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Technology Roadmap for Compressor Station Methane Emissions and Mitigation Scenarios

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EXECUTIVE SUMMARY

Compressors and compressor stations are used across several segments of the natural gas supply chain, from gathering and boosting to distribution. These complex systems have been shown to emit large quantities of methane, which offers a potential opportunity to reduce emissions while keeping more natural gas within the supply chain for ultimate delivery and use. The purpose of this project was to explore natural gas transmission compressor stations, specifically, dissecting the types of equipment that can be found at these stations and the points where leakage or releases of methane could occur then detail ways to quantify and mitigate these emissions. More importantly, the effort was focused on collecting existing information and organizing that information in the form of a technology roadmap that could be used to explore the options for determining, detecting, quantifying, and mitigating methane emissions from natural gas transmission compressor stations.

The project focused on three areas of effort - 1) gathering and distillation of existing information on leak detection, monitoring, quantification, and mitigation; 2) estimation of potential methane reductions; and 3) technology roadmap diagram and information spreadsheet model development. The completion of these three efforts involved extensive collaboration between GTI Energy and industry partner, Williams Companies, resulting in three key products 1) a Technology Roadmap Diagram to detail the extensive information at a high-level, 2) a User Interface Spreadsheet Model to streamline detailed explorations of extensive data on methane emissions detection, quantification, and mitigation solutions for individual equipment/components of a compressor station, and 3) detailed Use Cases for how to use the diagram and model together, to answer questions that an operator may have.

Briefly, the information summarized in this project divides the routes to mitigate methane emissions at a compressor station into three main categories: direct recovery, operational improvements, and upgrades and replacements. Each of these mitigation options must be thoroughly explored by a company to balance the potential for methane emissions mitigation with the intricacies of operational implementation, including costs. The Technology Roadmap Diagram and User Interface Spreadsheet Model developed in this project are aimed at helping operators and companies wade through the options to make the most informed decisions. The preparation of the diagram and model has revealed that the thought of a single easy-to-implement "low-hanging fruit" for methane mitigation from compressor stations is a nuanced discussion, involving difficult decisions between cost, reduction efficiency, and ease of implementation.

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INTRODUCTION

GTI Energy (GTI), through extensive collaboration with Williams Companies, an industry-leading natural gas midstream company, has developed a Technology Roadmap focused on identifying and mitigating methane emissions, specifically from natural gas transmission compressor stations. Although developed specifically for natural gas transmission compressor stations, the details in this report are broadly applicable to compressor stations across the natural gas supply chain and will be referred to as simply compressor stations. The Roadmap consists of two key products: 1) the Technology Roadmap Diagram ("the Diagram") and 2) the User Interface Spreadsheet Model ("the Model"). These two products were developed for the general user (e.g., regulator, policy maker, researcher), as opposed to an industry-specific effort,[1] to quickly explore the main components of a compressor station and to identify technologies and areas that may be prioritized to maximize methane emission mitigation while minimizing implementation effort and cost. Once areas of interest have been identified with the diagram, the user can turn to the model to explore detailed information on per-component and per-site strategies and methane emission mitigation quantities.

The process of developing the diagram and model took several months, including a comprehensive literature review to establish the types and sizes of emissions that may be encountered at a compressor station and available technologies to reduce or eliminate those emissions. There were also in-depth discussions between GTI, Williams, and other industry partners to agree on definitions of the fundamental components and areas of a typical natural gas transmission compressor station, along with recent advancements in emission mitigation. This report summarizes the effort, along with the final diagram and model.

Background

A major challenge associated with US energy systems is protecting people and the environment while also advancing the safe transportation of energy and hazardous materials through system infrastructure. There are also regulations from the US Environmental Protection Agency (EPA) to enforce standards that include emissions. The EPA provides operators with required standards in Subparts OOOOb/c (OOOOb/c) for new, modified, and reconstructed crude and natural gas facilities after December 6, 2022 (OOOOb), and emissions guidelines for State adoption and enforcement for existing crude and natural gas facilities (OOOOc). In the natural gas supply chain, a critical aspect of addressing that challenge is detecting, quantifying, and mitigating methane emissions and infrastructure leaks. These are immense efforts given the complex and expansive nature of natural gas infrastructure.

Compressors are used along the entire natural gas supply chain to move or store gas across the country. These include upstream gathering and boosting compressors, midstream transport and storage compressors, and even compressors in the delivery sector to help move gas and maintain operating pressures. Compression of the gas is the largest emission contributor within the gas transmission and distribution sector. The EPA 2023 Inventory of Greenhouse Gas Emissions and Sinks (GHGI) reported that within the transmission sector, 54.1% of emissions are due to compressor station fugitive emissions and an additional 12.6% from compressor exhaust for the year 2020.[2] Prior to the inclusion of methane slip, reciprocating engines were the most significant methane sources within compressor stations, followed by station venting, engine exhaust, and general fugitive emissions.

Several large-scale academic studies[3–9] and industry-led efforts[10–13] have focused on compressor stations across the natural gas supply due to the relatively large contribution to overall methane emissions. Based on the findings of these studies, several advancements have been made and opportunities identified in a variety of areas that can be useful to methane emission mitigation efforts from compressor stations. However, not all new solutions for emissions reduction are practical from an operational perspective due to the unique characteristics of each site. As such, the diagram and model were developed to provide a tool for users to contemplate the many options available.

Project Objectives

The Diagram and Model development efforts focused on options for methane emission quantification and mitigation that are appropriate for compressor stations. The effort focused on 3 areas: 1) gathering and distillation of existing information; 2) quantification of potential methane emission reductions through the implementation of new technologies at compressor station facilities; and 3) technology roadmap diagram and information spreadsheet model development. Specific goals and objectives for these three key areas are shown in Table 1.

Table 1: Project Goals and Objectives

Goal	Objective
Area 1 – Gathering and distillation of existing information on leak detection, monitoring, quantification, and mitigation	1a: Determine bounds of the current detection, monitoring, quantification, and mitigation landscape by performing a literature review of current efforts.
	1b: Form Technical Advisory Panel (TAP) consisting of operators, industry professionals, technology providers, and emissions specialists to both understand technical issues and disseminate information among the groups.
	1c: Identify common fugitive emission sources at natural gas compressor facilities, emissions from condensate storage facilities, along with flaring and reuse options to begin quantifying the potential for emissions mitigation.

Area 2 – Quantification of potential methane reductions	2a: Estimate the potential reduction in fugitive emissions from various emission mitigation pathways.
	2b: Examine whether it is feasible for fugitive emissions to be recaptured and used on site or recompressed and injected into the pipeline.
	2c: Determine whether operational efficiencies can be realized for the natural gas compressors at compressor facilities to reduce emissions.
	2d: Present commercially available or newly available methane quantification and monitoring technologies that can be used at compressor facilities.
Area 3 – Technology roadmap diagram and information spreadsheet model development.	3a: Assemble information gathered in key Focus Areas 1 and 2 to compile a Technology Roadmap Diagram and User Interface Spreadsheet Model to understand the current landscape of technologies that can be used to detect, quantify, and mitigate methane emissions at compressor facilities.

AREA 1 – INFORMATION GATHERING ON LEAK DETECTION, MONITORING, QUANTIFICATION, AND MITIGATION

The production of the final Technology Roadmap Diagram and User Interface Spreadsheet Model required detailed information gathering efforts through the TAP for the project, along with technical partner, Williams Companies[14] and co-funder Operations Technology Development.[15] The following sections summarize this effort.

Compressors are widely used and appear in several supply chain segments, including gathering and boosting, transmission, storage, and distribution.

Due to the supply-chain-wide use, the information presented in the final products of this project (the diagram and the model) is widely applicable to compressor stations across the natural gas supply chain, despite being developed specifically for compressor stations in the natural gas transmission segment.

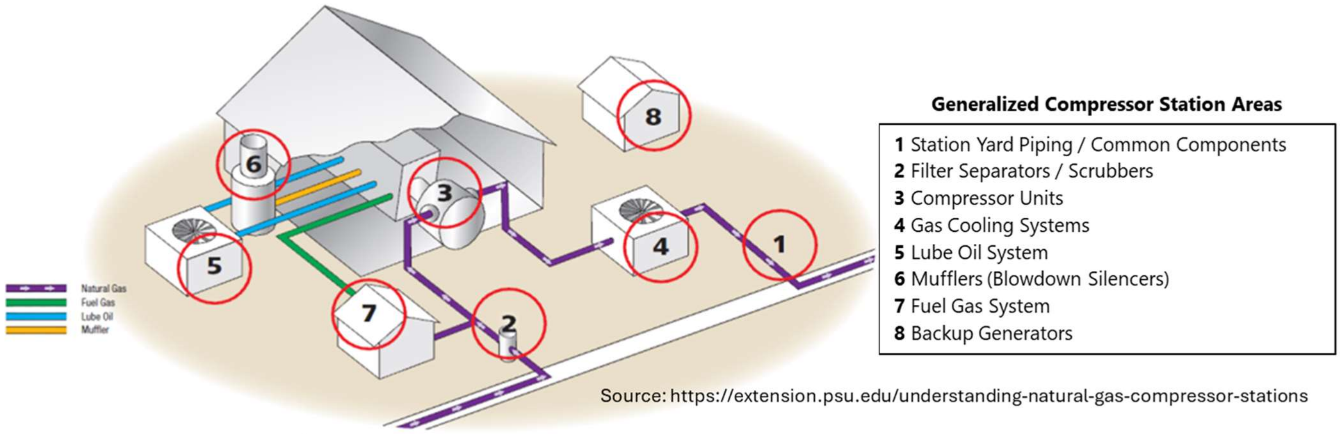
Natural Gas Transmission Compressor Station Components

Completing the Area 1 effort required that the team first establish an inventory of the primary components and equipment found at a natural gas transmission compressor station. These facilities integrate a wide variety of equipment types, each with processes and subcomponents that have the potential to release methane. Extensive discussions were held to establish the major equipment groups and processes of a typical natural gas transmission compressor station, factors that contribute to methane emissions, and potential mitigation measures.

While many common elements exist, variations exist in what specific equipment is present at a given site. In some environments, compressor units may be housed in structures to protect them from weather conditions, whereas in other areas, the compressors are outdoors. Some facilities may include equipment needed to remove moisture or other impurities from the gas. Equipment housing structures, poor survey access, or challenging operational scenarios can hinder emissions detection and mitigation.

Figure 1 is a simplified illustration of the major elements of a compressor station, adapted from Messersmith (2015).[16] Several main segments are identified, with corresponding numbers in the figure. For ease of reference, these same major segment descriptions and numbering are used throughout the project, including in the diagram and model. One note, Section 1 Station Yard Piping/Common Components also includes information about common components used throughout the facility, such as valves and their applications, pneumatic devices, and fittings.

Figure 1: Compressor station yard diagram



Compressor Station Methane Emissions Background

A number of studies have focused on methane emissions from compressor stations across the natural gas supply chain in recent years, including several well-known academic studies[3–9]. These studies generally conclude that there is a discrepancy between the reported emissions and actual emissions seen at midstream compressor stations. Some of this difference can be attributed to the high variability in emissions from 4-stroke lean-burn engines and 4-stroke rich-burn engines,[3,4,6] the issue is that engine-driven stations have significantly higher emissions than those that were turbine-driven[5] and emission factors/activity factors may not be representative of compressor stations due to the shift in engine use to turbines and the reduction in gas-driven pneumatics.[9]

In addition to academic studies, several industry-led efforts have been made to understand methane emissions from compressor stations and how to approach mitigation strategies. In particular, it has been identified that the industry needs to understand the methodologies used by the Greenhouse Gas Reporting Program (GHGRP) and GHGI in developing the emission factors.[11,12] Generally, the industry-led efforts focus on the operational aspect to mitigate methane emissions, including the implementation required to reduce the emissions at compressor stations[10,17] and specifically the methodology needed to create operator factors, prioritize leaks, and implement leak detection and quantification (LDAQ) processes.

The completed studies have generated a breadth of information that, when combined with existing information in the GHGRP, GHGI, and Natural Gas STAR programs, can be quite daunting to navigate. The Technology Roadmap Diagram and User Interface Spreadsheet Model were created to simplify the exploration of this information.

Common Methane Emission Types

Understanding methane emissions and potential mitigation opportunities from compressor stations requires a broader understanding of methane emissions and their potential sources. In this section, we provide a broad background of the natural gas supply chain, including methane emissions that can be applied to compressor stations.

Methane emissions from any equipment can be highly variable, a multivariate phenomenon of flow rate, time, and conditions. Methane can be emitted by malfunctioning equipment, maintenance events, venting that occurs in normal operations, or as non-combusted methane fuel in engine emissions. Normal operational emissions (e.g., control valves, pneumatic devices, pressure relief valves) are often intermittent or do not occur consistently, are measured, and typically considered venting rather than failure leakage.

Methane emissions at a compressor station are divided into three categories for this project: fugitive emissions from leaks and losses, emissions vented in normal operations, and emissions associated with incomplete combustion and methane slip.

Leaks and Fugitive Emissions

Federal regulations define fugitive emissions as those emissions that could not reasonably pass through a stack, chimney, vent, or other functionally equivalent opening.[18] As such, these emissions include leaks arising from damage, malfunction, or other unintended sources. Equipment leaks are also commonly referred to as fugitive emissions and characterized as unintentional emissions. Component leaks/fugitive emissions have many different causes, some examples are:

- *Improper or loose fittings and connections:* bolted flanges as well as threaded, compression, and bell-and-spigot connections may not have proper fit or become loose.
- *Damaged valves:* Fouled or damaged gates or plug seats in valves prevent tight closure (e.g., through-valve leaks).
- *Worn valve stem seals:* the packing around the shaft connecting the external valve hand wheel or actuator and the internal valve plug (stem) must be loose enough to allow stem movement, but tight enough to prevent significant leakage. Stem packing will wear out with frequent valve usage.
- *Corrosion/damage:* deterioration of metal causes equipment connections and other components to degrade.
- *Worn/damaged gaskets:* thief hatches on storage tanks may not properly seal if the gasket is worn or damaged.
- *Human error:* components such as valves or thief hatches are inadvertently left open.

Fugitive emissions can occur anywhere in the system that conveys gas from the field to the end user, presenting numerous challenges in finding and repairing leaks. Emissions due to a leak are generally constant with operations, although certain conditions may prevent a small leak from venting for a short duration (e.g., ice forming and blocking mechanics).

Venting for Operational Reasons

Methane is frequently vented across the natural gas supply chain due to changes in pressures, temperatures, or to release/relieve pressure, such as during blowdowns (e.g., maintenance, unit). These practices often result in a relatively large emission rate for a short duration. These short-duration events (i.e., intermittent) are often difficult to quantify with typical methane detection and quantification technologies. The US Department of Energy provided the following definitions in their report "Natural Gas Flaring and Venting: State and Federal Regulatory Overview, Trends, and Impacts":[19]

- Venting of natural gas diverted from oil and gas compression or processing equipment due to a system upset condition or a pressure release emergency
- Blowdown of gas from processing equipment, pipelines, or compressors prior to repairs
- Bleed-off of gas pressure during routine operation of pneumatic devices (e.g., motor valve controllers, pressure and level controllers)
- Routine emissions from natural gas-driven pneumatic pumps
- Venting to avoid pressure buildup in crude oil, condensate (light liquid hydrocarbons recovered from lease separators or field facilities at associated and non-associated natural gas wells. Mostly pentanes and heavier hydrocarbons. Normally enters the crude oil stream after production, or water storage tanks operating without vapor recovery systems
- Leakage from compressor seals (both reciprocating and centrifugal compressors).

Combustion-related Sources

Engines for compressor drivers and power generation may emit some amount of unburned fuel. This Non-Combusted Methane (NCM) is commonly referred to as "methane slip." This occurs as a normal result of internal combustion engine design, which does not completely burn all fuel available, but varies greatly with engine operating conditions such as speed and load. NCM may also be emitted from flares and other combustion devices, especially if malfunctioning. In 2023, Subpart W applicable transmission compression facilities reported ~0.05% of quantified CO_2 equivalent (CO2e) emissions to be associated with methane from combustion equipment.[20] Methane slip research is ongoing to improve estimates of the magnitudes of these emissions in comparison to overall compressor station emissions.

These efforts point toward combustion-related sources as more significant than previously known when methane slip is included. Zimmerle et al.[21] indicated that across all compressor stations, 38% of all emissions are due to methane slip, making it the largest category of methane emissions, a significant difference from the EPA GHGI estimates of compressor exhaust emissions. This is largely due to the majority, about 96%, of compressors are driven by natural gas-powered engines.

Methane Emission Quantification Methods for Compressor Stations

Each year, the different types of methane emissions for the natural gas industry are estimated in two greenhouse gas (GHG) emission inventories across the US. The first is the GHGI [22], which has a specific section that details GHG emissions from "natural gas systems." The other emissions estimate is the GHGRP. It uses company-reported emissions estimates to determine individual facility or network emissions for facilities emitting 25,000 metric tons of CO2e or greater each year. The emissions calculations for both programs rely heavily on information contained in the Pipeline and Hazardous Materials Safety Administration (PHMSA) pipeline database.[23]

The GHGI and GHGRP emissions estimates highlight emissions from specific categories of assets across the various segments of the natural gas value supply chain. These programs use established emission and activity factors to determine a total emission estimate in an "accounting style." Emission factors are represented on a kilogram of methane per mile or per component or other activity metric, such as the total run time in hours for the different operating modes. The activity factors are then the number of miles, components, or running time. To determine total emissions for a category of assets, the emission factor for that category is multiplied by the activity factor for that category.

Unfortunately, these "accounting-style" methods of quantifying methane emissions have some significant shortcomings when it comes to the determination and reduction of the methane that is truly emitted from the natural gas supply chain. These estimation methods tend to broadly represent emissions for large groups of components. Further, the pathways to emissions reductions under these accounting-style inventory methods are based on blanket elimination or reduction of infrastructure rather than targeted replacement or repair of the leakiest components. Therefore, to realize real-world methane emissions reductions, more granular examinations must be performed.

Regulatory agencies are realizing this gap between the accounting-style bottom-up inventories and top-down measurement-based inventories. Recently, the US EPA, PHMSA, and some state regulators have proposed amendments to their regulations to incorporate more empirical (measured) data in their reporting requirements.[24] This is seen in the addition of direct measurement options to several sources, such as reciprocating and centrifugal compressors and pneumatic devices.

Although changes to those inventories are expected, the industry is quickly moving toward the use of leak detection and measurement-informed emissions quantification to provide actionable information on when leaks occur, how large they are, and how they can be eliminated (mitigated). These efforts have also led to programs like the Oil and Gas Methane Partnership (OGMP) 2.0[25] and GTI Energy's Veritas Program[26] to develop methods for companies to use methane measurements to inform their emissions inventories. These programs provide actionable data that companies can use to track real-world methane emissions reductions, determine how they change over time, and compare them to other companies. The efforts to properly understand, quantify, and mitigate these methane emissions, however, are non-trivial, and this is part of the motivation behind compiling information for the Technology Roadmap Diagram and User Interface Spreadsheet Model.

AREA 2 - QUANTIFICATION OF POTENTIAL EMISSION REDUCTIONS

Technology for Quantification and Monitoring at Compressor Stations

Efforts to understand methane and ultimately mitigate methane emissions from compressor stations require cost-effective technologies and approaches to detect, quantify, and understand methane emissions in a broad range of scenarios. These efforts include better prioritization of leak response and repair, complying with current and potential future regulations, and meaningfully reducing greenhouse gas emissions. Broadly referred to as LDAQ, there is a diverse landscape of existing and emerging technologies capable of detecting, locating, and quantifying methane emissions. The value of these technologies involves mitigation of enforceability risks, the economic reward of retained product, and the commercial value of decarbonization.

Technologies vary in capability, application, and cost. Depending on the system, these technologies and the methods by which they are applied have a range of capabilities for the localization of leaks. Emission measurement methods vary depending on the scale of the source. For site-level measurements, the total emissions from the entire facility are given. For equipment-level measurements, emissions are measured from a standalone equipment group or section of a site, like separators or scrubbers. The finest resolution of measurement is component-level measurements, where emissions are measured from a single element, like a fitting or valve.

Table 2 broadly highlights some measurement methods at multiple levels of operations: site, equipment, and component levels applicable across the natural gas supply chain (i.e., not just for compressor stations).

Table 2: Measurement Method Application Levels

Measurement Method	Site Level	Equipment Level	Component Level
Satellite Infrared (IR) Optical Imaging	■		
Aerial IR Optical Imaging	■	■	
Aerial IR Laser Imaging and Detection	■	■	
Aerial Spiral Method	■		
UAV Spiral Method	■	■	
UAV Vertical Flux Plane Method	■	■	
Mobile Vehicle Path Method	■	■	
Open Path Continuous Monitor Method	■	■	
Point Continuous Monitor Method	■	■	
IR Optical Gas Imaging (OGI)		■	■
Infrared laser beam illuminated instruments		■	■
High Volume Sampler			■
Calibrated Bagging			■
Acoustic Leak Detection Device			■
Method 21			■

Table 3, adapted from LaFleur et al.[17], shows how these technologies have been classified by type and in relation to the method of deployment, to include systems for routine monitoring like handheld instruments, mobile (vehicle-mounted) sensors, aerial surveys, and orbital remote sensing. Four methods are shown. Walking surveys involve a deployed technician who is deployed in a boots-on-the-ground type of practice. Fixed monitors are sensors that are installed on-site to detect changes in methane concentrations in the air. Unmanned aerial vehicles (UAV) and aerial methods use either unmanned or traditional aerial vehicles to fly above, around, or downwind of the location being surveyed. Finally, satellite-deployed technologies use sensors deployed in Earth's orbit to remotely sense methane emissions.

Table 3: Leak Detection Methods, Limitations, and Applicable Uses

Method	Instruments	Description	Limitations	Applicable Uses
Walking	Pumped	Handheld instrument which draws in a gas sample from the ground or above ground pipe fittings, etc.	Short distance from source: Must be able to probe within the gas plume.	Approved for EPA leak detection
Walking	Laser	Handheld methane laser which can scan the ground or above ground piping from a standoff distance	Distance limited (~30m). Requires reflective background (can't scan into the sky).	Approved for EPA leak detection
Walking	OGI	Handheld camera that is highly sensitive to temperature difference and IR absorption of the gas	Operational or environmental conditions may prevent imaging. Identification of gas plume subjective. Detection of small leaks difficult.	Approved for EPA leak detection
Walking	Acoustic	Single or array of sound sensors	Detection may be limited due to background noise and low-pressure differential. Above ground piping use only.	Approved for EPA leak detection and quantification
Fixed Monitor	Point sensor	Various point sensor technology which may be either convection or pumped. Located either near or remote from possible sources	The plume must be transported from the source to the sensor via wind. Further away the sensor, the higher the sensitivity must be. Multiple sensors are typically used to cover a wide area.	Can be used for EPA defined "Other Large Release Events" only in Subpart W

Method	Instruments	Description	Limitations	Applicable Uses
Fixed Monitor	Mass flow	Various methods capable of measuring the gas flow directly.	Must be placed in line with the gas stream.	Approved for EPA quantification
Fixed Monitor	Acoustic	Single or Array of sound sensors placed near possible sources	Detection may be limited due to background noise and low-pressure differential. Above ground piping use only.	Approved for leak detection but not currently approved for EPA quantification
Fixed Monitor	Laser	Laser (fixed or scanning) of possible source locations. Can be placed at the fence line to detect site level emissions.	Distance limited (~30m). Requires reflective background (high stacks may require a reflector). Observation of source locations may be blocked by obstructions.	Can be used for EPA defined "Other Large Release Events" only in Subpart W
Fixed Monitor	OGI	OGI camera (fixed or scanning) of possible source location.	Operational or environmental conditions may prevent imaging. Identification of gas plume Detection of small leaks not likely. Observation of locations may be blocked by obstructions.	Can be used for EPA defined "Other Large Release Events" only in Subpart W
UAV	High sensitivity point sensors. Downward scanning Laser.	Area flight grid pattern can be used for detection of localized leaks. Specialized pattens can be used for measurement of site level emission rate estimation.	Point sensor must be of high sensitivity. Altitude is limited by sensors effective distance. UAV restrictions over the site	Can be used for EPA defined "Other Large Release Events" only in Subpart W

Method	Instruments	Description	Limitations	Applicable Uses
UAV	OGI	OGI camera mounted to the UAV	UAV restrictions over the site Low leaks are not likely detectable.	Can be used for EPA defined "Other Large Release Events" only in Subpart W
Aerial	High sensitivity point sensors.	Piloted plane or helicopter. Specialized pattern over site can be used for site level emission detection and emission rate estimation.	Point sensor must be of high sensitivity. The altitude of flight is restricted. Lower emission rates may not be measurable. Can be impacted by wind/weather conditions	Can be used for EPA defined "Other Large Release Events" only in Subpart W
Aerial	Downward scanning Laser.	Piloted plane or helicopter. Gridded pattern over site can be used for detection of localized leaks.	The altitude of flight is restricted. Altitude limited by sensors effective distance.	Can be used for EPA defined "Other Large Release Events" only in Subpart W
Aerial	Radiometric Spectroscopy	Downward pointing Passive infrared sensor mounted on plane or helicopter.	Detection and imaging of larger leaks only. Site level measurements only. Atmospheric conditions may limit or prevent detection. Solar intensity may limit or prevent detection.	Can be used for EPA defined "Other Large Release Events" only in Subpart W
Satellite	Radiometric Spectroscopy	Downward pointing Passive infrared sensor place in orbit.	Detection and imaging of very large leaks only. Site level measurements only. Atmospheric conditions may limit or prevent detection. Solar intensity may limit or prevent detection.	Can be used for EPA defined "Other Large Release Events" only in Subpart W

New leak surveys and monitoring methods are constantly emerging that can estimate emission rates. As leak survey programs have moved toward higher-sensitivity detectors conducting more frequent surveys, understanding the capabilities of leak detection and quantification technologies is important for implementation.

Common Emission Solutions

Available emission reduction strategies for compressor stations can be broken into three main categories: 1) mitigation via recovery of otherwise fugitive natural gas (i.e. vapor recovery unit), 2) mitigation via operational improvements (i.e., increasing the length of pressurized hold times on compressors during maintenance blowdowns), and 3) mitigation via upgrades/ repairs/ replacements (i.e., performance-based replacements of rod packing).

Mitigation via Recovery

Recovery describes the capture of methane that would otherwise be vented or leaked. This reduces direct methane emissions and often improves gas utilization efficiency. Examples of this include vapor recovery units (VRUs). VRUs capture and reuse the methane that would otherwise be vented to the atmosphere. This is particularly useful on compressor station tanks, seals, and blowdown systems.

Another example of recovery occurs through blowdown gas recovery, when compressors are retrofitted to recompress blowdown gas instead of venting it. Capturing from pneumatic devices requires retrofitting systems to route gas from pneumatic controllers or pumps to recovery systems. Examples are summarized in Table 4.

Table 4: Mitigation Solutions via recovery, summarizing cost, emissions impact, and regulatory benefits.

Solution	Cost	Emissions Impact	Regulatory Requirement
Rod packing vent capture	Medium	High (for reciprocating compressors)	Voluntary Avoids need to report to Subpart W
Blowdown gas recovery	Medium	High (large volume events)	Voluntary
Vapor Recovery Units	Medium- High	Medium	Voluntary Avoids methane venting and reporting to Subpart W from various equipment types
Pneumatic Device Recovery	Low – High	High (per device) Low – High (per site) *	OOOOb/c requires all new and existing pneumatic controllers at compressor stations in the oil and natural gas sector to achieve zero methane emissions where feasible.

More details about pneumatic device recovery and replacement are located in the following section: *Mitigation via upgrades, repairs, and replacements*.

Feasibility of Recapturing and Reinjection

Recapturing and reinjecting methane emissions at natural gas compressor stations is technically feasible and increasingly cost-effective, especially in the context of regulatory compliance and corporate environmental, social, and governance goals. However, feasibility depends on site-specific factors, including equipment type, operating conditions, infrastructure, and economics.

As mentioned previously, recapturing and reinjecting typical target emissions from blowdowns, compressor rod packing vents, pneumatic device bleeding, and storage tank venting is then captured using closed systems and compressed, if necessary, before being reinjected back into the station intake, pipelines, or used as on-site fuel.

A few practical barriers make recapturing and reinjection challenging. For example, some stations have space constraints that do not allow the additional infrastructure.[27] ONE Future and EPA Natural Gas STAR partners have deployed rod packing recovery and blowdown capture with much success. Midstream operators have achieved greater than 50% methane reduction at compressor stations using pneumatic device recovery and swapping high-bleed pneumatics for low-bleed pneumatics.[28] Projects typically reduce tens to hundreds of metric tons of methane/year, making them very cost-effective under potential Inflation Reduction Act methane fees.

Mitigation via Operational Improvements

Operational improvements optimize procedures and maintain practices to reduce emissions from existing equipment. These options are often low-cost, have a fast return on investment, and improve reliability and compliance. Table 5 summarizes a few common examples of operational improvements to mitigate methane emissions

Maintenance and operational best practices involve regular maintenance of seals, valves, and packing to reduce fugitive emissions. Additional staff training to implement low-emission practices during operations and maintenance is encouraged.

Compressors must be depressurized for maintenance, which can release large volumes of gas. Solutions to this include low-bleed or no-bleed pneumatic devices, gas capture systems to recover blowdown gas, and pigging operations that minimize depressurization frequency. Optimization and control systems can be used to minimize idling time, optimize fuel-air ratios for better combustion efficiency, and adjust operations dynamically to reduce emissions.

Table 5: Mitigation Solutions via Operational Improvements: summarizing cost, emissions impact, and regulatory benefits

Solution	Cost	Emissions Impact	Regulatory Requirements
Advanced Emissions Monitoring (beyond normal leak detection and repair)	Low - High (depending on option selected)	Low - High	Voluntary Could be used for exploration of “other large release events”
Automated compressor optimization software	Low - Medium	Medium - High	Voluntary Improves compliance and performance

Mitigation via upgrades, repairs, and replacements

Replacements, repairs, and upgrades are commonly the most expensive mitigation solutions because they involve replacing or retrofitting equipment with modern, lower-emission alternatives. Table 6 summarizes a few solutions. Many compressors are powered by reciprocating engines, either lean burn or rich burn. Emissions from these engines can be reduced with emissions control retrofit technologies such as three-way catalytic converters for rich burn engines, selective catalytic reduction for lean burn engines, or plasma-catalytic technologies.[29] Additionally, replacing gas-driven compressors with electric motor-driven compressors can eliminate combustion-related emissions reported under the GHGRP. However, companies that track Scope 2 emissions still account for combustion emissions associated with the electricity generation needed to power electric motor-driven compressors.

Methane leaks from seals, valves, and connectors can be significant. Leak detection and repair (LDAR) involves regular inspections and prompt repair of the identified leaks. Another upgrade option is to replace high-bleed process controllers with low- or no-bleed devices and convert gas-actuated process controllers to instrument air systems when feasible. Currently, all process controllers must be replaced to adhere to OOOOb/c. However, many in the industry desire a more functional definition of process controllers, for example, including clarification that isolation valve actuators are not process controllers because they do not maintain a process condition such as liquid level, pressure, delta-pressure, and temperature.

Additionally, the vague term process controllers under the OOOOb/c rule doesn't consider the price range of these replacements. High-pressure valve actuators with large diameters that rarely emit, for example, are much more expensive to replace than their low-pressure counterparts. Furthermore, the OOOOb/c requirements to replace all process controllers do not recognize that some of these valves cannot be replaced with electric power-driven devices because they are safety-critical devices. More can be found on process controllers and pneumatic devices in the Technology Road Map Specific Use Cases document

Driver electrification and the replacement of older engines with new, lower-emitting engines require higher investment but yield large reductions. However, these replacements are not viable for every site.

Table 6: Mitigation Solutions via upgrades, repairs, and replacements, summarizing cost, emissions impact, and regulatory benefits

Solution	Cost	Emissions Impact	Regulatory Requirements
Replace low-pressure process controllers (i.e., temperature and liquid level controllers)	Low - Medium	High (per device) Low - Medium (per site)	Required under OOOOb/c
Replace high-pressure process controllers (i.e., valve actuators)	High	High (per device) Low (per site)	Required under OOOOb/c
Electrify compressors	High	High (no combustion/fugitive gas)	Long-term compliance solution

Estimation of Potential Reduction in Emissions

Programs such as the EPA Natural Gas STAR Partnership (1993-2022) have provided operators with examples of emission reduction strategies, but do not emphasize the accuracy of reported emission reductions, which are estimated or voluntarily measured.[30] The EPA Natural Gas STAR program has since been replaced by the EPA Methane Challenge (2016-2024), a voluntary methane reduction initiative that provides guidance targets for emission reductions to be achieved by implementing specific emission reduction strategies.[31]

The EPA Methane Challenge is divided into two commitment options: the Best Management Practice Commitment and the ONE Future Emissions Intensity Commitment Option. The ONE Future methane intensity challenge does not require companies to compute and report voluntary emissions reductions. These methane intensities can be calculated based on throughput and pipeline miles.[32] Rather than prescribe specific emission reduction measures to participating operators, ONE Future sets specific methane emission reduction goals on the basis of marginal abatement costs.

ONE Future vs. EPA Gas Star Recommendations

The main difference between the recently phased-out EPA Natural Gas STAR recommendations for the transmission and storage segment and the newer ONE Future recommendation is that the EPA Natural Gas STAR recommended optimizing glycol dehydration systems and recovering methane released from Pig Receiving and Launching during maintenance events. In addition, ONE Future recommends the use of pipeline sleeves instead of opting for full pipe replacements and engine retrofits to improve efficiency. As a newer program, ONE Future also recommends a more accurate accounting of sources, such as methane slip.

Current methane emission reduction goals released by ONE Future rely on referenced reductions from EPA Natural Gas STAR assumptions, findings from ICF analyses,[33] updates from vendors and industry commenters, and field measurement studies completed by the University of Texas. Table 7 summarizes the ONE Future recommended emission reduction strategies for the transmission and storage segments of the natural gas industry.[34] Expected emission reductions with the ONE Future recommended actions for transmission and storage originate from a 2016 ICF study,[33] EPA Natural Gas STAR data, and various field studies.[35–45] While numerous reduction strategies can be implemented at a midstream compressor or storage site, assumed reductions must be critically reviewed to understand the expected emissions at a compressor station. EPA Natural Gas STAR data, for instance, relies on operator-reported data quantified with current GHGRP reporting requirements. Alternatively, referenced field studies differ in measurement techniques, data collection, and interpretation practices.

Some emission sources applicable to midstream compressor stations are difficult to quantify, as well as difficult to abate. The GHGRP allows flexibility for the difficulties of some sources by allowing engineering estimates to be used for reporting. For example, blowdown vent emissions have two main pathways, with estimates based on volume and pressure between isolation valves as one pathway and the other using a flowmeter. Given the various quantification pathways allowable under the EPA GHGRP, it is imperative to consider the accurate estimation of site-level emissions to understand the effectiveness of deploying various methane mitigation strategies at a midstream compressor station.

Table 7: ONE Future Recommended Methane Reduction Methods: Transmission & Storage

Technology/Methodology for Reducing Emissions**	Assumed Reduction	Source assumptions
Voluntary LDAR programs to identify and fix equipment leaks at aboveground sites. (Annual basis)	40%	I) -Gathered individual OGI surveys at various oil and natural gas sites -Colorado Air Quality Control Commission Report on OGI monitoring of well production tank batteries -EPA's "engineering judgment"
Performance-based monitoring and replacement for reciprocating compressor rod packing.	31%	II) ICF Analysis Estimate
Replacement of 4-stroke lean burn engines with more efficient turbines that have lower combustion exhaust methane emissions.	Not provided	Additional literature reviewed
Use of compressors driven by electric motors as an alternative to gas-fired engines.	Not provided	Additional literature reviewed
Conversion of reciprocating engines and turbine gas starters to electric or air-operated starters.	100%	EPA Natural Gas STAR data
Reduction of maintenance blowdown emissions by operating practice changes (such as increasing the length of pressurized hold times on compressors to reduce the number of compressor unit blowdowns to atmosphere).	80%	EPA Natural Gas STAR data
Use of Vent Gas Recovery systems for compressor-related venting and reroute for beneficial use. These systems capture gas that would be vented to the atmosphere from sources such as case venting (rod-packing), dry gas seals, and compressor unit blowdowns.	95%	EPA Natural Gas STAR data, independent ICF analysis

Technology/Methodology for Reducing Emissions**	Assumed Reduction	Source assumptions
Reduction of blowdown emissions by implementing pipeline pump-down techniques that lowers the pipeline pressure prior to transmission pipeline blowdowns and conducting regulatory required Emergency Shutdown tests (ESDs) utilizing "vents blocked" tests.	95%	EPA Natural Gas STAR data
Use of sleeves and composite wraps to repair pipelines, eliminating the need to blowdown the pipeline. Use of pipeline isolation systems and hot taps to make new connections, eliminating the need to blowdown the pipeline.	Not provided	Additional literature reviewed
Where possible, replacing or repairing high emitting pneumatic devices with low or no-bleed devices.	78%	III) Two UT Austin field studies

Note, the assumed reductions associated with ONE Future recommended methane mitigation strategies, outlined in Table 7, rely on various sources, including operator-reported data, as well as academic field research studies. These referenced reductions can be difficult to interpret in terms of true expected emissions reductions at midstream compressor stations and storage sites. Literature on the implementation of mitigation technologies can be further reviewed to understand the potential uncertainties regarding the expected emission reductions. Given these uncertainties with assumed reductions of methane mitigation strategies, greater measurement accuracy and increased data coverage of emissions are necessary to understand and mitigate methane emissions at compressor stations.

AREA 3 - TECHNOLOGY ROADMAP

The extensive information gathered for Areas 1 and 2 of this project can be daunting to navigate. Therefore, much discussion was had by the GTI Energy and Williams teams on how to best display the volumes of information in a way that is easier to interpret and utilize. The distillation of information had to serve multiple purposes. The resource created needed to be "easy to understand" for a new user and/or someone with limited knowledge of compressor stations, while also being useful to an advanced user with detailed knowledge of compressor stations and methane emissions. To satisfy these requirements, the team developed a final output that includes three main parts, a Technology Roadmap Diagram ("the Diagram") to summarize high-level information, a User Interface Spreadsheet Model ("the Model") to contain and display the extensive information, and the Use Cases that can be applied to specific scenarios to demonstrate how to utilize and the capabilities of the diagram and the model.

Technology Roadmap Diagram

The Diagram is a high-level visualization of the technology roadmap, which is shown in Figure 2. The visual roadmap condenses the dense information in the spreadsheet model into a static, easier-to-understand, organized format. The Diagram was designed to allow the user to identify emission mitigation strategies that have impactful results at varying "implementation difficulty" levels shown on the x-axis, divided into three categories: standard operating procedure, equipment retrofits, and deployment of new assets. These categories, like the three categories of emission solutions, were decided to facilitate all types of desired outcomes at a variety of different compressors with varied age, size, and throughput. This visual aid aims to be approachable for readers of all knowledge levels to gain an understanding of the requirements of the potential mitigation strategies.

The y-axis represents the two categories ("large" or "small") of unmitigated emissions quantification from the broad category types of equipment. The strategies are sorted based on the implementation difficulty (x-axis) and emission size (y-axis), which shows the estimated size of the unmitigated emissions. The strategies are represented by shapes. The shape is based on the relative emission reduction potential of that strategy, with a circle being a low reduction potential, a square being moderate reduction, and a hexagon being a large reduction potential. The information for the strategy relies on relevant literature and operator feedback.

Each shape has a colored border that outlines the shape. The color(s) indicate the type of emission event associated with the equipment that the strategy is targeting. The three types of emission events are equipment failure/leak (light blue), procedural emission (orange), and operational emission (purple). For the Diagram, procedural emissions are defined as emissions resulting from operator practices inherent to the safe and efficient operation of the facility, as seen when a blowdown occurs to make a repair on equipment, while operational emissions result from equipment design, as seen with equipment that "burps" or vents to properly operate.

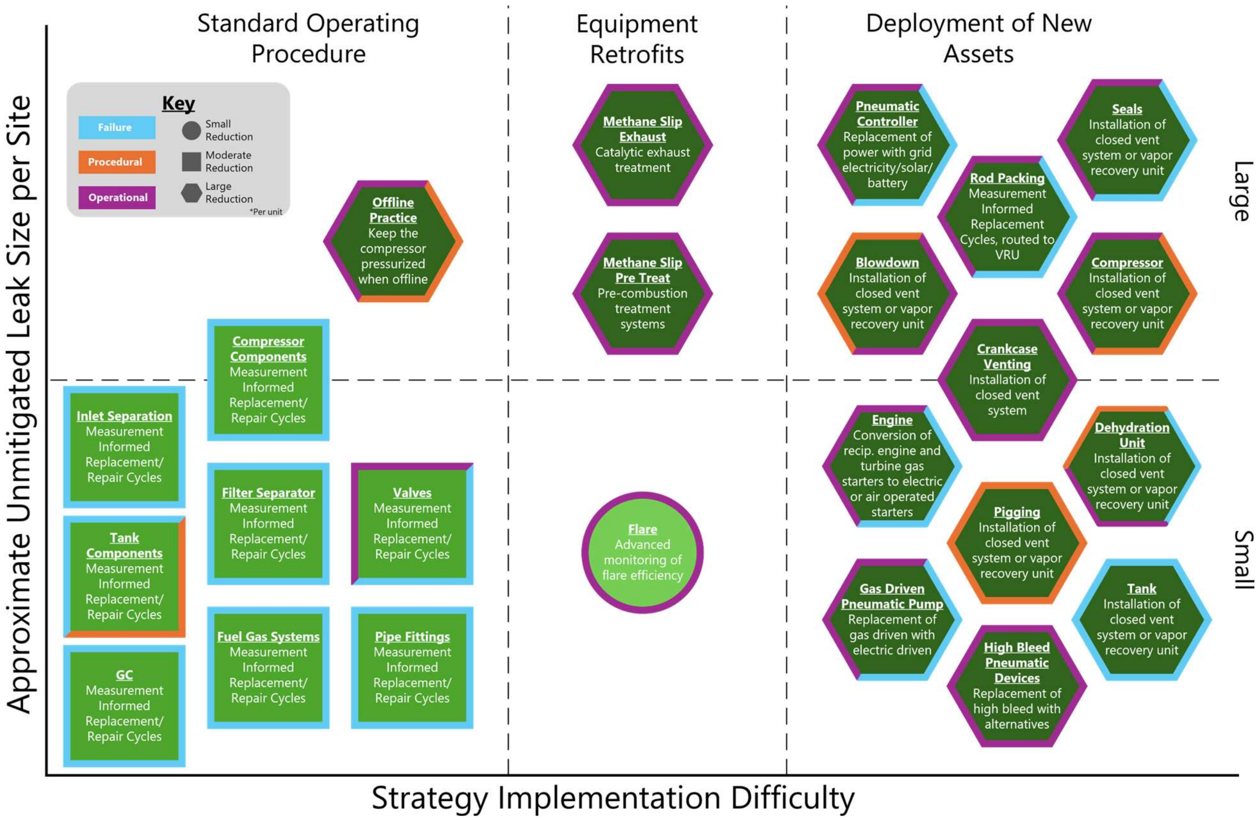


*Figure 2: Technology Roadmap Diagram**

**See separate document for a full-size version.*

The goal of the Diagram is to aid users in identifying strategies to prioritize equipment and their associated strategies to achieve the mitigation goal set by the user. The suggested strategies that would be considered the easiest to implement with the largest payoff, or the "low-hanging fruit", are found in the top left corner of the Diagram. These strategies indicate a relatively easy solution to reduce the emissions from high-emitting equipment.

The Technology Roadmap Diagram will be posted to the PHMSA project page - https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=1013, or can be obtained by emailing methane@gti.energy.

User Interface Spreadsheet Model

The Model was created to distill information gathered in Area 1 and can be used to evaluate and estimate potential emission reductions via various pathways. The spreadsheet-based model serves as a centralized tool to identify the range of mitigation opportunities across a midstream compressor station. Importantly, the Model outlines key information around the current state of understanding emissions for each equipment/component type included, giving context to the level of uncertainty in achievable methane mitigation quantities and whether a reduction would be expressed in subsequent Subpart W annual reporting cycles.

The interactive portion and the first few columns of the User Interface portion of the model are pictured in Figure 3. The Model acts as a foundation for future developed applications that can be used by industry to identify how market-available mitigation opportunities can impact emissions reduction reporting and enhance the safe operation of compressor stations in transmission.

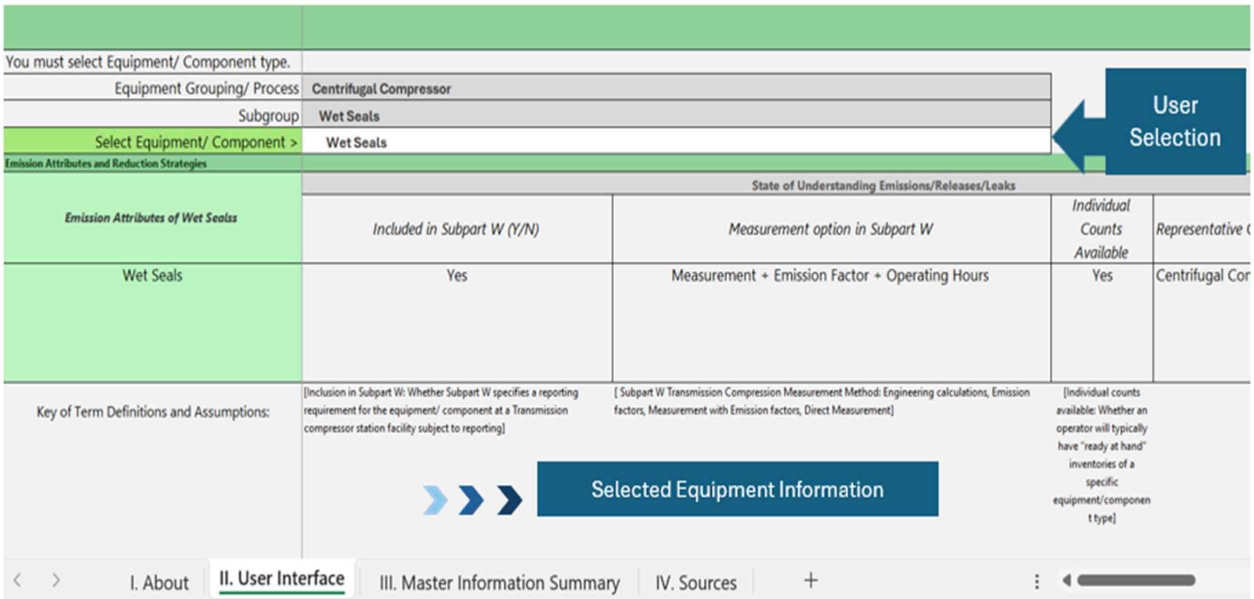


Figure 3: Initial Columns of User Interface for the User Interface Spreadsheet Model

The spreadsheet includes mitigation strategies that are readily available to operators and range from work practice changes, additional measurement-informed replacements, and major equipment upgrades. The GTI Energy and Williams teams collaborated to define each mitigation strategy in terms of implementation difficulty to inform the practicality of all considered reduction strategies and potential challenges that may occur with any one mitigation strategy. This categorization of implementation difficulty also accounts for simple mitigation opportunities, which may be more difficult to implement for component types that are common across the facility (e.g., replacing valves with low-emission versions may not be the most practical). Each equipment/component type is characterized in terms of the following:

- *Individual Counts Available (Yes/ No)* – indicates whether individual counts of each type of equipment are readily available
- *Inclusion in GHGRP Subpart W* – details whether the component appears, and is regulated, per Subpart W as of the 2025 reporting cycle.
- *Subpart W Quantification Method Category* – shows the type of quantification method available in Subpart W.
- *Representative Category in EPA GHGI* – indicates whether the component appears in the EPA Greenhouse Gas Inventory (GHGI).
- *Emission Causes (Fugitive, Operational, Procedural)* – types of leaks or emissions that can occur from the component.

  - *Fugitive*: fugitive releases associated with decreased material integrity of equipment/components due to manufacturer defects, corrosion, over-pressurization events.
  - *Operational*: occurring because of equipment/component design
  - *Procedural*: directly resulting from operational practices, such as to ensure the safety or efficiency of equipment/components
- *Relative Emission Size per Unit (Small – Large)* – the sizes of emissions that can occur from each individual component/unit.
- *Relative Emission Size per Site (Small – Large)* – the relative size of total emissions from all components/units at a site.
- *Mitigation Strategies and associated % Reduction* – a list of potential emission/leak mitigation strategies and how much emissions reduction is expected if the emission is addressed.
- *Implementation Cost/Abatement over Lifetime* – Indication of the cost to implement a mitigation strategy.
- *Difficulty to Implement Mitigation Strategy (1-5)*—Estimate of how difficult the mitigation strategy would be to implement. 1 indicates that it is relatively easy to implement, and 5 indicates maximum difficulty.

The User Guide document for the User Interface Spreadsheet Model provides additional discussion of the categorization assumptions and references in the spreadsheet. The User Interface Spreadsheet Model is posted to the PHMSA project page (https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=1013) or can be obtained by emailing methane@gti.energy.

Use Cases for the Spreadsheet Model

Examples of how to use the model were showcased through the development of Use Cases. After instructions on how to utilize the resources, the use cases also offer some discussion on the resulting output. These Use Cases were developed for 1) pneumatic devices/process controllers, 2) methane slip, and 3) rod packing and can be found in the separate Use Cases document found on the PHMSA project https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=1013.

CONCLUSIONS

Natural gas transmission compressor stations are complex systems containing many different types of components and equipment, each with some potential to emit methane. Through this work, the team has systematically explored each of these types of components and equipment to deliver a detailed breakdown of compressor stations that includes extensive information on how to track, measure, and mitigate these emissions, where possible. This reveals the vast number of options available to quantify and mitigate.

Routes to mitigate methane emissions at a compressor station can be separated into three main categories: direct recovery, operational improvements, and upgrades and replacements. Each of these mitigation options must be thoroughly explored by a company to balance the potential for methane emissions mitigation with the intricacies of operational implementation, including costs. The Technology Roadmap Diagram and User Interface Spreadsheet Model developed in this project are aimed at helping operators and companies wade through the options to make the most informed decisions. The preparation of the diagram and the model has revealed that the thought of a single easy-to-implement solution for methane mitigation from compressor stations is a nuanced discussion, involving difficult decisions between cost, reduction efficiency, and ease of implementation.

GLOSSARY

The following list of acronyms, abbreviations, and terms are applicable for this report:

Acronym or Term	Definition
CO2e	CO_2 equivalent
EPA	US Environmental Protection Agency
ESD	Emergency Shut Down
GHG	Greenhouse Gas
GHGI	EPA Inventory of Greenhouse Gas Emissions and Sinks
GHGRP	EPA Greenhouse Gas Reporting Program
GTI	GTI Energy
IR	Infrared
OGI	Optical Gas Imaging
OGMP	Oil and Gas Methane Partnership
OOOOb/c	EPA Subparts OOOOb and OOOOc
LDAQ	Leak Detection and Quantification
LDAR	Leak Detection and Repair
NCM	Non-Combusted Methane (combustion/methane slip)
PHMSA	Pipeline and Hazardous Materials Safety Administration
TAP	Technical Advisory Panel
UAV	Unmanned Aerial Vehicle
VRU	Vapor Recovery Unit

LIST OF TABLES AND FIGURES

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