 30-50% of total installation costs
Frequency/Lifetime	50
ARPAEnergy[86]	Minimum life of 50 years
Oatland Plumbing Services[87]	Average 50-year lifespan, but vary depending on materials used, environmental conditions and maintenance practices.
Effectiveness	Dependent on the type of pipeline being replaced. If the pipeline is unprotected steel, the effectiveness can be as high as 97%

Centrifugal Compressor (Wet Seal)

Emission Descriptions: While wet seals leak little gas at the seal face seal oil degassing may vent 40 to 200 scf/minute.

Emission Mitigation Activities:

1) Replacement of wet seal centrifugal compressors with dry seal centrifugal compressors when feasible
2) Wet Seal Degassing Recovery System for Centrifugal Compressors



Source: EPA Natural Gas Star Program

Replacement of wet seal centrifugal compressors with dry seal centrifugal compressors	
Compressor Seal Selection and Justification[88]	$124,000 to $154,000 for a dry gas seal and support compressor system in 2003
IEA Methane Abatement Model [89]	$567,000 with a lifespan of 15 years for a wet seal retrofit to a dry seal compressor
EPA Natural Gas Star Program[90]	$324,000 to replace wet seals with a dry seal $14,100 annual O&M
One Future Member	Approximately, $1-5 Million depending on whether the compressor can be retrofitted or if the compressor needs to be replaced.
Frequency/Lifetime	15
Effectiveness	35%

Wet Seal Degassing Recovery System	
IEA Methane Abatement Model [91]	$264,600
EPA Natural Gas Star Program[92]	$33,000 to $90,000 in implementation costs Minimal O&M costs
Global Methane Initiative[93]	$22,000 for installing separators and related piping for two seals.
Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems[94]	Capital cost $70,000 Operating costs $0
Climate & Clean Air Coalition[95]	$19,000 for two seal oil Gas Disengagement Vessels $9,000 for Seal Oil Gas Demister – Low Quality Gas $5,000 for Seal Oil Gas Demister – High Quality Gas $33,000 total for one centrifugal compressor Labor costs included O&M costs expected to be minimal
Frequency/Lifetime	15
Effectiveness	95%

Methane Oxidation Catalysts

Emission Descriptions: Palladium-based catalysts are typically selected for controlling methane emissions from lean burn gas engines. Pd is the most active CH4 oxidation catalyst, but high catalyst temperatures are required to oxidize methane and other short-chain hydrocarbons. Pd catalysts are sensitive to sulfur poisoning and can be deactivated even at trace levels of sulfur in the exhaust gas. The deactivation by sulfur can be reversed by thermal regeneration, preferably under reducing conditions.

Emission Mitigation Activities:

3) Methane oxidation catalysts (MOCs) can achieve low T50% (<350° C) when properties are in line with Sample 1, which had a 335 g/ft^3 (11,800 g/m^3) PGM loading, a 5.9:1 Pd:Pt ratio, and a high alumina washcoat with a 20.1 m2/mL washcoat surface area and a 0.075 cm^3/mL washcoat pore volume.
4) The high PGM loadings of Sample 1 increased costs, which may be reduced by using metallic system substrates, such as Sample 3.
5) Additional MOC chemistries may improve performance and lower costs.
6) After-treatment of DF engine exhaust could achieve significant reductions in CH4 emissions, but MOCs must be appropriately sized and have correct catalyst formulations.
7) While MOCs can achieve meaningful methane emission reductions, many commercially available MOCs do not meet the requirements for low-temperature (<400° C) oxidation.
8) Suggested strategies for MOC improvement include locally increasing the catalyst surface temperature by injecting volatile hydrocarbons (e.g., diesel fuel) into the exhaust upstream of the MOC.
9) These strategies should be employed carefully to avoid increasing the absolute magnitude of unburned hydrocarbons exhausted and consider overall energy consumption and CO2e emissions.

Methane Oxidation Catalyst	
ARPA-E[96]	$3,253,088
EPA[97]	On the catalytic tab: Heat recovery 0%: $1,636/ton Heat recovery 35%: $1,130/ton Heat recovery 50%: $1,087/ton Heat recovery 70%: $905/ton Heat recovery 95%: $935 /ton
EPA[98]	Total capital investment for thermal-recuperative incinerators: $483,000 Total capital investment for fluid-bed catalyst incinerators: $889,000 Annual costs for thermal incinerator: • **Labor: $14,582** (Operator 0.5 hr/shift $12.95/hr. - $6,480, Supervisor 15% of operator - $972, Maintenance 0.5 hr/shift - $7,130)

	- **O&M minus labor costs: $306,618** (maintenance materials 100% of maintenance labor - $7,130 7, Natural Gas $3.30/kft3 - $264,500, Electricity $0059/kWh - $36,500) - **Total: $422,000** Annual costs for fluid-bed catalyst: - **Labor: $14,582** (Operator 0.5 hr/shift $12.95/hr. - $6,480, Supervisor 15% of operator - $972, Maintenance 0.5 hr/shift - $7,130) - **O&M minus labor costs: $129,818** (maintenance materials 100% of maintenance labor - $7,130 7, Catalyst replacement $650/ft^3 - $15,100, Natural Gas $3.30/kft^3 - $63,400, Electricity $0059/kWh - $44,200) - **Total: $316,000**
Frequency/Lifetime	
Effectiveness[99]	90%

4.4 Marginal Abatement Cost Curves for Vented and Combustion-related Emissions

This section describes the data sources and results of the marginal abatement cost (MAC) analysis for vented and combustion-related emission sources (i.e., non-fugitives). By incorporating the source-level emissions described in **Chapter 2** and the mitigation technology costs and reduction effectiveness discussed earlier in this chapter, MAC curve results were generated. These curves display the volume of achievable reductions through the implementation of mitigation measures at varying cost levels. The curve begins with reduction volumes achieved using mitigation measures which are the most economic and then adding additional reductions from technologies which entail higher costs.

The MAC curve results included in this chapter for vented and combustion-related emission are provided for each of the Study's four "main cases":

1. **2023 Current Protocol**: Emissions from current ONE Future members in the year 2023 as estimated under the current ONE Future Protocols.
2. **2030 Current Protocol**: Projected emissions from current ONE Future members in the year 2030 estimated under the current ONE Future Protocols.
3. **2023 Revised Subpart W Protocol**: Emissions from current ONE Future members in the year 2023 re-calculated using a revised protocol that incorporates certain expected changes to EPA's GHGRP Subpart W rules.
4. **2030 Revised Subpart W Protocol**: Emissions from current ONE Future members in the year 2030 re-calculated using a revised protocol that incorporates certain expected changes to EPA's GHGRP Subpart W rules.

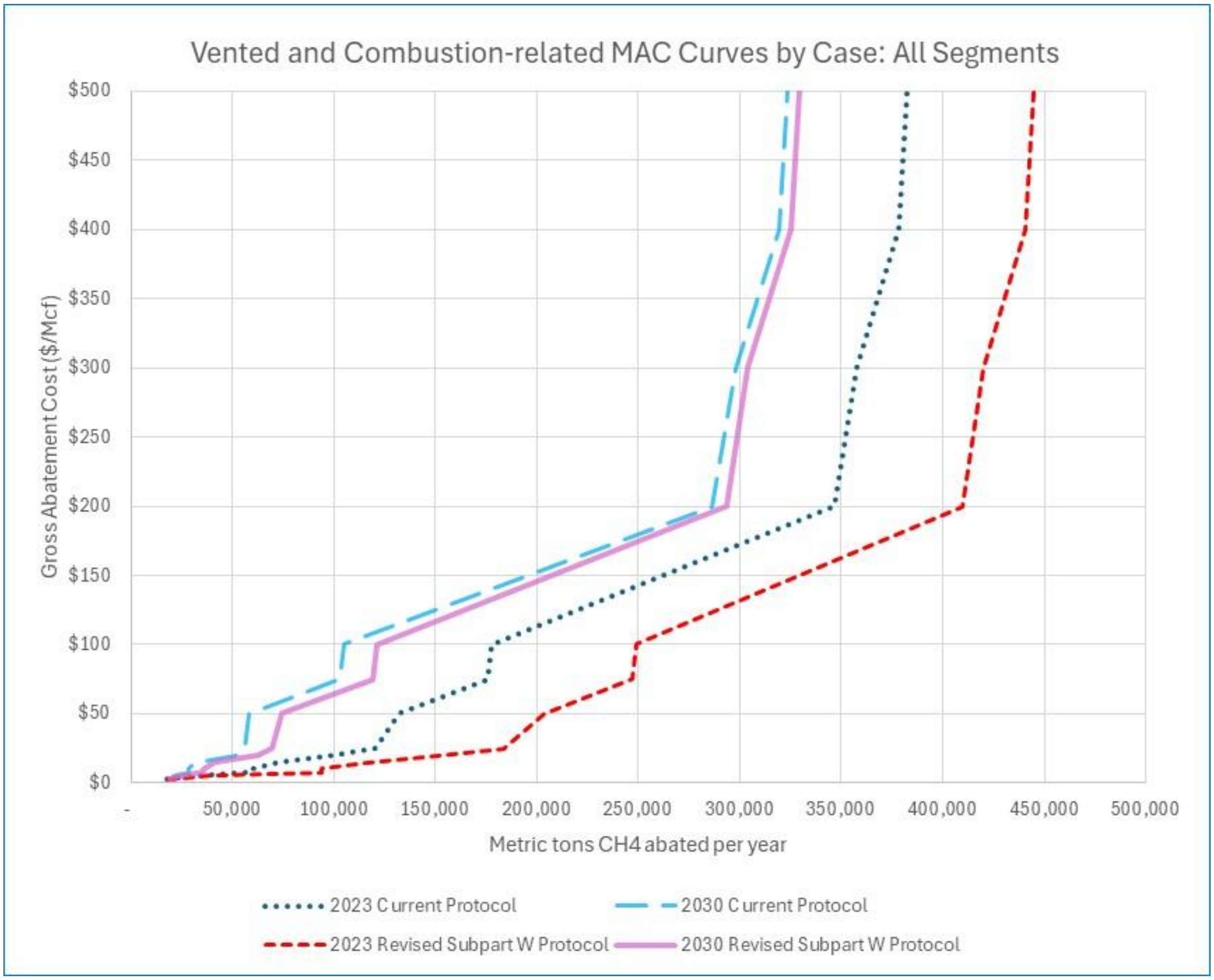
More information on each of these cases is provided in **Chapter 2**.

4.4.1 MAC Curve Results for All Cases

Exhibit 32 below provides a summary of the MAC curve results for vented and combustion-related emission sources for all main cases. Reduction volumes are represented on the x-axis and costs are shown on the basis of gross cost per methane volume reduced using the calculation discussed in **Chapter 1**. The amount of abatement achievable by industry segment is presented in the next section of this chapter.

A greater volume of methane reduction can be achieved in the Revised Subpart W Cases in both the 2023 and 2030 due to the higher baseline volume of methane emissions. Differences in the baseline emissions among the cases are the result of assumptions (discussed in **Chapter 2**) on the expected impact from the Subpart W revisions as well as projections of future gas supply by region, gas consumption by sector and region, and the overall technology mix along the natural gas supply chain.

Exhibit 32: All-Segment Vented and Combustion-related MAC Curves for the Four Main Study Cases



4.4.2 2023 and 2030 Current Protocol MAC Curves Results

Exhibit 33 and Exhibit 34 provide the MAC curve results for vented and combustion-related emission sources for the 2023 and 2030 under the Current Protocol. The 2023 results utilize the baseline emissions inventory described in **Chapter 2**. The 2030 Current Protocol results employ the same method of calculating baseline emissions but use activity levels which reflect expected changes in the regional mix of gas supply and consumption, as well as expected changes to the technology mix of pneumatic devices and distribution mains and services.

There are two emission volumes shown in the last two rows in both exhibits. The first of these two rows indicate the emissions associated with the vented and combustion-related sources that were included in the application of the mitigation strategies considered in this study. The bottom row represents the emissions associated with all vented and combustion-related sources in the baseline inventory. The values shown in the last column represent the amount of abatement achieved at each cost level, but only across the sources which were included when applying the mitigation strategies in this study. The emissions from all vented and combustion-related sources are not considered in the abatement amounts shown to avoid understating. Doing so would understate the abatement as there are additional mitigation technologies which could be employed with those sources that are not considered in this study.

Including all industry segments, 76% of abatement is achievable across the applicable vented and combustion-related sources in the 2023 results and 71% of abatement in the 2030 results at $500/Mcf. The sources with the greatest potential reductions are found in the gathering and transmission segments, specifically methane catalyst usage to reduce methane slip and dry seal capture and recovery.

Exhibit 33: Vented and Combustion-related MAC Curves by Segment 2023 Current Protocol

2023 Vented and Combustion-related MAC Curve for Cur. Protocol, National Region: metric tons per year of methane abated vs. baseline									
Gross Abatement Cost ($/Mcf)	**Onshore Production**	**Gathering**	**Processing**	**Transmission**	**Storage**	**Distribution**	**Other Segments**	**All Segments**	**All Segments as % of Sources Included in MAC**
$3	-	2,587	11	13,919	1,545	37	-	18,099	4%
$5	11,272	2,587	11	13,919	1,545	70	-	29,404	6%
$8	30,740	12,936	11	13,919	1,545	70	-	59,221	12%
$10	30,740	12,936	11	13,919	1,545	203	-	59,353	12%
$15	35,607	16,145	11	17,299	3,976	203	-	73,240	14%
$20	43,881	17,316	11	31,100	6,895	564	-	99,766	20%
$25	55,365	18,240	11	39,791	6,895	564	-	120,865	24%
$50	65,653	18,240	48	40,908	6,895	564	-	132,308	26%
$75	65,653	18,240	48	84,088	6,895	564	12	175,499	35%
$100	65,653	18,240	2,183	84,117	6,895	564	12	177,664	35%
$200	75,339	124,071	3,177	109,649	33,832	564	162	346,793	69%
$300	75,339	124,071	14,095	109,649	33,832	802	162	357,950	71%
$400	75,339	124,071	14,095	130,281	33,832	802	162	378,581	75%
$500	75,339	124,071	18,107	130,281	33,832	802	183	382,615	76%
$1,000	75,339	124,071	18,197	132,890	33,832	802	183	385,314	76%
$2,000	75,339	133,424	18,197	132,890	33,832	802	183	394,668	78%
Sources Included in MAC Analysis (MT/y)	**77,328**	**142,310**	**22,101**	**224,351**	**37,245**	**1,007**	**1,449**	**505,791**	**100%**
All Vented and Combustion-Related Sources (MT/y)	**96,998**	**161,507**	**28,653**	**294,698**	**40,743**	**1,007**	**4,552**	**628,158**	**124%**

Note: "Other Segments" include offshore production, distribution storage and LNG export.

Exhibit 34: Vented and Combustion-related MAC Curves by Segment 2030 Current Protocol

2030 Vented and Combustion-related MAC Curve for Cur. Protocol, National Region: metric tons per year of methane abated vs. baseline									
Gross Abatement Cost ($/Mcf)	Onshore Production	Gathering	Processing	Transmission	Storage	Distribution	Other Segments	All Segments	All Segments as % of Sources Included in MAC
$3	-	3,087	12	14,430	1,508	39	-	19,076	4%
$5	2,505	3,087	12	14,430	1,508	75	-	21,617	5%
$8	6,831	5,386	12	14,430	1,508	75	-	28,243	6%
$10	6,831	5,386	12	14,430	1,508	216	-	28,384	6%
$15	7,913	6,100	12	15,181	2,048	216	-	31,470	7%
$20	9,751	6,360	12	29,489	4,898	600	-	51,110	11%
$25	12,303	6,565	12	31,420	4,898	600	-	55,798	12%
$50	14,590	6,565	20	31,668	4,898	600	-	58,341	13%
$75	14,590	6,565	20	76,433	4,898	600	12	103,117	23%
$100	14,590	6,565	2,257	76,439	4,898	600	12	105,361	23%
$200	26,211	121,885	3,391	102,909	31,191	600	176	286,363	63%
$300	26,211	121,885	14,795	102,909	31,191	857	176	298,025	66%
$400	26,211	121,885	14,795	124,298	31,191	857	176	319,413	71%
$500	26,211	121,885	18,998	124,298	31,191	857	198	323,638	71%
$1,000	26,211	121,885	19,100	127,003	31,191	857	198	326,446	72%
$2,000	26,211	132,074	19,100	127,003	31,191	857	198	336,635	74%
Sources Included in MAC Analysis (MT/y)	**28,521**	**142,210**	**23,216**	**221,821**	**34,522**	**1,075**	**1,337**	**452,702**	**100%**
All Vented and Combustion-Related Sources (MT/y)	**50,170**	**164,744**	**30,100**	**294,751**	**37,937**	**1,075**	**4,663**	**583,441**	**129%**

Note: "Other Segments" include offshore production, distribution storage and LNG export.

4.4.3 2023 and 2030 MAC Curves Results for Emissions Under Revised Subpart W

Exhibit 35 and Exhibit 36 below provide the MAC curve results for vented and combustion-related emission sources for the 2023 and 2030 cases using baseline emissions which reflect estimated impacts from Subpart W revisions. The percent reduction in these cases are comparable with the 2023 and 2030 Current Protocol results shown in Exhibit 33 and Exhibit 34 as measured in terms of achievable abatement across all industry sectors (77% and 70% respectively at $2,000/Mcf). However, the volume of reductions achievable are larger due to higher baseline emissions. The largest sources of reductions in these results include installing catalysts to reduce methane slip from combustion sources, dry seal capture and recompression from compressors, and installation of vapor recovery units.

Exhibit 35: Vented and Combustion-related MAC Curves by Segment: 2023 Revised Subpart W Protocol

2023 Vented and Combustion-related MAC Curve for Revised Sp W, National Region: metric tons per year of methane abated vs. baseline									
Gross Abatement Cost ($/Mcf)	**Onshore Production**	**Gathering**	**Processing**	**Transmission**	**Storage**	**Distribution**	**Other Segments**	**All Segments**	**All Segments as % of Sources Included in MAC**
$3	-	2,587	11	13,919	1,545	37	-	18,099	3%
$5	20,463	2,587	11	13,919	1,545	70	-	38,595	6%
$8	55,805	22,400	11	13,919	1,545	70	-	93,750	16%
$10	55,805	22,400	11	13,919	1,545	203	-	93,883	16%
$15	64,641	28,544	11	17,955	4,912	203	-	116,264	20%
$20	79,660	30,787	11	31,756	7,831	564	-	150,608	25%
$25	100,508	32,555	11	42,133	7,831	564	-	183,602	31%
$50	119,185	32,555	65	43,468	7,831	564	-	203,668	34%
$75	119,185	32,555	65	86,647	7,831	564	12	246,859	42%
$100	119,185	32,555	2,201	86,682	7,831	564	12	249,030	42%
$200	127,913	131,291	3,194	112,215	34,621	564	162	409,959	69%
$300	127,913	131,291	13,202	112,215	34,621	786	162	420,190	71%
$400	127,913	131,291	13,202	132,568	34,621	786	162	440,543	74%
$500	127,913	131,291	17,215	132,568	34,621	786	183	444,577	75%
$1,000	127,913	131,291	17,304	135,178	34,621	786	183	447,276	75%
$2,000	127,913	140,014	17,304	135,178	34,621	786	183	455,999	77%
Sources Included in MAC Analysis (MT/y)	**135,849**	**162,355**	**27,413**	**226,746**	**38,809**	**989**	**1,810**	**593,970**	**100%**
All Vented and Combustion-Related Sources (MT/y)	**158,567**	**187,864**	**33,964**	**297,094**	**42,307**	**11,191**	**4,913**	**735,899**	**124%**

Note: "Other Segments" include offshore production, distribution storage and LNG export.

Exhibit 36: Vented and Combustion-related MAC Curves by Segment: 2030 Revised Subpart W Protocol

2030 Vented and Combustion-related MAC Curve for Revised Sp W, National Region: metric tons per year of methane abated vs. baseline									
Gross Abatement Cost ($/Mcf)	**Onshore Production**	**Gathering**	**Processing**	**Transmission**	**Storage**	**Distribution**	**Other Segments**	**All Segments**	**All Segments as % of Sources Included in MAC**
$3	-	3,087	12	14,430	1,508	39	-	19,076	4%
$5	4,547	3,087	12	14,430	1,508	75	-	23,659	5%
$8	12,401	7,490	12	14,430	1,508	75	-	35,916	7%
$10	12,401	7,490	12	14,430	1,508	216	-	36,057	7%
$15	14,365	8,855	12	15,327	2,256	216	-	41,031	8%
$20	17,702	9,353	12	29,635	5,106	600	-	62,408	13%
$25	22,335	9,746	12	31,941	5,106	600	-	69,740	14%
$50	26,486	9,746	24	32,237	5,106	600	-	74,199	15%
$75	26,486	9,746	24	77,002	5,106	600	12	118,975	24%
$100	26,486	9,746	2,261	77,010	5,106	600	12	121,220	25%
$200	36,958	117,337	3,395	103,479	31,255	600	176	293,201	60%
$300	36,958	117,337	13,848	103,479	31,255	840	176	303,894	62%
$400	36,958	117,337	13,848	124,580	31,255	840	176	324,995	67%
$500	36,958	117,337	18,051	124,580	31,255	840	198	329,219	68%
$1,000	36,958	117,337	18,154	127,286	31,255	840	198	332,027	68%
$2,000	36,958	126,839	18,154	127,286	31,255	840	198	341,530	70%
Sources Included in MAC Analysis (MT/y)	**45,946**	**151,646**	**28,847**	**222,215**	**35,343**	**1,056**	**1,388**	**486,441**	**100%**
All Vented and Combustion-Related Sources (MT/y)	**71,068**	**181,204**	**35,731**	**295,145**	**38,759**	**3,323**	**4,715**	**629,944**	**130%**

Note: "Other Segments" include offshore production, distribution storage and LNG export.

5. Conclusions

5.1 Findings

Over 75% abatement is achievable across ONE Future member operations at a cost of \$500/Mcf. At a cost of \$100/Mcf of gross abatement (approximately equivalent to \$186 per metric ton of CO2 equivalent at a GWP of 28), it is feasible to achieve 46% abatement across all industry segments by 2030 under the Current Protocol. Under the Revised Subpart W Protocol, total abatement could increase to 49% at the same \$100/Mcf cost by 2030. A greater percentage methane reduction can be achieved in the cases where Subpart W revisions have been incorporated due to the higher volume of methane emissions quantified in the baseline. This leads to greater mitigation volumes when abatement technologies are applied and, thus, lower per-unit abatement costs.

Generally speaking, the case results for 2023 and 2030 show similar reduction volumes for all industry segments. The differences between the 2023 and 2030 cases are due to assumptions for the activity and infrastructure parameters which were adjusted to reflect expectations for a larger overall US natural gas market size, changes in the regional mix of US gas supplies and consumption, declines in miles of iron and steel distribution mains and a corresponding increase in plastic miles, and reduced use of pneumatic devices which emit methane.

Exhibit 37: All-Segment MAC Curves for the Four Main Study Cases, All Sources by Reduction Volume (mt CH_4)

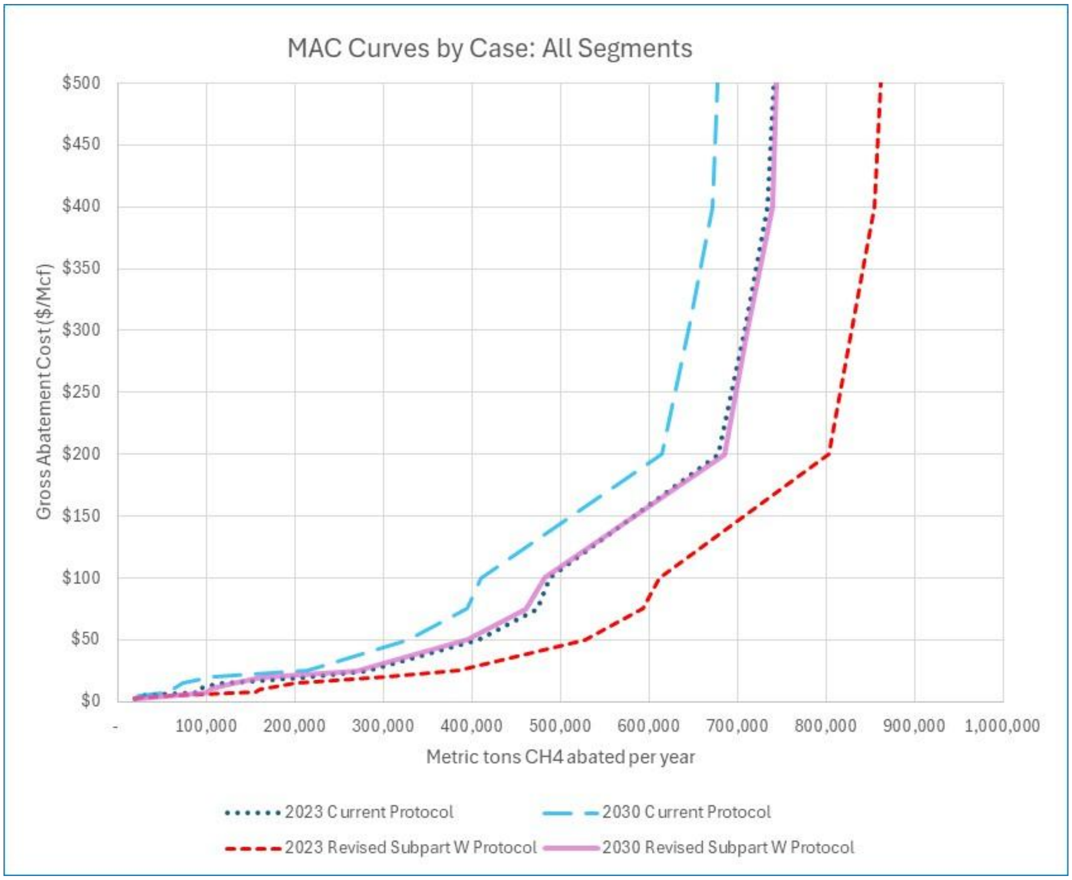
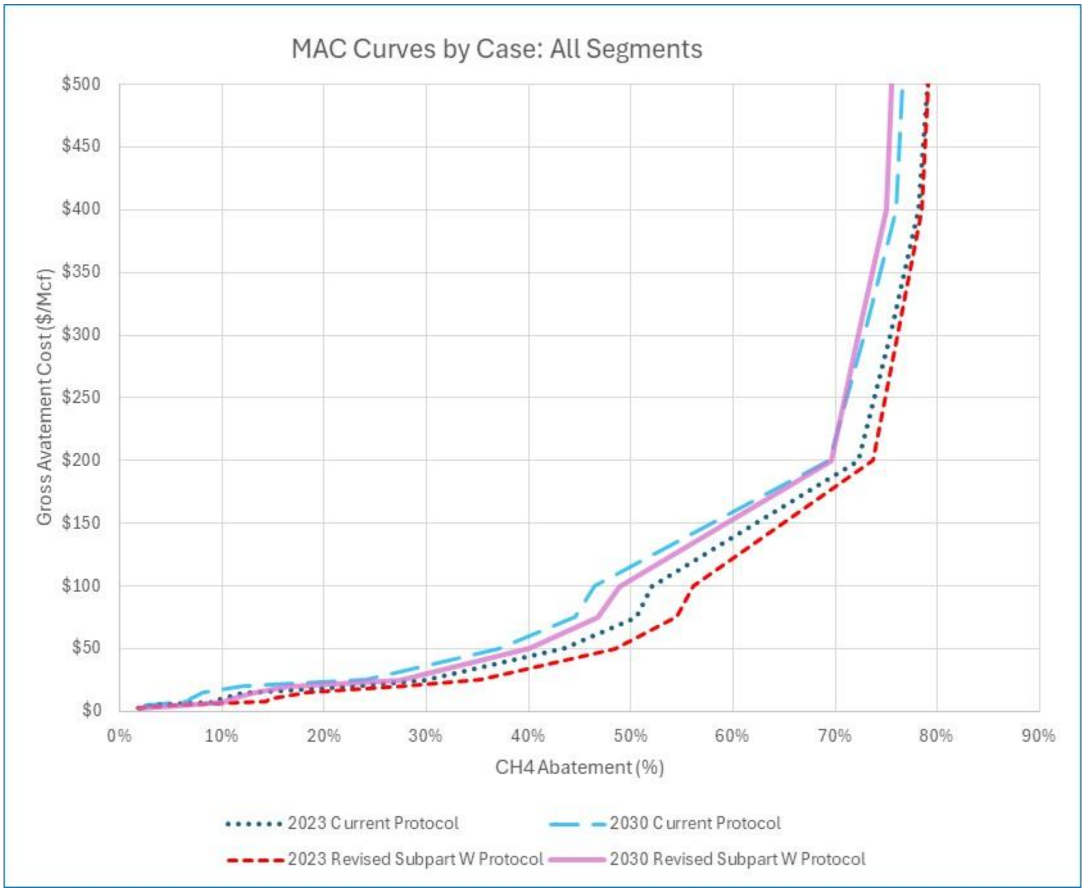


Exhibit 38: All-Segment MAC Curves for the Four Main Study Cases, All Sources by Abatement (%)



5.2 Caveats

Readers should keep in mind that this Study's results were developed using several important data elements and assumptions whose true values are not known with certainty or which, even if known, might change within the time frame covered by the Study. The data elements and assumptions for which caveats are warranted include:

> **Historical emission volumes**: Methane emission reported by ONE Future members for 2023 are based on a variety of methodologies including the use of emission factors applied to historical activity counts and direct measurements of equipment and facilities. The emission factors used in this process may be outdated or may not be appropriate for all situations in which they are applied. The application of direct measurement methods solves many problems associated with the use of emission factors but introduces its other issues (related to selection of the appropriate technologies, application of survey protocols, and data processing/ statistical reporting) that will take time to resolve.
>
> **New emission protocols**: Two of the four main cases analyzed in this report are the "Revised Subpart W Cases" that reflect possible changes to which emissions sources are included in the methane inventory for each industry segment and how those emissions are estimated. While the impact of many of these changes can be estimated

with a high degree of confidence (e.g., the introduction of new emission factors for sources whose methane emissions are already being estimated), there is considerable uncertainty around how some of the new sources (especially Large Release Events) will change emission volumes.

Emissions projected to 2030: The projection of future emissions in the year 2030 carries forward all of the uncertainties and caveats contained in the estimates for the year 2023 plus it introduces the additional unknowns related to (a) how supply and demand in the natural gas market will change in the next six years and (b) what new infrastructure and new equipment will be employed in each segment of the natural gas supply chain.

Characterization of fugitive leaks: The estimation of the MAC curves for LDAR programs is based on assumptions regarding the number, average size, size distribution and persistence of fugitive leaks. There is considerable uncertainty regarding these values – all of which can affect the economics of LDAR programs.

Technology performance and costs: Assumptions were made for the efficacy of mitigation technologies and their costs for the year 2023 and those assumptions were carried forward unchanged in developing the MAC curves for the year 2030. These assumptions may not be accurate for all of the situations in which they are applied to create the MAC curves. For example, small companies might have to pay higher costs compared to larger companies that can negotiate large-volume discounts. Furthermore, technological advances or market forces can change these technology performance and cost parameters in future years.

Current implementation of mitigation/LDAR efforts: The baseline emissions upon which the MAC curves are built may already contain the effects of various mitigation measures undertaken by ONE Future members. For example, certain members may already implement LDAR programs involving periodic monitoring and repair of leaks. The extent to which these measures have been deployed is not known and the factor of baseline leak survey frequencies has not been incorporated into the MAC analysis. This might overstate the potential abatement volumes that can be achieved for any given leak survey technology in that that it may have already been applied to a subset of facilities.

6. Appendix A: Acronyms and Abbreviations

Acronym/ Abbreviation	Meaning
AACE	Association for the Advancement of Cost Engineering
AAPG	American Association of Petroleum Geologists
AEO	Annual Energy Outlook from the U.S. Energy Information Administration
AFUDC	Allowance for funds used during construction
ALD	Advanced leak detection
AMLD	Advanced Mobile Leak Detection
ANL	Argonne National Laboratory
ASTM	ASTM International
AVO	Audio, Visual, Olfactory
bbl	Barrel
bcf	Billion cubic feet
Btu	British thermal unit
Capex	Capital expenditure
CH4	Methane
CM	Continuous monitoring
CO	Carbon monoxide
CO2	Carbon dioxide
CO2e	Carbon dioxide equivalent
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration (within U.S. DOE)
EOR	Enhanced oil recovery
EPA	U.S. Environmental Protection Agency
ESG	Environmental, Social, and Governance (a framework used to evaluate a company's sustainability and ethical impact)
FOM	Fixed operating and maintenance costs
GHG	Greenhouse gas
GHGRP	The US EPA's Greenhouse Gas Reporting Rule
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GTI	Gas Technology Institute
GW	Gigawatt
GWh	Gigawatt-hour
H or H2	Hydrogen
HHV	Higher heating value
HP	Horsepower
ICE	Internal combustion engine
IEA	International Energy Agency
IRA	Inflation Reduction Act of 2022
IRA-MERP	Methane Emissions Reduction Program established by the Inflation Reduction Act and implemented by EPA

kg	Kilogram
kg/d	Kilograms per day
kg/h	Kilograms per hour
kWh	Kilowatt-hour
LCA	Life cycle analysis
LCOE	Levelized cost of electricity
LDAR	Leak detection and repair
LHV	Lower heating value
LiDAR	Light Detection and Ranging
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas (mostly propane and butane)
LST	Laser Spectroscopy Tower
MAC	Marginal abatement cost
Mcf	Thousand cubic feet
MMBtu	Million British thermal units
MMcf	Million cubic feet
MMCFD	Million cubic feet per day
MMRV	Measurement, monitoring, reconciliation and validation
MPa	Megapascal (35 MPa = 5,000 psig = 350 bar)
MT	Metric ton
MW	Megawatts
MWh	Megawatt-hour
NETL	National Energy Technology Laboratory (U.S. DOE)
NG	Natural gas
NGL	Natural gas liquid
Nm3/h	Normal cubic meters per hour
NOM	Normal Operations Monitoring
NREL	National Renewable Energy Laboratory
NTP	Normal temperature and pressure
O&M	Operations and maintenance
OCS	Outer continental shelf
OGI	Optical gas imaging
Opex	Operating and maintenance expenditures
PHMSA	Pipeline and Hazardous Materials Safety Administration
PoD	Probability of detection
PPA	Power purchase agreements
psi	Pounds per square inch
psig	Pounds per square inch (gauge pressure)
Q90	Leak quantity in kg/h which has a 90% probability of detection
Qmin	Leak quantity in kg/h which has a 0.1% probability of detection
quads	Quadrillion British thermal units
RNG	Renewable natural gas
S	Sulfur
SCF	Standard cubic feet
Sp W	Subpart W

SWIR	Short Wave Infrared
t or MT	Metric ton
TBtu	Trillion British thermal units
TWh	Terawatt-hour
Vol	Volume
VOM	Variable operating and maintenance costs

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