Climate Protection Project Opportunities Study for PTT Thailand – Lan Krabue S1, Phitsanulok, Thailand

Natural Gas STAR International
PTT Thailand Measurement Study

March 2014

EXECUTIVE SUMMARY

The United States Environmental Protection Agency (EPA) supports the Global Methane Initiative's (GMI) engagement with the oil and natural gas sector through the Natural Gas STAR International program. Natural Gas STAR International (NGSI) is a voluntary partnership between EPA and the international oil and natural gas industry to identify and promote cost-effective technologies and practices to reduce methane emissions. In March 2013, PTT Thailand joined Natural Gas STAR International, EPA's first Partner company in Thailand. In doing so, PTT Thailand agreed to work with the EPA to identify and implement projects to cost effectively reduce methane emissions. Methane is a potent greenhouse gas and it's global warming potential is estimated to be 21 times that of carbon dioxide over a 100-year period. Consequently, reducing methane emissions has imperative energy, economic, and environmental benefits. In September of 2013, EPA and PTT Thailand cooperated to conduct an on-site methane emissions measurement study and analysis to identify and quantify baseline methane emissions levels at two PTT Thailand facilities, Lan Krabue S1 and Nongtum-A Substation Satellite, henceforth referred to as S1. The study was conducted using GasFindIR™ infrared camera technology to identify emission sources and a combination of a Hi-Flow™ sampler and volumetric bagging techniques to measure the natural gas emission rates.

This report provides an analysis of the facilities' measurements and recommends potential mitigation projects at PTT Thailand's S1 facilities. Recommendations assess technical feasibility, anticipated methane emission reductions, and economic value of proposed emission reduction projects. The report is the culmination of the two steps undertaken by EPA in support of this work at PTT Thailand:

1. **Measurement Study:** A targeted on-site campaign to identify and measure the leading methane emission sources (e.g., leaks and vents) at the Lan Krabue S1 Central and Nongtum-A Substation Satellite facilities. The measurement study at these S1 facilities was not a comprehensive study and focused on key emission sources, mainly compressors. Due to this, the results from the measurement study give a limited perspective on the emissions from the S1 facilities and are only representative of the areas surveyed;
2. **PTT Thailand Emissions Reduction Opportunity Analysis:** The identification and prioritization of emission reduction opportunities at the Lan Krabue S1 facility, taking into account associated costs and benefits based on the results from Step 1.

The limited scope measurement study measured emissions from PTT Thailand's S1 operations. At Lan Krabue S1, the team measured a limited number of emission sources including some compressors and tanks, and these emissions amounted to **28.3 million cubic feet per year of methane**. This is equivalent to **11.4 thousand metric tons of CO_2 per year,** for the calendar year 2013. These emissions do not represent a comprehensive facility emissions inventory because the EPA team identified and measured only the key emission sources such as compressors. This estimate also does not include emissions resulting from crude oil loading into trucks. EPA generated these estimates using quantitative and, in some cases, qualitative techniques. The emissions fall into four types of sources listed in order of standard methane emissions below:

1. Emissions from leaking components: 6.9 million ft^3/year of methane
2. Emissions from reciprocating compressors rod packing: 6.2 million ft^3/year of methane
3. Emissions from storage tanks: 3.6 million ft^3/year of methane
4. Emissions from flare gas: 11.0 million ft^3/year of uncombusted methane

This analysis shows that there are untapped opportunities that could benefit the company's bottom line and improve operational efficiency, environmental performance, and safety at PTT Thailand's S1 facilities. Economic analyses of all recommended activities revealed that implementation of certain methane emissions reduction projects could yield:

- Excellent paybacks on investment ranging from as low as 2 months; and

Comment [PA1]: The amount of methane emission from 4 sources are less than the above conclusion.

- Significant savings of methane emissions up to 23.5 million cubic feet per year[1]; the volume of actual methane saved will depend on the projects chosen to be cost-effective at a given gas price.

These potential natural gas reductions from the very limited measurement study have an annual economic value of up to 108.3 million Baht[2] (which is equivalent to $US 3.4 million per year) based on a gas price of 10.5 THB/kg. Of the $US 3.4 million, $US 3.2 million can be saved by implementing an emissions reductions project on the gas sent to flare. The EPA team would estimate a significantly higher annual economic value, if emission sources not analyzed as a part of this study from the S1 facilities, mainly Lan Krabue, are included. In terms of achieving PTT Thailand's climate protection goals, these projects, when fully implemented, will reduce annual methane emissions equivalent to 9.5 thousand metric tons of CO_2 per year. This level of emission reductions is equal to removing approximately 2,378 passenger vehicles from the roadways for a year[3].

The Natural Gas STAR International Program recommends that PTT Thailand consider these options and implement recommended technologies and practices where possible, thereby maximizing the benefits of Program participation. The Program can provide further support or analyses, if necessary, to facilitate the rapid implementation of these activities.

EPA would like to thank PTT Thailand, especially Mr. Pipit Hongjinda and Nathasith Chiarawatchai, for the company's close cooperation and participation in the Global Methane Initiative and for accepting EPA's offer to conduct a study of the S1 facilities. In addition, EPA would like to thank Mr. Naruechai Koonthong for coordinating this collaborative study. Last, but not the least, EPA would like to thank Mr. Panus Angkuladisai and other on-site personnel for supporting the EPA team at the various S1 facilities.

1 Equivalent to 535,300 thousand ft3/year of natural gas; note that the whole natural gas volume includes all of the gas being sent to the flare, whereas, the methane savings number includes only the un-combusted methane from flaring of gas.
2 Reduction value calculated using whole gas reductions of 535 million ft3/year.
3 Values accounting for only methane and not whole gas using http://www.epa.gov/cleanenergy/energy-resources/calculator.html

INTRODUCTION

Directly supporting the Global Methane Initiative (GMI)[4], the United States Environmental Protection Agency's (EPA) Natural Gas STAR International Program[5] is a voluntary partnership between the EPA and the international oil and natural gas industry to identify and promote cost-effective technologies and practices to reduce methane emissions to the atmosphere. Now in its 21st year domestically and 8th year internationally, EPA's Natural Gas STAR Program has provided significant economic and environmental benefits in terms of reducing methane emissions and increasing revenue to companies through increased gas sales and improved operational efficiency. Since 1993, Natural Gas STAR domestic and international partners have reduced methane emissions by more than 1.15 Tcf (98 85.2 Bcf from international partners), saving an estimated $3.5 billion worth of natural gas[6] through the implementation of over 80 cost-effective technologies and practices. This demonstration of industry ingenuity and commitment illustrates that active participation in the Natural Gas STAR International Program not only offers quantifiable environmental benefits but also allows Partners to improve operational efficiency, maximize revenues, improve safety, and enhance each company's competitive edge in the marketplace.

PTT Thailand joined the Natural Gas STAR International Program in March 2013. PTT Thailand and EPA launched their partnership by conducting a measurement study at PTT Thailand's Ladlumkaew NGV System and Lan Krabue S1 facilities in September 2013. The EPA team conducted a limited scope measurement study at S1's facilities by focusing on key emission sources. This report provides measured volumes of emissions from these key methane emission sources and potential emission reduction opportunities for PTT Thailand's Lan Krabue S1 and Nongtum-A Substation Satellite operations based on the limited scope measurement study. For example, Natural Gas STAR International identified implementing a DI&M program utilizing PTT Thailand's IR camera as a potential emission reduction opportunity. By implementing this project, S1 facilities can reduce emissions by 5.9 million ft^3/year of methane for an initial investment of $US 67,750, yielding a net present value (NPV) of $US 75,120 and payback of 21 months at a gas price of 10.5THB/kg. These figures are based only on the gas volume measured from the leaking components. The net present value and payback of this potential mitigation project at a facility level will likely increase because this analysis, based on fugitive emissions at select compressors, does not include leaks from sections of the facility that were not surveyed as a part of this limited scope study. The findings from this study may provide PTT Thailand with cost-effective opportunities to improve operational efficiency and reduce significant methane emissions sources. **Based on the results of the measurement study, the team evaluated S1 facilities' methane emissions from four types of sources; all of which can be targeted with proven mitigation projects.**

EPA completed the study and analysis for PTT Thailand using the following two steps:

1. Measurement Study: EPA organized a measurement team equipped with methane emissions screening and measuring equipment, such as Hi-Flow™ Sampler, GasFindIR™ infrared camera, and calibrated bags and conducted an on-site study to detect and measure emissions sources; and
2. Emissions Reduction Opportunity Analysis: EPA identified applicable emission reduction opportunities and the associated costs and benefits of each project based on the methane emissions measured.

This report details the process and findings of the measurement study, as well as the recommendations for PTT Thailand to implement methane emission mitigation options. With this report, EPA has also included labeled videos of methane emission sources from the measurement study, so that PTT Thailand can easily reference the highlighted emission sources listed in the Appendices.

[4] *Global Methane Initiative*. http://www.globalmethane.org.
[5] *Natural Gas STAR International*. http://www.epa.gov/gasstar/international/index.html.
[6] Natural gas priced at U.S. $3 per thousand ft^3

MEASUREMENT STUDIES

Measurement Study Approach

EPA and PTT Thailand scheduled an on-site measurement study to provide an accurate and complete identification and quantification of actual methane emissions and performed the following two steps:

1. **Screen processes and equipment for methane emissions**: The EPA team screened and tagged the S1 facilities for leaks using the FLIR™ infrared (IR) camera, which presents a visual image of hydrocarbon emissions. The EPA team's expert camera operator identified any significant hydrocarbon emission sources and recorded results on video so that PTT Thailand can reference location and details of emission sources. See Appendix D for more detailed information on the IR camera, and the leak images included with this report.
2. **Measure tagged methane emissions sources**: The EPA team conducted measurement of emissions using the Bacharach Hi-Flow™ Sampler, and calibrated volumetric bagging techniques. Each of these technologies is briefly described below (for more detailed information see Appendix D):

   Hi-Flow™ Sampler: The Hi-Flow™ Sampler is a variable-flow rate sampling system that provides total capture of the emissions from a leaking component. The Hi-Flow™ can measure leaks as large as 0.3 m^3/ minute.

   Calibrated Bagging: Calibrated bagging uses bags of known volume (e.g., three cubic feet), made from antistatic plastic with a neck shaped for easy sealing around the vent. Measurements are made by sealing the bag around the emissions stream (usually a vent) and measuring the time it takes for the bag to expand to full capacity.

In some cases, it was not possible to conduct an actual measurement of the emissions flow rate due to vents being physically inaccessible, unsafe conditions, or an inability to direct all emission flow to a single source. In cases where actual measurements were partial or missing completely, the EPA team's experts estimated emission rates based on a library of videos of known leak rates (taking into account such factors as weather conditions and vent diameter) and extensive experience in conducting such measurements. Note that EPA is not implying that the camera can be used for measurement. Rather, due to the expertise, experience and resources of the team, the EPA team believes that directionally correct emissions estimates can be confidently presented. In all cases, the EPA team used a very conservative approach in making these estimations so as not to overstate emission reduction potential.

Measurement Findings

Figure 1 summarizes results of the limited scope measurement study by showing the measured methane emissions sources at S1. These results are not comprehensive, but do represent a significant amount of emissions with limited coverage of the facility. The results do not estimate the emissions from crude oil loading into trucks, although, the EPA team did observe large volume of emissions (both methane and Volatile Organic Compounds) at the truck loading terminal.

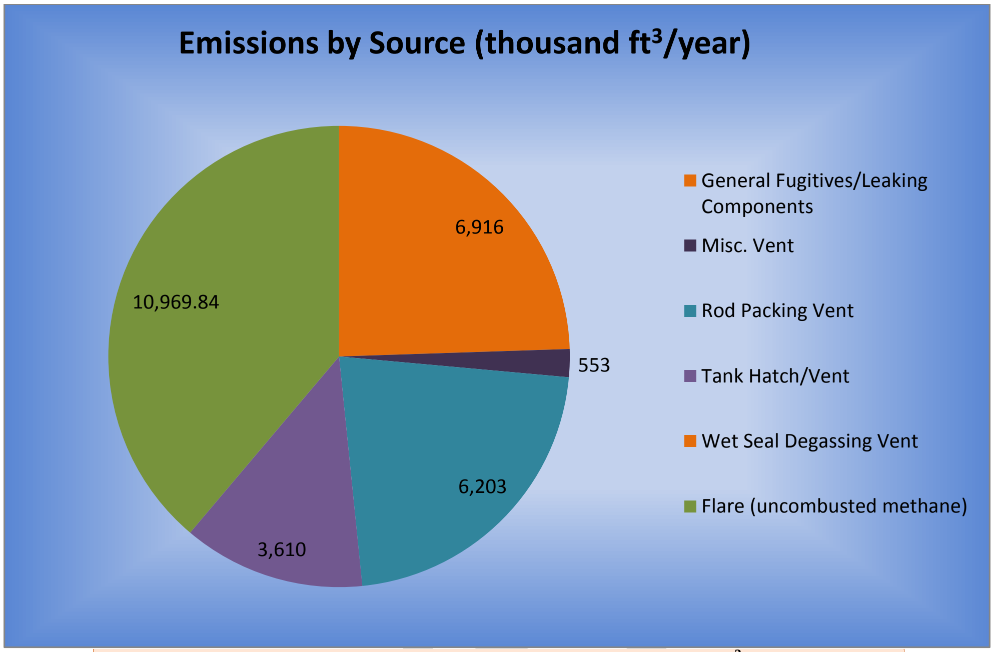


Figure 1: Summary of Methane Emission Sources (28,250 thousand ft^3/year of methane)

Comment [PA2]: These data should be separated between S1 LKU F/STN and NTM-A.

Where possible, the EPA team measured or acquired the total flow rate of the emissions stream, and later applied a methane content percentage (provided by PTT Thailand) to this flow rate to obtain a total methane emissions value. For the majority of measurements, the EPA team utilized the Hi-Flow Sampler. As such, these overall flow volumes measured by these devices have an accuracy bound of ±10 percent. However, in some cases it was not possible to physically measure all fugitive/vented emissions sources, either because 1) they were physically out of reach, or 2) all flow could not be directed to the measurement device.

For situations where the EPA team could not undertake physical measurements, the EPA team roughly estimated emission volumes based on evaluating hydrocarbon plume images from the IR camera videos. For situations where there was incomplete capture of the flow from the emissions source (i.e., measurements represent only a fraction of the total emissions), the EPA team revised the actual measurements (using Hi-Flow or calibrated bagging techniques) based on evaluations of the leak plume images of non-captured hydrocarbon emission sources. Note that in all cases, the EPA team made extremely conservative estimates and erred on the side of underestimating rather than overestimating emissions potential. Additional details regarding methane content and leak size estimation can be found in Appendix A. The following provides a brief description of the measurement approaches implemented for the methane emissions sources.

Comment [PA3]: What is the measurement approach for flare emission?

- Emissions from leaking components are a combination of *actual* and *estimated* measured quantities of emissions. In cases where the *actual* measurement was possible, the EPA team employed Hi-Flow sampler and calibrated bagging techniques to assess the volume of emissions. In cases where the sources were inaccessible for measurement, the EPA team *estimated* emissions volumes using IR camera video images.
- Emissions from vents are actual measurements performed by Hi-Flow sampler and calibrated bag techniques. The EPA team used FLIR IR video estimations for emission sources that could not be measured.

Measurement Analysis

This study paired four of the largest emissions sources with potential emission reduction projects. These projects include a Directed Inspection and Maintenance (DI&M) program, rod packing replacement on the reciprocating compressors, and vapor recovery unit installation to recover flare gas at the Lan Krabue facility, and vapor recovery unit installation on storage tanks at the Nongtum-A Satellite. Table 1 lists the most promising project recommendations under a 10.5 THB per kilogram ($ 5.8/MMBtu) gas price scenario. This is the price at which PTT sells its natural gas to its customers; hence EPA used this price in the base case scenario.

Replacing reciprocating rod packing is dependent on the compressor emissions, the annual hours of operations of the compressor, and the price of gas used for the economic analysis and varies across compressors. Compressors K-3700, K-3900, and K-3950 at Lan Krabue have the largest rod packing emissions and, therefore, the highest potential for economic returns at a gas price of 10.5 THB per kilogram. The DI&M program can yield large reductions, but has a longer payback on investment of close to two years. The DI&M economics are based on the assumption that the leak detection and measurement equipment will be used across two facilities at S1. However, if the equipment is used at more facilities, thereby, amortizing the costs across multiple facilities, the cost effectiveness of the DI&M program will increase. The Lan Krabue facility has a large volume of gas being sent to the flare annually that can be cost-effectively recovered using a vapor recovery unit. In fact, a flare recovery project would yield the quickest payback on investment and the largest GHG footprint reduction at the Lan Krabue facility. Finally, the Nongtum-A Satellite emits all of the tank vapors to the atmosphere that can be captured using a vapor recovery unit with an attractive payback on investment of less than a year.

Table 1: Recommended Methane Emissions Reductions Projects for S1

Categorization	Reduction Method	Comments on Recommended Method	Standard Methane Reductions (thousand ft^3/year)	Standard Whole Gas Reductions (thousand ft^3/year)	Net First Year Cost (U.S. $)	NPV[a] (U.S. $)	IRR[a] (%)	Payback Period[a] (Months)
General Fugitives/Leaking Components	Directed Inspection and Maintenance (DI&M)	IR camera, Hi-Flow Sampler, and calibrated bag capital costs can be shared among the two of PTT Thailand's assets	5,824	6,832	-$67,750	$75,120	51%	21
Reciprocating Compressors	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3900. Economics are for Unit L.	837	1,185	-$9,720	$3,637	29%	15
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3950.	2,293	3,247	-$9,720	$38,922	175%	6
Storage Tanks	Install Vapor Recovery Unit	Install Vapor Recovery Units at Ladlumkaew	3,429	15,697	-$93,007	$530,943	185%	8
Flare Gas Recovery	Install Vapor Recovery Unit	Install Vapor Recovery Units at Lan Krabue S1	430,382	504,822	-$415,835	$9,283,951	721%	2

a Net present value, internal rate of return and payback period are calculated using the whole gas reductions and not methane reductions utilize a gas value of 10.5 THB/kilogram for natural gas.
b Capital costs for DI&M include: IR Camera cost of $115,000 (typical range of $85,000-$115,000), High Flow Sampler cost of $20,000, and 10 calibrated bags for $50 each (based on Natural Gas STAR discussions with vendors). The cost of IR camera is conservatively high. These costs are shared by two PTT Thailand sites –Ladlumkaew and Lan Krabue S1.
c Represents the capital and installation cost of replacing the rod packing on the compressors which is estimated at $1,620 per cylinder.

These projects represent solutions to reducing methane emissions sources measured at the S1 facility. The economic evaluation is based on a gas price of 10.5 THB per kilogram. This report also provides a sensitivity analysis for other gas prices at 15 THB per kilogram, 280 THB per MMbtu, U.S $1.75 per MMbtu, and $16/ MMBtu with a project discount rate of 12 percent. Table 2 provides a listing of the various gas prices, their

Comment [PA4]: Gas price should be 1.4 USD/MMBtu (based on sell gas price from S1 to EGAT)

Comment [PA5]: This table is only the recommendation for S1 LKU F/STN or included NTM-A.

What is the data source of standard methane and standard whole gas reduction?

The amount of reduction are not aligned with the emission in the executive summary and figure 1.

equivalent in U.S. dollars per MMBtu, and the rationale behind using these gas prices in the sensitivity analysis. Table 2 also lists the gas price plus a carbon price of $50/tonne CO_2e to evaluate the impact on the cost-effectiveness of methane mitigation projects in a carbon controlled regime. Figure 2 represents the impact of these different gas prices on the cost effectiveness of the various projects. A more detailed analysis of each cost can be found in Appendix A. Figure 3 presents scenarios at the various gas prices plus a $50/tonne CO_2e price on carbon[7]. An internal price on carbon within PTT will make most of the projects discussed in this report very cost-effective.

Table 2: Gas Prices used in Sensitivity Analysis of Methane Mitigation Projects

Gas Price as used in Thailand	Gas Price in U.S. $ / MMBtu	Gas Price including a price for carbon[a] (U.S. $ / MMBtu)	Rationale for Gas Price
10.5 THB / kg	5.80	21.5	The retail price of natural gas that PTT sell to customer
15 THB / kg	8.29	23.9	The real price of natural gas (the cost of PTT for producing natural gas)
280 THB / MMBtu	8.86	24.5	The price of Natural gas that PTT sells to EGAT
U.S. $ 1.75 / MMBtu	1.75	17.4	Subsidized gas price based on discussions with site operators
U.S. $ 16 / MMBtu	16	31.7	LNG Import Price

a Carbon price based on a value of $50/tonne CO2e

Comment [PA6]: How are the source of gas price? May be based on PTT.

7 Carbon price based on an average of $60/tonne CO2e used by Exxon Mobil (http://www.environmentalleader.com/2013/12/05/big-oil-major-firms-plan-for-carbon-price/) and $40/tonne CO2e used by BP (http://www.c2es.org/business/belc/members/bp).

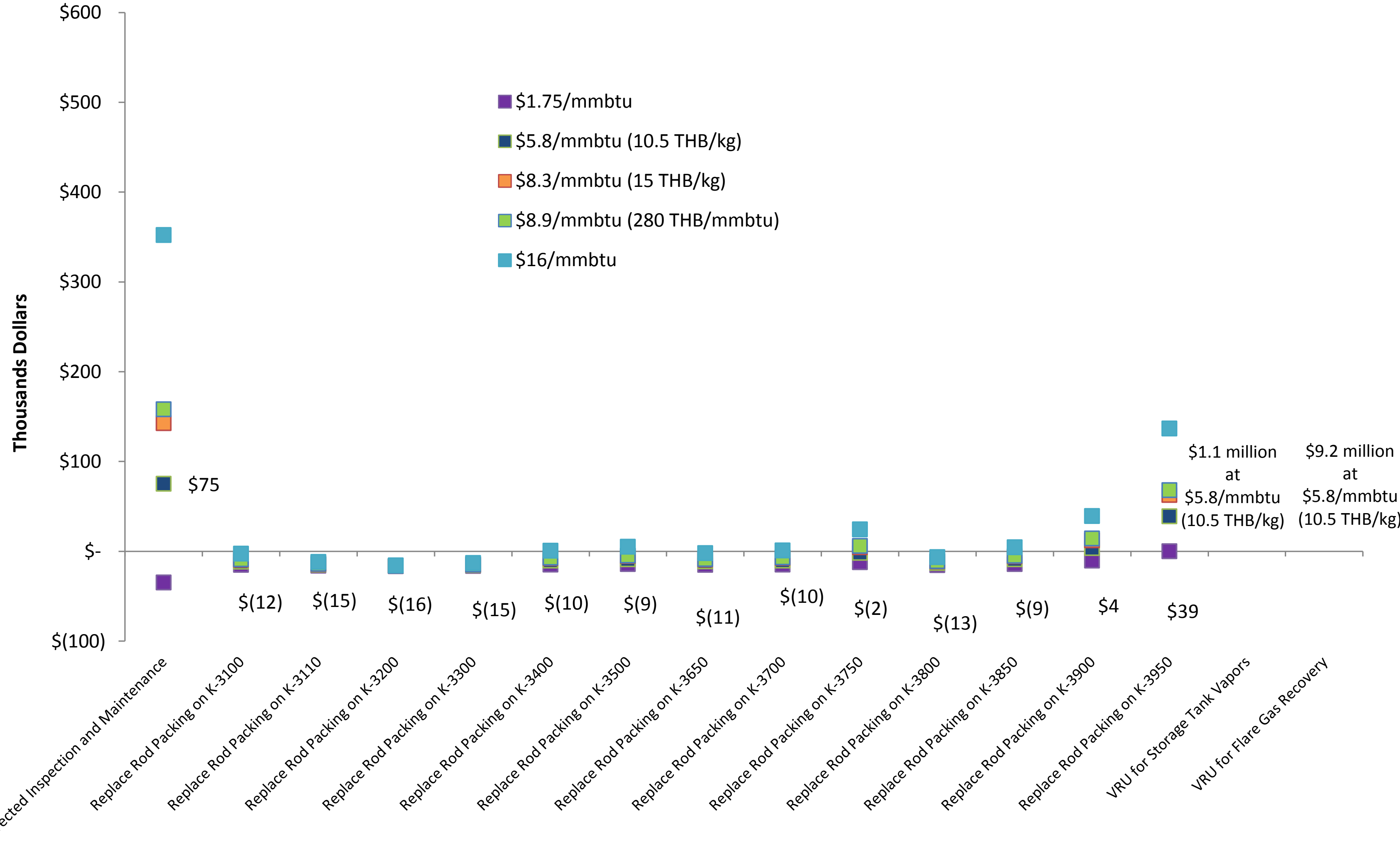


Figure 2: Net Present Value of projects based on different gas prices

Note: Vapor recovery unit gas was based on values for methane ($3/mmbtu), propane ($281.8/ton), and butane ($265.5/ton). So, it did not change based on gas value change.
Note: Values shown are NPVs of 10.5THB/kg.
Note: Some values are beyond the scale of this chart. Please refer to Appendix A-3 through A-12 for further information.

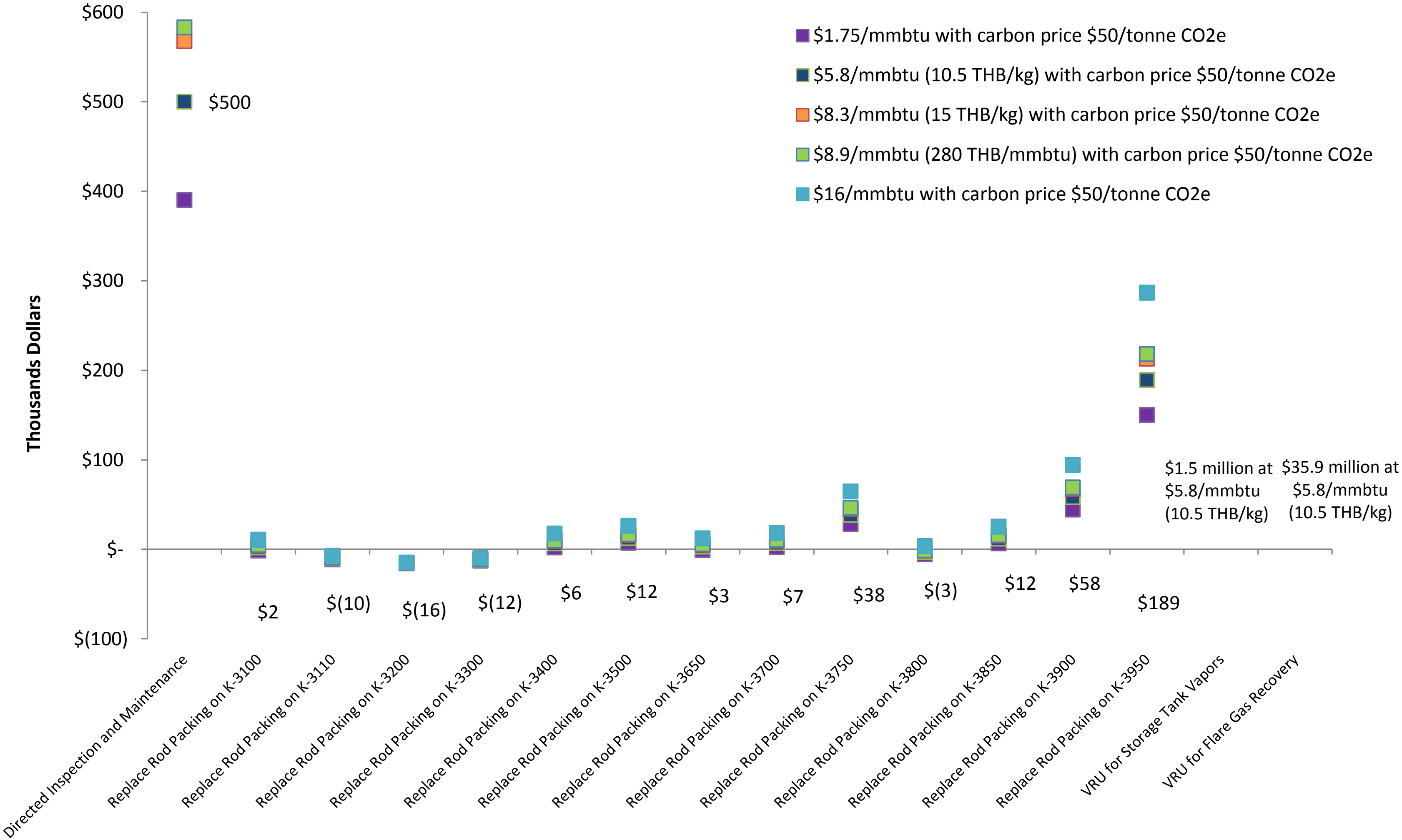


Figure 3: Net Present Value of projects based on different gas prices with carbon price

Note: Vapor recovery unit gas was based on values for methane ($3/mmbtu), propane ($281.8/ton), and butane ($265.5/ton). So, it did not change based on gas value change.
Note: Values shown are NPVs of 10.5THB/kg.
Note: Some values are beyond the scale of this chart. Please refer to Appendix A-3 through A-12 for further information.

Figure 4 shows the payback on investment periods for the various projects at varying gas prices and carbon prices. The gas price of $1.75/ MMBtu allows for only three cost-effective opportunities – replacement of rod packing on Unit K-3950, and installation of vapor recovery units on flare gas at Lan Krabue and on storage tanks at Nongtum-A. The negative payback on investment for the DI&M program at a gas price of $1.75/ MMBtu indicates that the mitigation project is not economical as the cost of implementing the program is higher than the value of gas that can be recovered. However, if PTT includes the price of carbon at the gas price of $1.75/ MMBtu, then the mitigation project is economical. EPA reckons that the gas price of $1.75 is a highly subsidized gas price that should not be used in the evaluation of methane mitigation projects. Ideally, the price of gas to customer or cost to produce the gas should be used in the evaluation as it represents the lost opportunity cost.

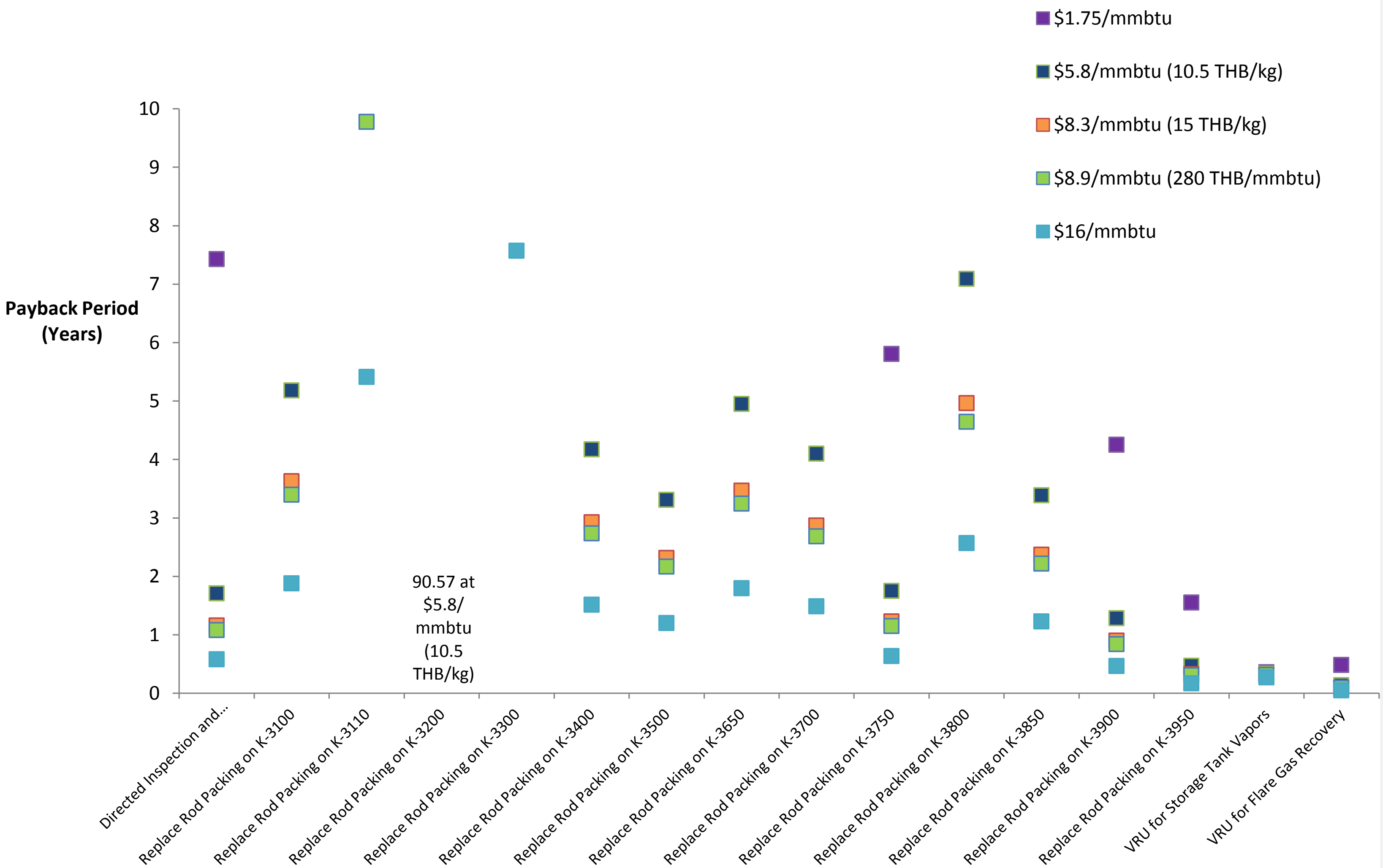


Figure 4: Payback Period of projects based on different gas prices

Note: Some values are beyond the scale of this chart. Please refer to Appendix A-3 through A-12 for further information.

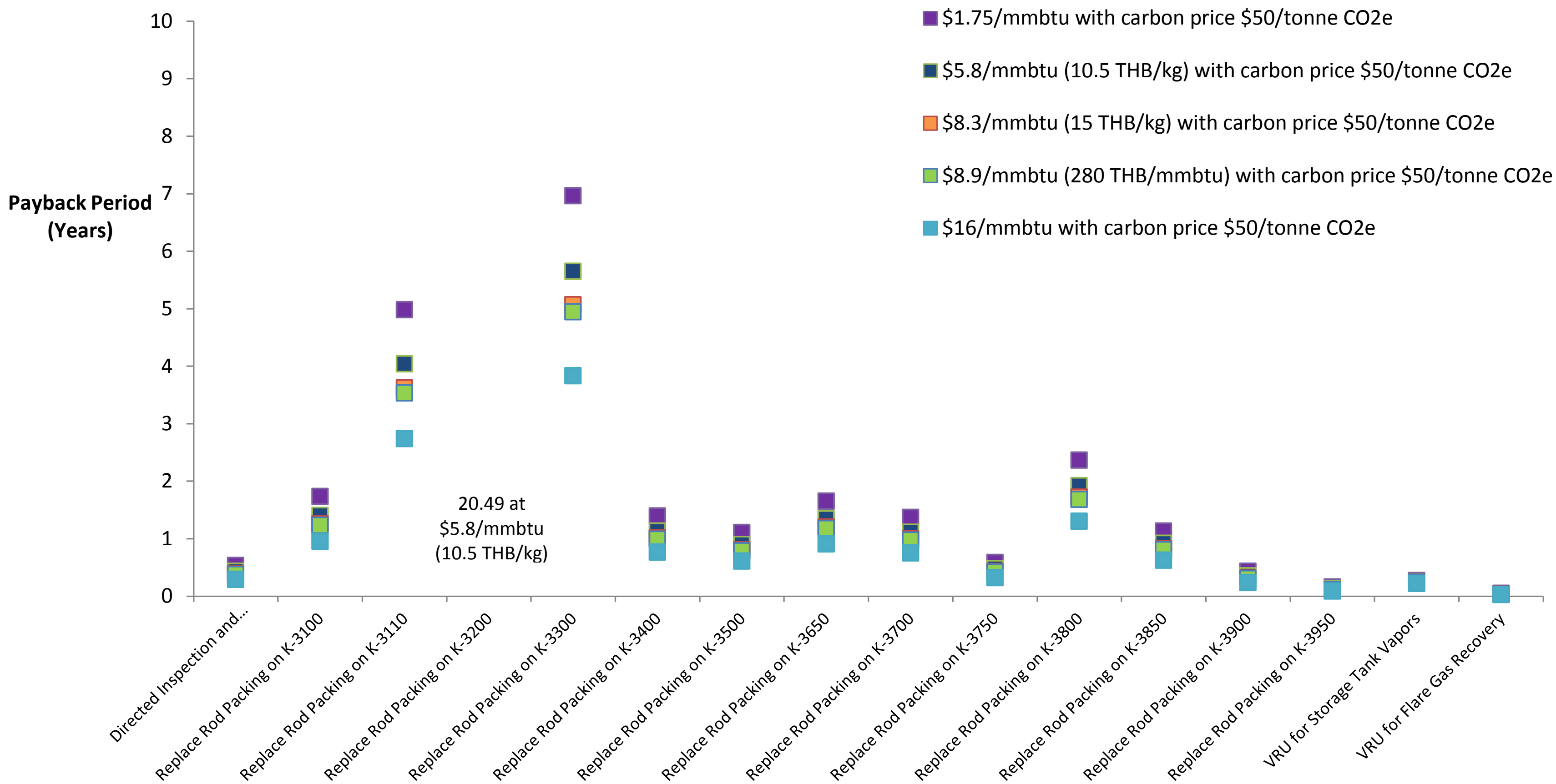


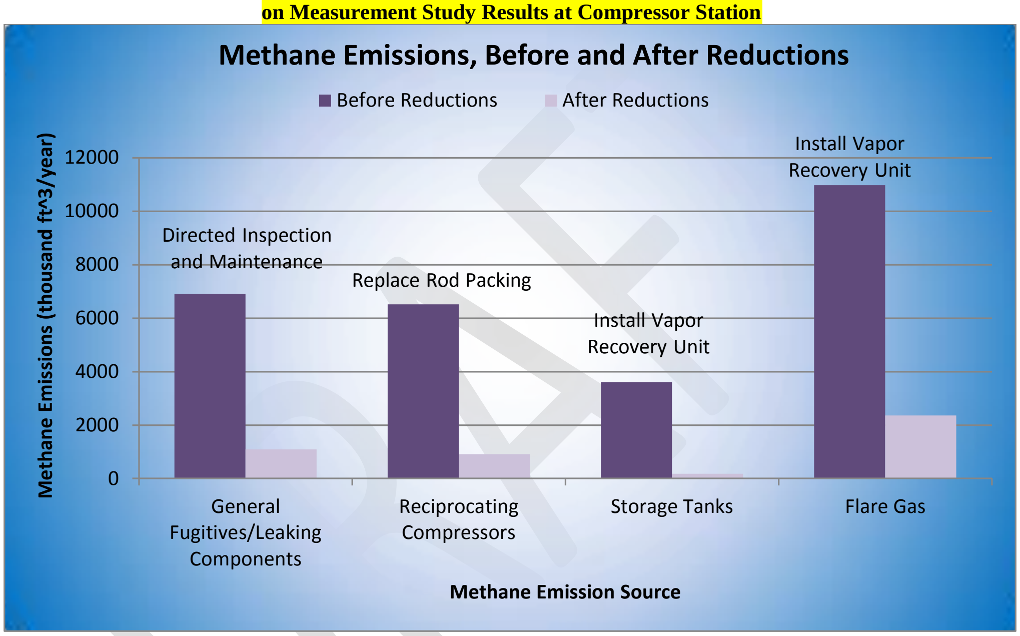
Figure 5: Payback Period of projects based on different gas prices with carbon price

Note: Some values are beyond the scale of this chart. Please refer to Appendix A-3 through A-12 for further information.

Figure 6 shows emission reductions that PTT Thailand can achieve by implementing these potential economic reduction opportunities. Potential reductions from the limited scope measurement study are up to 23.5 million ft^3/year of methane. Other Natural Gas STAR Partners have found economic justification for implementing these projects.

These recommendations are based on the results of the measurement study, the goal of which was to quantify emission levels and make preliminary recommendations for mitigation options. In all cases, PTT should undertake further study and engineering analyses in evaluating and designing equipment and technical requirements for actual project implementation. EPA can provide more detailed analysis and support to facilitate the S1 facilities' decision-making process in evaluating implementation of these activities.

Figure 6: Comparison of Methane Emissions from Current Operations and after Project Implementation, Based on Measurement Study Results at Compressor Station



DISCUSSION OF SELECTED PROJECT IDEAS

The paragraphs below provide a brief description of potential emission reductions projects for PTT Thailand's S1 facilities

Compressor Rod Packing:

Packing systems in reciprocating compressors maintain a tight seal around the piston rod, preventing the gas compressed to high pressure in the compressor cylinder from leaking, while allowing the rod to move freely. The rod packing is a combination of packing rings and packing cups which creates the tight seal. Figure 7 shows a typical compressor rod packing system where the piston rod can move freely inside the rod packing.

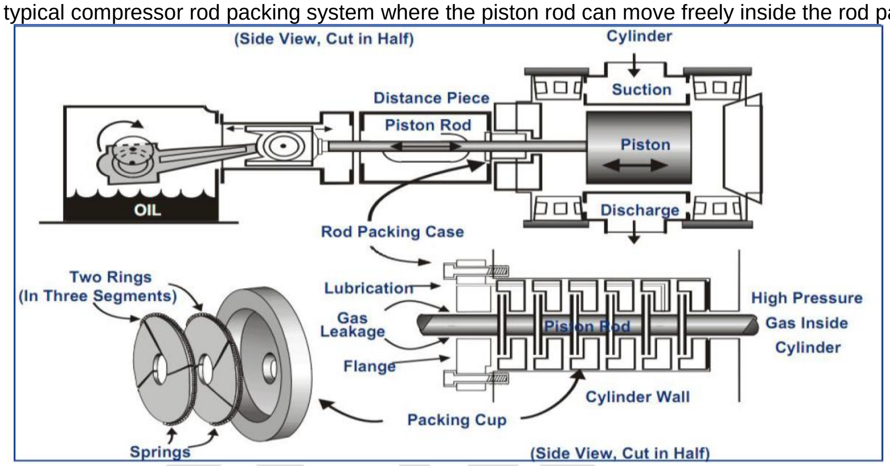


Figure 7: Compressor Rod Packing Schematic[8]

Leaks from compressor rod packing are a consequence of an issue with the preciseness of fit, alignment of the packing parts, or wear over time. Piston rods that have logged many operating hours, that are old, or that are reused may not be in alignment with the packing, which causes oblique packing wear. The packing itself is also subject to alignment and wear issues. A poorly aligned rod, pitted, scratched or worn rod surfaces, poorly fitted packing, and/or worn rings creates gaps allowing methane leakage from the cylinder and through the rod packing stack to the atmosphere or packing vent.

Mitigating compressor rod packing emissions requires technicians to fit rods and packing in alignment along with periodic replacement of each. New rod and packing materials can reduce leakage and decrease wearing issues. Rods coated with tungsten carbide have proven to increase service life by reducing wear. Rings manufactured with carbon-impregnated Teflon have replaced bronze metallic rings as state-of-the art and have lower leakage rates but shorter life.

Costs of replacing packing rings and piston rods vary with each individual reciprocating compressor design and service location, but costs can be estimated. For packing ring replacements, variables include the number of compressor cylinders and the type of replacement ring, rod dimensions and type of rod. Special coatings, such as ceramic, tungsten carbide, or chromium, can increase costs by $1,350 or more. Installation costs vary depending on site location and difficulties encountered during replacement. For estimation purposes, installation costs are roughly equal to equipment costs. Procurement issues such as shipping and customs duties are another cost to consider.

[8] http://www.epa.gov/gasstar/documents/ll_rodpack.pdf

At the S1 facilities, the EPA team surveyed 13 compressors of which only two (Unit K-3950 and K-3900) had a rod packing worn out to the extent of justifying a cost-effective replacement. The compressor rod packings on the other compressors were venting emissions which do not justify a replacement yet. However, rod packing vent volume increases over time as wear and tear increases. Therefore, it is important to monitor the rod packing vent volumes over time and determine the emissions volume at which replacement of rod packing can be justified. Figure 8 below shows the rod packing vent volumes measured at the S1 facilities and the emissions volume at which the replacement of rod packing is economical for a gas price of 10.5 THB per kilogram. "Breakeven emissions" represents the emissions volume at which the net present value of costs is equal to the value of gas being lost through the rod packing. "Emissions where payback equals 1 year" indicates the emissions level at which replacement of rod packing will yield payback on investment in 1 year. These two benchmarks vary for each compressor due to the variable operating hours of each compressor. Higher operating hours and higher price of gas would achieve quicker payback on investment. Figure 9 shows the same analysis at a gas price of 10.5 THB per kilogram including a carbon price of \$50/tonne CO_2e.

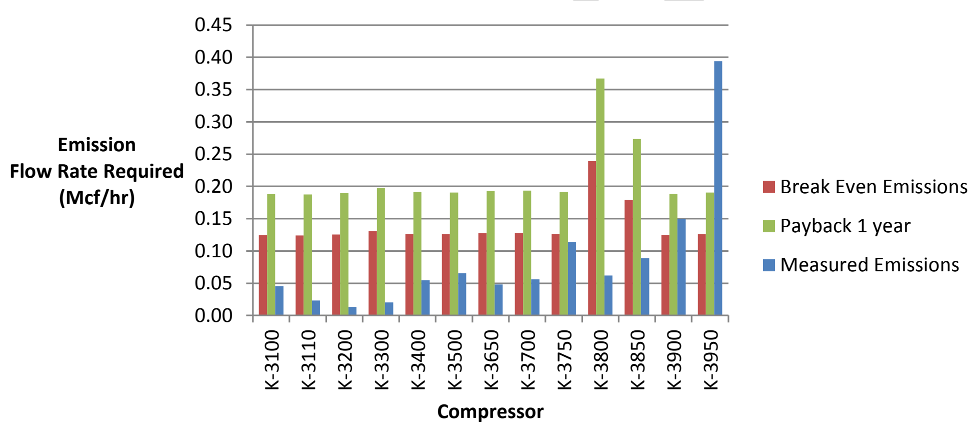


Figure 8: Rod Packing Emission Analysis (Based on a gas value of 10.5 THB/kg without a carbon price)

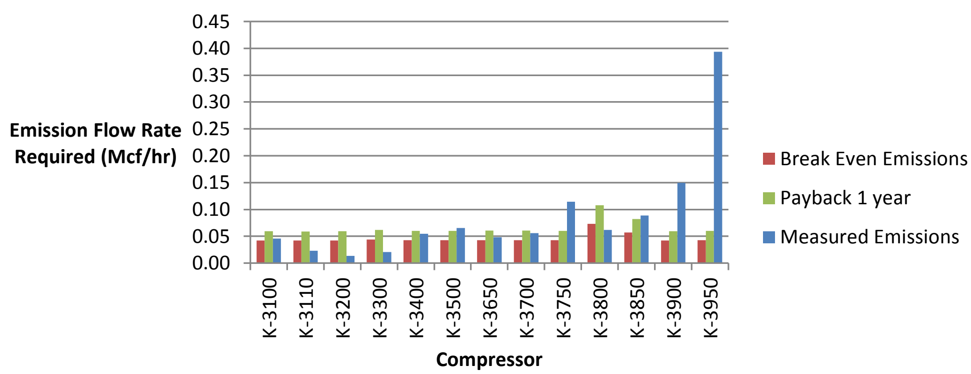


Figure 9: Rod Packing Emission Analysis (Based on a gas value of 10.5 THB/kg with a carbon price of \$50/tonne CO2e)

Installing a Vapor Recovery Unit

When oil is stored, vapors composed of methane and other volatile organic compounds accumulate in the space between the liquid and the roof of the tank. Typically, this vapor will remain in the tank unused until it is eventually vented to the atmosphere. Instead of venting or sending it to flare, the vapors from the tank can be routed to a vapor recovery unit (VRU) and used for other purposes on site. The recovered vapor stream can then be sold for profit or used as fuel gas for other processes.

An example of a VRU is depicted in Figure 10. The vapors drawn out of the storage are routed to a separator from which the liquid drop out is sent back to the storage tank. The remaining vapors are compressed and directed either to a sales line or other operational unit and used as fuel.

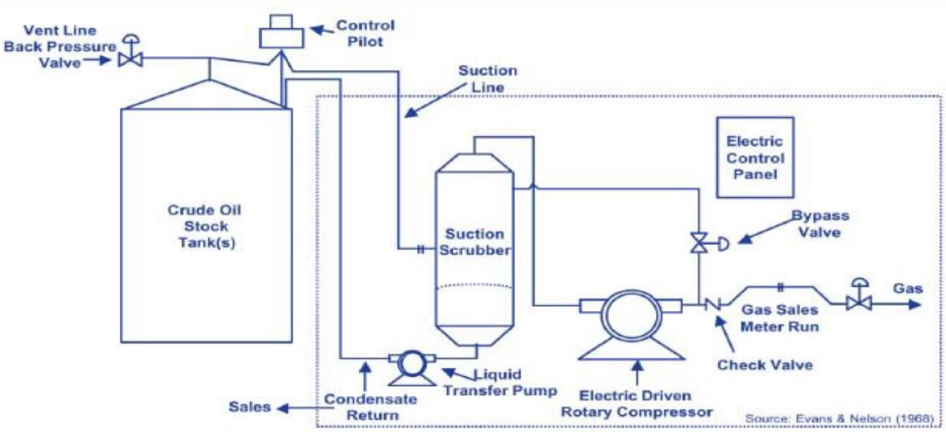


Figure 10: Standard Stock Vapor Recovery System[9]

The EPA team estimated emissions from crude oil storage tanks at the Nongtum-A Substation facility to be 45.3 Mcfd whole gas using IR camera videos. These vapors can be captured by installing a VRU. The EPA team calculated the capital cost for a VRU at Nongtum-A assuming a VRU capacity equal to twice the vapor volume. The EPA team assumed the installation costs to be 25% of the capital cost, and the shipping and packaging to be a flat cost of $US 15,000.

Comment [PA7]: The emission is too high compared with the executive summary.

Given that emissions data was only available for the Nongtum-A facility, the EPA team scaled the emissions for other S1 satellites according to the ratio of production at the satellite to the production at the Nongtum-A facility. Similarly, the EPA team approximated capital costs for VRUs at the various satellites using the Nongtum-A facility as the basis.

Table 3 provides the crude oil throughput (assumed to be the same as production at the satellite), expected vapor volumes from the tanks, and approximate capital cost for a VRU at the satellite. The volume of tank vapors at each of the satellites can vary significantly if the processes upstream of the tank are different from the processes and operating characteristics at the Nongtum-A facility. These costs indicate which satellite facilities PTT Thailand should focus on to reduce its overall methane (and, hence, GHG) footprint. Finally, in some cases, an ejector system could be more cost-effective than a VRU. The determination of whether to use an ejector or a VRU depends largely on the availability of high pressure motive gas necessary for the functioning of an ejector.

[9] Installing Vapor Recovery Units on Storage Tanks, Environmental Protection Agency, http://www.epa.gov/gasstar/documents/ll_final_vap.pdf

Table 3: Capital Cost for VRU installation[10]

Site	Oil Production (bbl.)	Tank Vapor Volumes (Mcfd)	Theoretical Capital Cost* (Thousand dollars)
Pru Krathiam - A	46,066	39	$66
Pru Krathaim - B	127,366	108	$121
Nong Tum - A	620,955	527	$314
Nong Tum - D	22,155	19	$43
Pratu Tao - A	166,374	141	$142
Pratu Tao - D	181	0.2	NA[#]
Lan Krabu - M02	44,217	38	$64
Sao Thian - A	314,015	267	$209
Nong Saeng - A	216,136	184	$167
Noan Pluang	4,386	4	$16
Prada - A	329,746	280	$215
Nong Makham - I	164,258	139	$141
Nong Ooh - A	884	0.8	NA[#]
Wat Taen - A	144,958	123	$131
Thap Raet - A	24,946	21	$46
Nong Taku	28,564	24	$49
Total	2,255,206	1,914	$ 1,733

Note: *Installation, shipping and packing costs are not included in the capital cost
[#] The tank vapor volume at Pratu Tao – D and Nong Ooh – A are small and may not justify a VRU

Directed Inspection and Maintenance

Fugitive emissions account for 24% of measured methane emissions from this limited scope measurement study at the S1 facilities, for an estimated loss of $US 43,230 yearly[11]. Because these leaks are odorless and invisible, Natural Gas STAR Partner companies find conducting leak surveys to be a popular mitigation technique that achieves increasing economics with higher gas prices and improved survey methods. Since methane leaks occur from all types of equipment, even small leaks compound into significant revenue losses. One solution to methane leaks is directed inspection and maintenance (DI&M), which is prioritized leak surveys targeted at specific components. Figure 11 shows a leak at the Lan Krabue S1 facility as visible to the naked eye. Figure 12 shows the same leak as seen through the IR camera. A DI&M program begins with a baseline survey to identify and quantify leaks and follows up with a subsequent leak survey based on the results of all previous surveys, allowing operators to focus on components that are likely to have large leaks and components that are profitable to repair. Investment in portable IR imaging cameras greatly increases the survey speed because leaks are clearly visible as plumes emanating from leak points. Additional methods are required to quantify leaks discovered by cameras. For quick repairs such as valve stem packing replacement, cameras can also be used for immediate verification of the leak reduction.

[10] Values based on assumption that no capture systems are currently in place at satellite facilities
[11] Based on a gas value of $6.40/1000ft^3 or 10.5 THB/kg

Figure 11: Leaking Valve on Tank

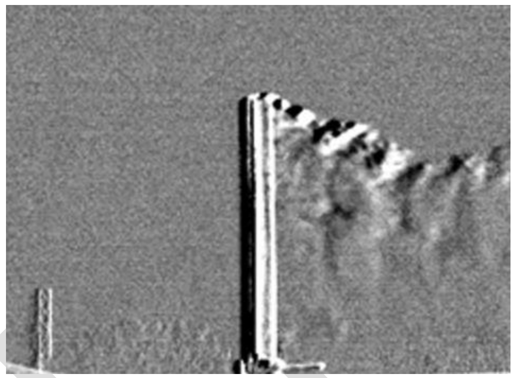


Figure 12: Leaking Valve on Tank using IR camera

Leaks that are not released directly to the atmosphere, known as through-valve leakage, cannot be detected using conventional methods or an optical gas imaging device. To detect these leaks, an acoustic leak detection device can be used. These devices detect the acoustic signal produced when pressurized gas flow passes through an orifice. With an acoustic leak detector, Partner companies have identified valves leaking to a flare header and then repaired the valves at the next maintenance shutdown. In addition, certain acoustic device models have supplementary software packages that can use the detected acoustic signal, along with details about the valve, to estimate a leak rate. However, what sets this device apart from other methods is its capability of detecting through-valve leakage. More information on leak survey and repair is available in a set of technical documents available online at http://www.epa.gov/gasstar/tools/recommended.html#other.

After an operator identifies an emission source, the source can be repaired. A repair is determined to be economical if the net present value of the gas lost is greater than the cost for repair of the leak. While these repair costs can vary between countries, an average repair cost for various components in Table 4 give a perspective on the relative cost of fixing different kinds of leaks.

Table 4: Average Repair Cost at Compressor Stations[12]

Component Description	Type of Repair	Average Cost
Ball Valves -1”	Replace	$120
Bull Plug on Valve	Add Teflon Tape & Tighten	$15
Compressor Blow Down	Replace	$600
Compressor Blow Down	Rebuild	$200
Compressor Valve Cap	Replace Gasket	$60
Flange – 30”	Change Gasket	$1,250
Flange – 6”	Change Gasket	$300
Fuel Valve	Replace	$200

[12] Lessons Learned from Natural Gas Star Partners. *Directed Inspection and Maintenance at Compressor Stations,* Retrieved from: http://www.epa.gov/gasstar/documents/ll_dimcompstat.pdf

Component Description	Type of Repair	Average Cost
Gate Valve	Teflon Repack	$40
Grease Port	Replace	$80
Head End of Compressor	Pull & Change Gaskets	$450
Loader Valve Flange	Replace Gasket	$80
Loader Valve Stem	Rebuild	$300
Needle Valve	Replace	$100
OEL on Valve	Grease	$45
Pig Receiver Door	Tighten	$120
Pipe Thread Fitting	Tighten, Add Teflon Tape	$30
Plug Valves	Grease	$40
Pressure Relief Valve -1"	Replace	$1,000
PRV Flange	Tighten	$40
Rod Packing	Change Packing Rings Without Removing Rods	$750
Rod Packing	Pull Packing Case and Rods to Change Rings, Rework Packing Case	$2,600
Rod Packing	Pull Packing Case and Rods to Change Rings, Rework Packing Case & Replace Rod	$5,600
Station Blow Down	Reverse Plug	$720
Tubing	Tighten	$10
Union	Tighten	$10
Unit Valve	Clean & Inject Sealant	$70
Unit Valve - 10" Plug	Replace	$2,960

Ejector System for Truck Loading gas:

An ejector system is able to capture vapors at low pressure and route them into a high pressure motive gas line. The motive gas line drops in pressure and needs to have a flow 3.7 to 5.7 times that of the captured vapor stream[13]. Due to these restrictions, the proper candidate for the motive gas stream needs to be on site to make this reduction technique suitable and economic. Like a VRU which pressurizes gas, an ejector system is able to capture the majority of the vapors and route them into a motive gas stream. An example of an ejector is shown below where the Venturi principle allows the system to capture the vapor gas. The low pressure vapor comes in with a low velocity while the high pressure motive gas flows with high velocity through a small orifice creating suction on the low pressure system.

13 Environmental Technology Verification Report, COMM Engineering, USA Environmental Vapor Recovery Unit (EVRUTM), http://www.epa.gov/etv/pubs/sriusepaghgvr19.pdf

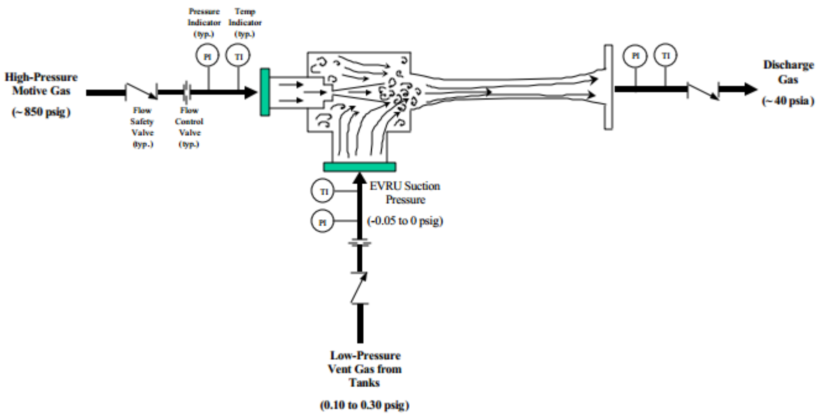


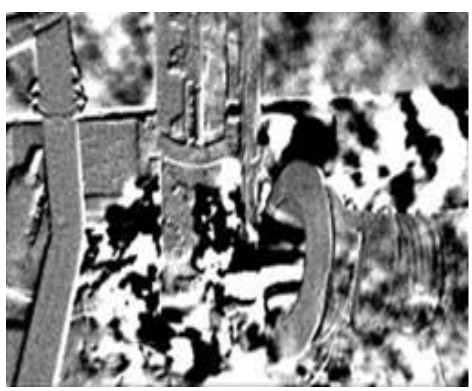
Figure 13: COMM Engineering EVRU diagram[13]

Since there are no moving parts in the ejection system, the operating and maintenance costs are low. The economics for an ejector system depend on the throughput of the vapor stream and the availability of a potential motive gas stream. This system could be used to capture gas from the truck loading area and route it back into the system just like tank vapors at the Lan Krabue facility.

Health and Safety

During the survey at the Lan Krabue site, the EPA team observed that the vapors from the crude oil loading into the trucks at the loading dock were being vented to the atmosphere close to where the operators stand on the dock. The facility has a rudimentary system for routing the crude oil vapors to a vent, but this is not functioning effectively. Crude oil vapors contain significant amount of volatile organic compounds that are regulated by the EPA. **Error! Reference source not found. Error! Reference source not found.**and **Error! erence source not found.** show the truck loading operation with the vapor routing hose. Some of the vapors are routed through the routing hose, but much of the vapors are vented at the loading point itself. In either case, all of the vapors from the truck loading are vented to the atmosphere. EPA recommends PTT Thailand to work with a loading arm manufacturer to develop a vapor capture system to recover these emissions. EPA notes that this report does not account for these emissions from truck loading. EPA believes that an ejector system might be an effective capture system to recover crude oil loading vapors.

Figure 14: Truck Loading Process with Vapor Routing



Hose to Naked Eye

Figure 15: Truck Loading Process with Vapor Routing Hose using an IR Camera

CONCLUSION AND NEXT STEPS

EPA's Natural Gas STAR International Program works closely with its oil and natural gas sector partners to identify, evaluate, and deploy practical methane emissions reduction activities. As outlined in the Memorandum of Understanding signed between EPA and PTT Thailand, the study presented here was designed to provide technical assistance and advance our shared goal of minimizing methane emissions to the atmosphere. The close collaboration between the PTT Thailand and EPA technical teams helps improve GMI's understanding of methane mitigation opportunities and challenges while also building PTT's institutional capacity to independently assess and implement future methane emission reduction projects.

This report presents key findings of a measurement study conducted in September 2013 to assess fugitive and vented methane emissions at PTT Thailand's S1 facilities. This measurement study had a limited scope due to the amount of time available, evaluating most of the compressors and limited processes at the Lan Krabue S1's Central facility and the compressor at Nongtum-A facility. As detailed in Figure 1, this limited scope measurement study estimates the S1 facilities' methane emissions to equal approximately **28,250 thousand ft^3/ year.** Some of the emission sources studied appear to be strong candidates for cost-effective mitigation project opportunities. Additionally, PTT Thailand can make progress towards it climate protection goals by implementing the projects recommended here. These proposed projects, if fully implemented, will also help PTT Thailand maximize its production efficiency and improve operational safety. For example, EPA recommends PTT Thailand to install VRUs on their crude oil storage tanks at the S1 Satellite facilities. This type of project helps conserve energy resources and supports Thailand's national goal of achieving cumulative CO2 emission reductions at an average of 49 million tons/year as stated by the Ministry of Energy in the Thailand 20-Year Energy Efficiency Development Plan (2011-2030). Since methane is 21 times more potent than CO2, PTT will help the country achieve this goal more cost-effectively and at a rapid pace.

To their credit, PTT Thailand already has methane mitigation measures in place in the form of dry seals on the centrifugal compressor at the Lan Krabue site.

EPA recommends the following next steps at the S1 facilities;

1) Flare gas reduction –PTT should systematically analyze all the sources of emissions currently directed to the flare gas header and identify any opportunities to reduce those emissions. This activity will reduce the total volume of gas being sent to the flare, reducing a range of air pollutants including methane and black carbon. Also, the smaller volume of gas being sent to the flare warrants a smaller sized VRU, thereby, reducing capital costs.
2) Development of a DI&M Team – EPA recommends that PTT establish and train a designated team that focuses on conducting DI&M periodically across all PTT facilities. EPA also recommends the purchase and application of an IR camera for leak detection and methane emissions measurement equipment that will help the DI&M team evaluate and justify methane mitigation projects. EPA can provide any support necessary in the training of a DI&M team.
3) Revise and update GHG emissions inventory – To achieve the larger objective of GHG Management, it is important that PTT develop a GHG inventory that can track emissions by source from its facilities over time. Currently, the PTT inventory only has two line items, fugitives and flaring, to represent methane emissions from its facilities. It is important to know where emissions are occurring to be able to mitigate those emissions. EPA can provide PTT with the expertise necessary to develop a GHG inventory.
4) Identify Opportunities at S1 Satellite facilities – From the limited information available, EPA notes that there might be opportunities to capture tank vapors at many of the S1 satellites. EPA can provide any support necessary to further evaluate the potential for methane mitigation projects at the S1 satellites.

PTT Thailand's cooperation with GMI and its concrete actions to minimize methane emissions will help the company demonstrate its commitment to sustainable and responsible growth. PTT's achievements of the projects identified here will also support Thailand's national goals to reduce GHG emissions. EPA encourages PTT Thailand to adopt and implement the recommended practices and technologies that best fit its business and then to share its experience and results with the broader Natural Gas STAR community. The knowledge developed and shared through this public / private cooperation is the true energy that drives the Partnership and propagates future successes. For further information about this activity and the project recommendations, please contact Scott Bartos, Natural Gas STAR International Program Manager, +1-202-343-9167 or at bartos.scott@epa.gov.

APPENDICES

Appendix A: Summary of Measurements at Lan Krabue S1

Table A-1: Fugitive Leak Measurements – Raw Data

ID	Category	Description	Measured/ Estimated flow of gas (whole gas) ft^3/min	Measurement/ estimation technique	% C1 (MOL %)	Total Standard Methane Emissions (ft^3/year)
1	Valve	Passing valve on top north side of T301. Gas sample taken from source	0.05	HiFlow	23.6%	55,152
2	Connector	gasket on man way. Top south end of tank T301.	0.25	Estimate	23.6%	131,400
3	Connector	Gasket on top east manway flange on tank T304	0.33	HiFlow	23.6%	364,006
4	Connector	Gasket on manway flange on top south side of T305.	0.45	Estimate	23.6%	236,520
5	Valve	Thief hatch on top east side of T3o6	0.02	HiFlow	23.6%	22,061
6	Valve	Breather valve on top south side of T303.	0.46	HiFlow	23.6%	507,403
7	Connector	Threaded connection on north side of south east cylinder.	0.01	HiFlow	85.3%	2,839
8	Connector	Threaded connection on east side of engine.	0.09	HiFlow	85.3%	25,548
9	Valve	Lower east valve cover on east cylinder.	0.01	HiFlow	85.3%	2,839
10	Connector	Tubing connection on south end of compressor.	0.26	HiFlow	85.3%	73,806
11	Connector	Liquid sep manway access on cooling skid.	0.09	Estimate	85.3%	47,304
12	Valve	Fuel gas regulator on east side of engine.	0.12	HiFlow	85.3%	34,064
13	Connector	Drain plug on bottom of fuel gas sep sight glass.	0.04	HiFlow	85.3%	11,355
14	Valve	Stem packing on gate valve. !st stage charge line.	0.02	HiFlow	85.3%	5,677

Comment [SU8]: Trial for calculation =0.05x60x24x365=26,280 ft3/yearx23.6%=6044 ft3 CH4/year?

ID	Category	Description	Measured/ Estimated flow of gas (whole gas) ft^3/min	Measurement/ estimation technique	% C1 (MOL %)	Total Standard Methane Emissions ($ft^3/year$)
15	Connector	Union on fuel gas line. East side of engine.	0.01	HiFlow	85.3%	2,839
16	Connector	Tubing connection on fuel gas regulator. east side of comp.	0.01	HiFlow	85.3%	2,839
17	Connector	Union before fuel gas regulator on west side of building.	0.56	Estimate	85.3%	294,336
18	Connector	Union before fuel gas regulator on east side of engine.	0.06	HiFlow	85.3%	17,032
19	Connector	Govenor arm seal on west side of engine.	0.02	HiFlow	85.3%	5,677
20	Connector	Tubing connection on east side of engine near fuel gas regulator.	0.06	HiFlow	85.3%	17,032
21	Connector	Distance piece cover gasket on north eastern most cylinder.	0.05	HiFlow	85.3%	14,193
22	Connector	Threaded connection for distance piece vent on north east cylinder	0.12	HiFlow	85.3%	34,064
23	Connector	Flange on fuel gas line, west side of engine	2.83	HiFlow	85.3%	803,347
24	Connector	Fuel gas regulator connection	0.6	HiFlow	85.3%	170,321
25	Valve	Fuel gas regulator body seal on east side of engine	3.8	Estimate	85.3%	1,997,280
26	Connector	Union connection on fuel gas line before Governor on west side of engine.	1.22	HiFlow	85.3%	346,319
27	Valve	Fuel gas regulator body seal on west side of engine.	0.85	Estimate	85.3%	446,760
28	Valve	Fuel gas regulator vent on west side of engine.	1.3	Estimate	85.3%	683,280
29	Connector	Union on fuel gas line before regulator on west	0.02	HiFlow	85.3%	5,677

ID	Category	Description	Measured/ Estimated flow of gas (whole gas) ft^3/min	Measurement/ estimation technique	% C1 (MOL %)	Total Standard Methane Emissions ($ft^3/year$)
		side of engine.				
30	Connector	Union on fuel gas line on east side of engine.	0.29	Estimate	85.3%	152,424
31	Connector	Union on fuel gas line. west side of engine.	0.07	HiFlow	85.3%	19,871
32	Connector	Governor arm seal on east side of engine. Both sides.	0.08	Estimate	85.3%	42,048
33	Connector	Threaded connection on east cylinder discharge bottle.	0.01	HiFlow	85.3%	2,839
34	Valve	Control valve stem packing on east side of engine.	0.14	HiFlow	85.3%	39,742
35	Connector	Threaded connection on east side of engine	0.35	HiFlow	85.3%	99,354
36	Connector	South east cylinder head seal	0.04	HiFlow	85.3%	11,355
37	Valve	Regulator body seal on south end of unit.	0.03	HiFlow	85.3%	8,516

Table A-2: Compressor Vent Measurements – Raw Data

ID	Description	Measured/ Estimated flow of gas (whole gas) ft^3/min	Measurement/ estimation technique	% C1 (MOL %)	Total Standard Methane Emissions (ft^3/year)
1	Common vent from truck loading operations	5	Estimate	1.29%	1,314,000
2	Un captured gas from truck loading operations, venting from oil fill hatch on aft of tanker truck. Bay 3	0.75	Estimate	1.29%	197,100
3	Un captured gas from truck loading operations, venting from oil fill hatch on front of tanker truck. Bay 3	0.5	Estimate	1.29%	131,400
4	Uncaptured gas from truck loading operations, venting from oil fill hatch on aft of tanker truck. Bay 2	0.5	Estimate	1.29%	131,400
5	Uncaptured gas from truck loading operations, venting from oil fill hatch on front of tanker truck. Bay 2	0.5	Estimate	1.29%	131,400
6	Combined distance piece and rod packing vent. Inside vent on north east side of engine.	0.2	HiFlow	70.63%	45,032
7	Distance piece oil drain vent. outside vent on northeast side of engine.	0.11	HiFlow	70.63%	24,768
8	Oil pot drain vent line.	0.26	HiFlow	70.63%	58,542
9	Variable volume pocket vent on south east cylinder	0.01	HiFlow	85.25%	1,419
10	Variable valve pocket vent on south west cylinder	0.02	HiFlow	85.25%	2,839
11	Combined distance piece and rod packing vent. south of compressoe off oil knockout tank.	0.22	HiFlow	70.63%	49,535
12	Distance piece oil drain vent. Vent on northeast side of engine.	0.32	HiFlow	70.63%	72,051
13	Oil pot drain vent line.	0.2	HiFlow	70.63%	45,032
14	Gooseneck distance piece vent on west cylinder.	0.02	HiFlow	70.63%	4,503
15	Combined distance piece and rod packing vent. Inside vent on north east side of engine.	0.24	HiFlow	70.63%	54,039

Comment [PA9]: The emission data should be identified the equipment tag so, we can refer to the total amount of compressor leakage in Table A-3

ID	Description	Measured/ Estimated flow of gas (whole gas) ft^3/min	Measurement/ estimation technique	% C1 (MOL %)	Total Standard Methane Emissions (ft^3/year)
16	Distance piece oil drain vent. outside vent on northeast side of engine. NOTE: 3 ft3 bag filled in 27 s = 6.7ft3/min. gas sample taken at this vent.	4.41	HiFlow	70.63%	992,959
17	Oil pot drain vent line.	0.4	Estimate	70.63%	105,120
18	Primary seal vent on east side of compressor. Stage 2.	0.4	Estimate	85.25%	105,120
19	Primary seal vent on south end of compressor. Stage 1.	0.02	Estimate	85.25%	5,256
20	Distance piece oil drain vent on north east side of unit.	0.32	HiFlow	70.63%	72,051
21	Combined distance piece and RPV vent off oil knockout.	0.44	Estimate	70.63%	115,632
22	Oil vent on north end of engine.	0.07	HiFlow	85.25%	9,935
23	Combined distance piece vent and RPV from west side of engine. southern vent.	0.25	Estimate	70.63%	65,700
24	Combined distance piece vent and RPV from east side of engine. northern vent.	0.3	Estimate	70.63%	78,840
25	Combined rod packing seal vent. north west side of coolers.	2.5	Estimate	70.63%	657,000
26	Combined distance piece vent. North middle of cooler.	0.13	Estimate	70.63%	34,164
27	Compressor crank case vent on east side.	0.05	Estimate	70.63%	13,140
28	Compressor crank case vent.	0.01	HiFlow	70.63%	2,252
29	Conbined rod packing vent. top eastern vent.	2	Estimate	70.63%	525,600
30	Compressor crank case vent	0.2	Estimate	70.63%	52,560
31	Combined rod pacling vent. Eastern vent	0.35	HiFlow	70.63%	78,806
32	Distance piece vent, western vent on east side of engine.	0.33	HiFlow	70.63%	74,303
33	Combined rod packing vent. Eastern most vent next to cooler.	0.28	HiFlow	70.63%	63,045
34	Distance piece vent. Western vent on east side of coolers.	0.4	HiFlow	70.63%	90,064
35	Combined rod packing vent. Eastern most vent near coolers.	0.13	Estimate	70.63%	34,164

ID	Description	Measured/ Estimated flow of gas (whole gas) ft^3/min	Measurement/ estimation technique	% C1 (MOL %)	Total Standard Methane Emissions (ft^3/year)
36	Distance piece vent. western vent on east side of engine near coolers.	0.09	Estimate	70.63%	23,652
37	Union leak on RPV vent line upstream of vent.	0.09	HiFlow	70.63%	20,264
38	Rod packing vent. northern most vent on west side of building	0.15	Estimate	70.63%	39,420
39	Distance piece vent. Middle vent on west side of building.	0.09	Estimate	70.63%	23,652
40	Rod packing oil drain vent. Middle vent on east side of building.	0.2	Estimate	70.63%	52,560
41	Combined distance piece vent on east side of building. North vent.	0.15	Estimate	70.63%	39,420
42	Oil vent on south end of engine.	0.4	HiFlow	85.25%	56,774
43	Atmospheric tank vent. Tank T-811. NOTE: flow too high to measure with hi flow. Inaccesible to measure thermal meter. Attempted to retrieve gas sample, however amount of gas posed a safety hazard.	10	Estimate	23.64%	2,628,000
44	Combined distance piece and rod packing vent	0.13	HiFlow	70.63%	29,271
45	Oil vent on northwest end of engine.	0.01	HiFlow	85.25%	1,419
46	Gooseneck distance piece vent on northwest.	0.06	HiFlow	70.63%	13,510

Table A-3: Recommended Methane Emissions Reductions Projects for Lan Krabue S1 utilizing the retail price of natural gas to consumers (10.5 THB/kilogram without carbon price)

Categorization	Reduction Method	Comments on Recommended Method	Standard Methane Reductions (thousand ft^3/year)	Standard Whole Gas Reductions (thousand ft^3/year)	Net First Year Cost (U.S. $)	NPV[a] (U.S. $)	IRR[a] (%)	Payback Period[a] (Months)
General Fugitives/Leaking Components	Directed Inspection and Maintenance (DI&M)	IR camera, Hi-Flow Sampler, and calibrated bag capital costs can be shared among the two of PTT Thailand's assets	5,824	6,832	-$67,750	$75,120	51%	21
Reciprocating Compressors	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3100.	207	293	-$9,720	-$11,621	NA	62
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3110.	72	102	-$9,720	-$14,896	NA	179
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3200.	12	17	-$9,720	-$16,351	NA	1087
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3300.	51	73	-$9,720	-$15,394	NA	251
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3400.	257	364	-$9,720	-$10,410	NA	50
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3500.	324	459	-$9,720	-$8,780	-34%	40
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3650.	217	307	-$9,720	-$11,385	NA	59
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3700.	262	371	-$9,720	-$10,291	-43%	49
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3750.	613	868	-$9,720	-$1,793	3%	21
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3800.	151	214	-$9,720	-$12,971	NA	85
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3850.	317	449	-$9,720	-$8,962	-35%	41
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3900. Economics are for Unit L.	837	1,185	-$9,720	$3,637	29%	15
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3950.	2,293	3,247	-$9,720	$38,922	175%	6
Storage Tanks	Install Vapor Recovery Unit	Install Vapor Recovery units at Ladlumkaew	3,429	15,697	-$93,007	$1,124,537	363%	4
Flare Gas Recovery	Install Vapor Recovery Unit	Install Vapor Recovery units at Lan Krabue S1	430,382	504,822	-$415,835	$9,283,951	721%	2

Notes:

a Net present value, internal rate of return and payback period are calculated using the whole gas reductions and not methane reductions utilize a gas value of 10.5 THB/kilogram for natural gas.

b Capital costs for DI&M include: IR Camera cost of $115,000 (typical range of $85,000-$115,000), High Flow Sampler cost of $20,000, and 10 calibrated bags for $50 each (based on Natural Gas STAR discussions with vendors). The cost of IR camera is conservatively high. These costs are shared by two PTT Thailand sites –Ladlumkaew and Lan Krabue S1.

c Represents the capital and installation cost of replacing the rod packing on the compressors which is estimated at $1,620 per cylinder.

Table A-4: Recommended Methane Emissions Reductions Projects for Lan Krabue S1 utilizing the retail price of natural gas to consumers (10.5 THB/kilogram with carbon price)

Categorization	Reduction Method	Comments on Recommended Method	Standard Methane Reductions (thousand ft^3/year)	Standard Whole Gas Reductions (thousand ft^3/year)	Net First Year Cost (U.S. $)	NPV[a] (U.S. $)	IRR[a] (%)	Payback Period[a] (Months)
General Fugitives/Leaking Components	Directed Inspection and Maintenance (DI&M)	IR camera, Hi-Flow Sampler, and calibrated bag capital costs can be shared among the two of PTT Thailand's assets	5,824	6,832	-$67,750	$500,070	232%	5
Reciprocating Compressors	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3100.	207	293	-$9,720	$1,916	21%	17
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3110.	72	102	-$9,720	-$10,196	NA	48
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3200.	12	17	-$9,720	-$15,577	NA	294
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3300.	51	73	-$9,720	-$12,034	NA	68
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3400.	257	364	-$9,720	$6,393	41%	14
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3500.	324	459	-$9,720	$12,424	67%	11
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3650.	217	307	-$9,720	$2,788	25%	16
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3700.	262	371	-$9,720	$6,833	43%	13
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3750.	613	868	-$9,720	$38,261	172%	6
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3800.	151	214	-$9,720	-$3,077	-3%	23
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3850.	317	449	-$9,720	$11,748	64%	11
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3900. Economics are for Unit L.	837	1,185	-$9,720	$58,342	251%	4
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3950.	2,293	3,247	-$9,720	$188,826	755%	2
Storage Tanks	Install Vapor Recovery Unit	Install Vapor Recovery units at Ladlumkaew	3,429	15,697	-$93,007	$1,507,536	477%	3
Flare Gas Recovery	Install Vapor Recovery Unit	Install Vapor Recovery units at Lan Krabue S1	430,382	504,822	-$415,835	$35,918,823	2711%	0.4

Notes:

a Net present value, internal rate of return and payback period are calculated using the whole gas reductions and not methane reductions utilize a gas value of 10.5 THB/kilogram for natural gas and a carbon price of $50/tonne CO2e.

b Capital costs for DI&M include: IR Camera cost of $115,000 (typical range of $85,000-$115,000), High Flow Sampler cost of $20,000, and 10 calibrated bags for $50 each (based on Natural Gas STAR discussions with vendors). The cost of IR camera is conservatively high. These costs are shared by two PTT Thailand sites –Ladlumkaew and Lan Krabue S1.

c Represents the capital and installation cost of replacing the rod packing on the compressors which is estimated at $1,620 per cylinder.

Table A-5: Recommended Methane Emissions Reductions Projects for Lan Krabue S1 utilizing the retail price of Natural gas sold to EGAT (280 THB/mmbtu without carbon price)

Categorization	Reduction Method	Comments on Recommended Method	Standard Methane Reductions (thousand ft^3/year)	Standard Whole Gas Reductions (thousand ft^3/year)	Net First Year Cost (U.S. $)	NPV[a] (U.S. $)	IRR[a] (%)	Payback Period[a] (Months)
General Fugitives/Leaking Components	Directed Inspection and Maintenance (DI&M)	IR camera, Hi-Flow Sampler, and calibrated bag capital costs can be shared among the two of PTT Thailand's assets	5,824	6,832	-$67,750	$158,034	89%	13
Reciprocating Compressors	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3100.	207	293	-$9,720	-$8,980	-35%	41
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3110.	72	102	-$9,720	-$13,979	NA	117
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3200.	12	17	-$9,720	-$16,200	NA	712
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3300.	51	73	-$9,720	-$14,738	NA	164
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3400.	257	364	-$9,720	-$7,132	-25%	33
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3500.	324	459	-$9,720	-$4,642	-11%	26
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3650.	217	307	-$9,720	-$8,620	-33%	39
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3700.	262	371	-$9,720	-$6,950	-24%	32
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3750.	613	868	-$9,720	$6,022	40%	14
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3800.	151	214	-$9,720	-$11,041	NA	56
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3850.	317	449	-$9,720	-$4,921	-13%	27
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3900. Economics are for Unit L.	837	1,185	-$9,720	$14,311	75%	10
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3950.	2,293	3,247	-$9,720	$68,171	289%	4
Storage Tanks	Install Vapor Recovery Unit	Install Vapor Recovery units at Ladlumkaew	3,429	15,697	-$93,007	$1,199,266	385%	4
Flare Gas Recovery	Install Vapor Recovery Unit	Install Vapor Recovery units at Lan Krabue S1	430,382	504,822	-$415,835	$14,480,809	1110%	1

Notes:

a Net present value, internal rate of return and payback period are calculated using the whole gas reductions and not methane reductions utilize a gas value of 280 THB/mmbtu for natural gas.

b Capital costs for DI&M include: IR Camera cost of $115,000 (typical range of $85,000-$115,000), High Flow Sampler cost of $20,000, and 10 calibrated bags for $50 each (based on Natural Gas STAR discussions with vendors). The cost of IR camera is conservatively high. These costs are shared by two PTT Thailand sites –Ladlumkaew and Lan Krabue S1.

c Represents the capital and installation cost of replacing the rod packing on the compressors which is estimated at $1,620 per cylinder.

Table A-6: Recommended Methane Emissions Reductions Projects for Lan Krabue S1 utilizing the retail price of Natural gas sold to EGAT (280 THB/mmbtu with carbon price)

Categorization	Reduction Method	Comments on Recommended Method	Standard Methane Reductions (thousand ft³/year)	Standard Whole Gas Reductions (thousand ft³/year)	Net First Year Cost (U.S. $)	NPV[a] (U.S. $)	IRR[a] (%)	Payback Period[a] (Months)
General Fugitives/Leaking Components	Directed Inspection and Maintenance (DI&M)	IR camera, Hi-Flow Sampler, and calibrated bag capital costs can be shared among the two of PTT Thailand's assets	5,824	6,832	-$67,750	$582,984	266%	5
Reciprocating Compressors	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3100.	207	293	-$9,720	$4,558	33%	15
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3110.	72	102	-$9,720	-$9,279	-37%	42
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3200.	12	17	-$9,720	-$15,426	NA	257
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3300.	51	73	-$9,720	-$11,379	NA	59
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3400.	257	364	-$9,720	$9,671	56%	12
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3500.	324	459	-$9,720	$16,561	85%	9
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3650.	217	307	-$9,720	$5,553	38%	14
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3700.	262	371	-$9,720	$10,175	58%	12
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3750.	613	868	-$9,720	$46,076	203%	5
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3800.	151	214	-$9,720	-$1,146	6%	20
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3850.	317	449	-$9,720	$15,789	81%	10
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3900. Economics are for Unit L.	837	1,185	-$9,720	$69,015	292%	4
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3950.	2,293	3,247	-$9,720	$218,074	868%	1
Storage Tanks	Install Vapor Recovery Unit	Install Vapor Recovery units at Ladlumkaew	3,429	15,697	-$93,007	$1,582,265	500%	3
Flare Gas Recovery	Install Vapor Recovery Unit	Install Vapor Recovery units at Lan Krabue S1	430,382	504,822	-$415,835	$41,115,681	3100%	0.4

Notes:

a Net present value, internal rate of return and payback period are calculated using the whole gas reductions and not methane reductions utilize a gas value of 280 THB/mmbtu for natural gas with a carbon price of $50/tonne CO2e.

b Capital costs for DI&M include: IR Camera cost of $115,000 (typical range of $85,000-$115,000), High Flow Sampler cost of $20,000, and 10 calibrated bags for $50 each (based on Natural Gas STAR discussions with vendors). The cost of IR camera is conservatively high. These costs are shared by two PTT Thailand sites –Ladlumkaew and Lan Krabue S1.

c Represents the capital and installation cost of replacing the rod packing on the compressors which is estimated at $1,620 per cylinder.

Table A-7: Recommended Methane Emissions Reductions Projects for Lan Krabue S1 utilizing the real price of natural gas (15 THB/kilogram without carbon price)

Categorization	Reduction Method	Comments on Recommended Method	Standard Methane Reductions (thousand ft^3/year)	Standard Whole Gas Reductions (thousand ft^3/year)	Net First Year Cost (U.S. $)	NPV[a] (U.S. $)	IRR[a] (%)	Payback Period[a] (Months)
General Fugitives/Leaking Components	Directed Inspection and Maintenance (DI&M)	IR camera, Hi-Flow Sampler, and calibrated bag capital costs can be shared among the two of PTT Thailand's assets	5,824	6,832	-$67,750	$142,622	82%	14
Reciprocating Compressors	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3100.	207	293	-$9,720	-$9,471	-38%	44
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3110.	72	102	-$9,720	-$14,150	NA	125
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3200.	12	17	-$9,720	-$16,228	NA	761
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3300.	51	73	-$9,720	-$14,860	NA	175
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3400.	257.	364	-$9,720	-$7,741	-28%	35
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3500.	324	459	-$9,720	-$5,411	-15%	28
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3650.	217	307	-$9,720	-$9,134	-36%	42
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3700.	262.	371	-$9,720	-$7,571	-27%	34
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3750.	613	868	-$9,720	$4,570	33%	15
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3800.	151	214	-$9,720	-$11,399	NA	60
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3850.	317	449	-$9,720	-$5,673	-17%	28
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3900. Economics are for Unit L.	837	1,185	-$9,720	$12,327	67%	11
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3950.	2,293	3,247	-$9,720	$62,734	268%	4
Storage Tanks	Install Vapor Recovery Unit	Install Vapor Recovery units at Ladlumkaew	3,429	15,697	-$93,007	$1,185,375	381%	4
Flare Gas Recovery	Install Vapor Recovery Unit	Install Vapor Recovery units at Lan Krabue S1	430,382	504,822	-$415,835	$13,514,817	1038%	1

Notes:

a Net present value, internal rate of return and payback period are calculated using the whole gas reductions and not methane reductions utilize a gas value of 15 THB/kilogram for natural gas.

b Capital costs for DI&M include: IR Camera cost of $115,000 (typical range of $85,000-$115,000), High Flow Sampler cost of $20,000, and 10 calibrated bags for $50 each (based on Natural Gas STAR discussions with vendors). The cost of IR camera is conservatively high. These costs are shared by two PTT Thailand sites –Ladlumkaew and Lan Krabue S1.

c Represents the capital and installation cost of replacing the rod packing on the compressors which is estimated at $1,620 per cylinder.

Table A-8: Recommended Methane Emissions Reductions Projects for Lan Krabue S1 utilizing the real price of natural gas (15 THB/kilogram with carbon price)

Categorization	Reduction Method	Comments on Recommended Method	Standard Methane Reductions (thousand ft^3/year)	Standard Whole Gas Reductions (thousand ft^3/year)	Net First Year Cost (U.S. $)	NPV[a] (U.S. $)	IRR[a] (%)	Payback Period[a] (Months)
General Fugitives/Leaking Components	Directed Inspection and Maintenance (DI&M)	IR camera, Hi-Flow Sampler, and calibrated bag capital costs can be shared among the two of PTT Thailand's assets	5,824	6,832	-$67,750	$567,572	260%	5
Reciprocating Compressors	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3100.	207	293	-$9,720	$4,067	31%	15
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3110.	72	102	-$9,720	-$9,450	-38%	43
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3200.	12	17	-$9,720	-$15,454	NA	263
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3300.	51	73	-$9,720	-$11,501	NA	61
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3400.	257	364	-$9,720	$9,062	53%	12
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3500.	324	459	-$9,720	$15,792.	81%	10
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3650.	217	307	-$9,720	$5,039	35%	14
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3700.	262	371	-$9,720	$9,554	55%	12
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3750.	613	868	-$9,720	$44,623.	197%	5
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3800.	151	214	-$9,720	-$1,505	5%	21
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3850.	317	449	-$9,720	$15,038	78%	10
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3900. Economics are for Unit L.	837	1,185	-$9,720	$67,031	285%	4
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3950.	2,293	3,247	-$9,720	$212,638	847%	1
Storage Tanks	Install Vapor Recovery Unit	Install Vapor Recovery units at Ladlumkaew	3,429	15,697	-$93,007	$1,568,375	495%	3
Flare Gas Recovery	Install Vapor Recovery Unit	Install Vapor Recovery units at Lan Krabue S1	430,382	504,822	-$415,835	$40,149,689	3028%	0.4

Notes:

a Net present value, internal rate of return and payback period are calculated using the whole gas reductions and not methane reductions utilize a gas value of 280 THB/mmbtu for natural gas with a carbon price of $50/tonne CO2e.

b Capital costs for DI&M include: IR Camera cost of $115,000 (typical range of $85,000-$115,000), High Flow Sampler cost of $20,000, and 10 calibrated bags for $50 each (based on Natural Gas STAR discussions with vendors). The cost of IR camera is conservatively high. These costs are shared by two PTT Thailand sites –Ladlumkaew and Lan Krabue S1.

c Represents the capital and installation cost of replacing the rod packing on the compressors which is estimated at $1,620 per cylinder.

Table A-9: Recommended Methane Emissions Reductions Projects for Lan Krabue S1 utilizing a proxy gas price of natural gas (1.75 $/MMBtu without carbon price)

Categorization	Reduction Method	Comments on Recommended Method	Standard Methane Reductions (thousand ft^3/year)	Standard Whole Gas Reductions (thousand ft^3/year)	Net First Year Cost (U.S. $)	NPV[a] (U.S. $)	IRR[a] (%)	Payback Period[a] (Months)
General Fugitives/Leaking Components	Directed Inspection and Maintenance (DI&M)	IR camera, Hi-Flow Sampler, and calibrated bag capital costs can be shared among the two of PTT Thailand's assets	5,824	6,832	-$67,750	-$34,872	-12%	89
Reciprocating Compressors	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3100.	207	293	-$9,720	-$15,125	NA	206
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3110.	72	102	-$9,720	-$16,113	NA	594
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3200.	12	17	-$9,720	-$16,552	NA	3603
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3300.	51	73	-$9,720	-$16,263	NA	831
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3400.	257	364	-$9,720	-$14,760	NA	166
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3500.	324	459	-$9,720	-$14,268	NA	132
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3650.	217	307	-$9,720	-$15,054	NA	197
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3700.	262	371	-$9,720	-$14,724	NA	163
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3750.	613	868	-$9,720	-$12,160	NA	70
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3800.	151	214	-$9,720	-$15,532	NA	282
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3850.	317	449	-$9,720	-$14,323	NA	135
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3900. Economics are for Unit L.	837	1,185	-$9,720	-$10,522	NA	51
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3950.	2,293	3,247	-$9,720	$122	13%	19
Storage Tanks	Install Vapor Recovery Unit	Install Vapor Recovery units at Ladlumkaew	3,429	15,697	-$93,007	$1,025,403	333%	4
Flare Gas Recovery	Install Vapor Recovery Unit	Install Vapor Recovery units at Lan Krabue S1	430,382	504,822	-$415,835	$2,389,917	206%	6

Notes:

a Net present value, internal rate of return and payback period are calculated using the whole gas reductions and not methane reductions utilize a gas value of $1.75 /mmbtu for natural gas.

b Capital costs for DI&M include: IR Camera cost of $115,000 (typical range of $85,000-$115,000), High Flow Sampler cost of $20,000, and 10 calibrated bags for $50 each (based on Natural Gas STAR discussions with vendors). The cost of IR camera is conservatively high. These costs are shared by two PTT Thailand sites –Ladlumkaew and Lan Krabue S1.

c Represents the capital and installation cost of replacing the rod packing on the compressors which is estimated at $1,620 per cylinder.

Table A-10: Recommended Methane Emissions Reductions Projects for Lan Krabue S1 utilizing a proxy gas price of natural gas (1.75 $/MMBtu with carbon price)

Categorization	Reduction Method	Comments on Recommended Method	Standard Methane Reductions (thousand ft^3/year)	Standard Whole Gas Reductions (thousand ft^3/year)	Net First Year Cost (U.S. $)	NPV[a] (U.S. $)	IRR[a] (%)	Payback Period[a] (Months)
General Fugitives/Leaking Components	Directed Inspection and Maintenance (DI&M)	IR camera, Hi-Flow Sampler, and calibrated bag capital costs can be shared among the two of PTT Thailand's assets	5,824	6,832	-$67,750	$390,078	186%	6
Reciprocating Compressors	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3100.	207	293	-$9,720	-$1,588	4%	21
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3110.	72	102	-$9,720	-$11,413	NA	60
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3200.	12	17	-$9,720	-$15,777	NA	362
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3300.	51	73	-$9,720	-$12,904	NA	84
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3400.	257	364	-$9,720	$2,044	22%	17
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3500.	324	459	-$9,720	$6,936	44%	13
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3650.	217	307	-$9,720	-$881	8%	20
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3700.	262	371	-$9,720	$2,401	23%	16
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3750.	613	868	-$9,720	$27,894	131%	7
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3800.	151	214	-$9,720	-$5,638	-16%	28
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3850.	317	449	-$9,720	$6,387	41%	14
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3900. Economics are for Unit L.	837	1,185	-$9,720	$44,182	195%	5
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3950.	2,293	3,247	-$9,720	$150,026	606%	2
Storage Tanks	Install Vapor Recovery Unit	Install Vapor Recovery units at Ladlumkaew	3,429	15,697	-$93,007	$1,408,403	448%	3
Flare Gas Recovery	Install Vapor Recovery Unit	Install Vapor Recovery units at Lan Krabue S1	430,382	504,822	-$415,835	$29,024,789	2196%	0.5

Notes:

a Net present value, internal rate of return and payback period are calculated using the whole gas reductions and not methane reductions utilize a gas value of $1.75 /mmbtu for natural gas with a carbon price of $50/tonne CO2e.

b Capital costs for DI&M include: IR Camera cost of $115,000 (typical range of $85,000-$115,000), High Flow Sampler cost of $20,000, and 10 calibrated bags for $50 each (based on Natural Gas STAR discussions with vendors). The cost of IR camera is conservatively high. These costs are shared by two PTT Thailand sites –Ladlumkaew and Lan Krabue S1.

c Represents the capital and installation cost of replacing the rod packing on the compressors which is estimated at $1,620 per cylinder.

Table A-11: Recommended Methane Emissions Reductions Projects for Lan Krabue S1 utilizing an LNG Import gas price of natural gas (16 $/MMBtu without carbon price)

Categorization	Reduction Method	Comments on Recommended Method	Standard Methane Reductions (thousand ft^3/year)	Standard Whole Gas Reductions (thousand ft^3/year)	Net First Year Cost (U.S. $)	NPV[a] (U.S. $)	IRR[a] (%)	Payback Period[a] (Months)
General Fugitives/Leaking Components	Directed Inspection and Maintenance (DI&M)	IR camera, Hi-Flow Sampler, and calibrated bag capital costs can be shared among the two of PTT Thailand's assets	5,824	6,832	-$67,750	$352,018	171%	7
Reciprocating Compressors	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3100.	207	293	-$9,720	-$2,800	-2%	23
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3110.	72	102	-$9,720	-$11,834	NA	65
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3200.	12	17	-$9,720	-$15,847	NA	394
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3300.	51	73	-$9,720	-$13,205	NA	91
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3400.	257	364	-$9,720	$539	15%	18
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3500.	324	459	-$9,720	$5,037	35%	14
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3650.	217	307	-$9,720	-$2,150	2%	22
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3700.	262	371	-$9,720	$867	16%	18
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3750.	613	868	-$9,720	$24,306	116%	8
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3800.	151	214	-$9,720	-$6,524	-21%	31
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3850.	317	449	-$9,720	$4,533	33%	15
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3900. Economics are for Unit L.	837	1,185	-$9,720	$39,283	176%	6
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3950.	2,293	3,247	-$9,720	$136,599	554%	2
Storage Tanks	Install Vapor Recovery Unit	Install Vapor Recovery units at Ladlumkaew	3,429	15,697	-$93,007	$1,374,100	437%	3
Flare Gas Recovery	Install Vapor Recovery Unit	Install Vapor Recovery units at Lan Krabue S1	430,382	504,822	-$415,835	$26,639,241	2018%	1

Notes:

a Net present value, internal rate of return and payback period are calculated using the whole gas reductions and not methane reductions utilize a gas value of $1.75 /mmbtu for natural gas.

b Capital costs for DI&M include: IR Camera cost of $115,000 (typical range of $85,000-$115,000), High Flow Sampler cost of $20,000, and 10 calibrated bags for $50 each (based on Natural Gas STAR discussions with vendors). The cost of IR camera is conservatively high. These costs are shared by two PTT Thailand sites –Ladlumkaew and Lan Krabue S1.

c Represents the capital and installation cost of replacing the rod packing on the compressors which is estimated at $1,620 per cylinder.

Table A-12: Recommended Methane Emissions Reductions Projects for Lan Krabue S1 utilizing a LNG Import gas price of natural gas (16 $/MMBtu with carbon price)

Categorization	Reduction Method	Comments on Recommended Method	Standard Methane Reductions (thousand ft^3/year)	Standard Whole Gas Reductions (thousand ft^3/year)	Net First Year Cost (U.S. $)	NPV[a] (U.S. $)	IRR[a] (%)	Payback Period[a] (Months)
General Fugitives/Leaking Components	Directed Inspection and Maintenance (DI&M)	IR camera, Hi-Flow Sampler, and calibrated bag capital costs can be shared among the two of PTT Thailand's assets	5,824	6,832	-$67,750	$776,967	346%	3
Reciprocating Compressors	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3100.	207	293	-$9,720	$10,737	60%	11
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3110.	72	102	-$9,720	-$7,133	-25%	33
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3200.	12	17	-$9,720	-$15,072	NA	199
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3300.	51	73	-$9,720	-$9,846	NA	46
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3400.	257	364	-$9,720	$17,342	88%	9
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3500.	324	459	-$9,720	$26,240	124%	7
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3650.	217	307	-$9,720	$12,023	66%	11
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3700.	262	371	-$9,720	$17,992	90%	9
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3750.	613	868	-$9,720	$64,360	274%	4
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3800.	151	214	-$9,720	$3,371	28%	16
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3850.	317	449	-$9,720	$25,243	120%	7
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3900. Economics are for Unit L.	837	1,185	-$9,720	$93,987	389%	3
	Replace Rod Packing	Replacing rod packing on every cylinder on Compressor K-3950.	2,293	3,247	-$9,720	$286,503	1131%	1
Storage Tanks	Install Vapor Recovery Unit	Install Vapor Recovery units at Ladlumkaew	3,429	15,697	-$93,007	$1,757,099	552%	3
Flare Gas Recovery	Install Vapor Recovery Unit	Install Vapor Recovery units at Lan Krabue S1	430,382	504,822	-$415,835	$53,274,113	4008%	0.3

Notes:

a Net present value, internal rate of return and payback period are calculated using the whole gas reductions and not methane reductions utilize a gas value of $1.75 /mmbtu for natural gas with a carbon price of $50/tonne CO2e.

b Capital costs for DI&M include: IR Camera cost of $115,000 (typical range of $85,000-$115,000), High Flow Sampler cost of $20,000, and 10 calibrated bags for $50 each (based on Natural Gas STAR discussions with vendors). The cost of IR camera is conservatively high. These costs are shared by two PTT Thailand sites –Ladlumkaew and Lan Krabue S1.

c Represents the capital and installation cost of replacing the rod packing on the compressors which is estimated at $1,620 per cylinder.

Appendix B: Measurement Study Approach

Prior to starting the measurement study, a site overview was conducted with PTT Thailand staff to explain gas flows/ lines and the equipment at each location; the overall facility layout to efficiently locate emission sources; and identify equipment and explain adjacent and connecting equipment. All information was logged into spreadsheets for analysis.

Screen Equipment

The operations were screened for leaks using portable leak detection equipment, such as hydrocarbon leak detectors, and the GasFindIR camera.

Tagging Method(s) for Leaks Identified

All leaks that are detected on the key emissions source were instantly tagged, using materials that are both weather-resistant, such as Tyvek®, and brightly colored to ensure longevity and provide clear identification for measurement personnel. The tag was fixed to the equipment (component) using steel wire, and a leak identification number assigned. The tag was logged with the following information by the detection personnel:

- Leak indication tag number;
- Equipment (component) identification (number);
- Equipment (component) description
- Equipment (component) location; and
- Leak description.

Conduct Measurements

Measurements were conducted based on the anticipated size of leak detected, and its location. For example, if leaks were greater than a certain cut-off level, then vent-bagging or thermal mass flow meter techniques were used. For the emissions sources that were physically inaccessible for measurement, emissions volumes were estimated using the FLIR estimation technique.

Each individual leak measurement was hand written into a data sheet that logged the date, facility name, component type, measured leak rate, and state of repair of the component. The leak measurement method, the Hi-Flow ™ Sampler, calibrated bagging or thermal mass flow meter, was also noted.

Leak Rate Calculation

Leak emissions quantification using the Hi-Flow sampler is based on the following principles:

$$Q_{CH4} = F_{sampler} \times (C_{main} - C_{back})$$

Where,

Q_{CH4} = leak rate of methane from component (m^3/hour);

$F_{sampler}$ = sample flow rate of the High Flow unit (m^3/hour);

C_{main} = concentration of methane in the sample flow (percent); and

C_{back} = concentration of methane in the background near the component (percent).

For calibrated bagging, the time taken to completely fill a bag on known volume was recorded. Readings were adjusted to both the gas composition and gas temperature (to correct the volume to standard temperature conditions).

QA/QC Procedures

Replicate measurements were made on a minimum of 10 percent of the leaks. Additionally, for large leaks (≥ 10 m^3/hour), additional independent measurements were be recorded to ensure good precision amongst readings.

Appendix C: Equipment Specifications

HiFlow^{TM} Sampler

Description: The HiFlow^{TM} Sampler is a variable-flow rate sampling system that provides total capture of the emissions from a leaking component. An assortment of specially-designed attachments is provided for use as needed to ensure total emissions capture, or to help prevent interference from other nearby sources. A dual-element hydrocarbon detector (i.e., catalytic-oxidation/ thermal-conductivity), inserted directly in the main sample line within the Hi-Flow^{TM}, measures hydrocarbon concentrations in the captured air stream ranging from 0.01 to 100 percent. A background sample-collection line and hydrocarbon detector allows the sample readings to be corrected for ambient gas concentrations. A thermal anemometer, also inserted directly into the main sample line, monitors the mass flow rate of the sampled air-hydrocarbon gas mixture.

Measurable Leak Rate: 0.05 to 8.00 SCFM (1.42 to 226 LPM)
Accuracy (of *calculated* leak rate): ± 10% of reading

Sampling Flow Rate: 10.5 SCFM (297 LPM) at full battery charge

Natural Gas Sensor:
- Catalytic Oxidation:
  - Range: 0 to 5% methane
  - Accuracy: ± 5% of reading or 0.02% of methane, whichever is greater
- Thermal Conductivity
  - Range: 5 to 100% methane
  - Accuracy: ± 5% of reading or 0.02% of methane, whichever is greater

Battery:
- Type: Intrinsically Safe NiMH rechargeable pack
- Voltage: 4.8 volts (V) max.
- Recharge Time: 8 to 10 hours
- Run Time: >4.5 hours continuous at 20 degrees Celsius (^{o}C)

Operating Temperature: 32 to 122°F

Dimensions: 18 x 12 x 7 inches

Weight: 20 pounds

Vendor: Bacharach Inc. [http://www.bacharach-inc.com/hi-flow-sampler.htm]
Heath Consultants [http://www.heathus.com/_hc/index.cfm/products/emissions]

Distributor Contact:
Milton Heath III
9030 Monroe Road
Houston, TX 77061
(713) 844-1304
milt.heath3@heathus.com

Price: No specific information at present; however, price will range between US$15,000-20,000.

More Information: Instruction manual and detailed specifications (Bacharach) [http://www.bacharach-inc.com/PDF/Instructions/55-9017.pdf]
Data sheet (Heath) [http://www.heathus.com/tasks/sites/_hc/assets/File/hiflow.pdf]

FLIR GF320 24° Fixed Lens

Description: Hydrocarbon emissions absorb infrared light in a certain wavelength. The IR camera uses this characteristic to detect the presence of gas emissions from equipment. The IR camera scans the leak area in real time at 60 hertz scan frequency and spectral range of 3.2-3.4 microns (μm). This scanned area is then converted into a moving image in real time such that the gas plumes are visible due their absorption of the IR light.

Imaging Performance:
- Field of view: 24 degrees x 18 degrees with 23 millimeter (mm) lens
- Focus near: <0.2 meters (m)
- Focusing: Automatic or Manual
- Thermal sensitivity: <15mK @ 30°C
- F-number: 1.5

Detector:
- Type: Focal Plane Array (FPA), Cooled InSb, 320 x 240 pixels
- Spectral range: 3.2-3.4 μm
- Time constant: 16 milli second (ms), user selectable

Power Input:
- Voltage: 7.6V
- Power consumption: <6 watts (W)

Physical Characteristics:
- Weight (with battery and lens): 2kg or less
- Color: Black
- Size: 254 x 132 x 145mm

Operation and Storage:
- Operating temperature range: -15°C to 50°C
- Storage temperature range: -40°C to 70°C
- Humidity: 20 to 80%

Vendor: FLIR Systems

Distributor Contact(s):
PRIME TOWER
287-288, Udyog Vihar Phase-II,
Gurgaon (Haryana) - 122015
Tel. 1: + 91-124-4111999
Tel. 2: + 91-124-6656999
e-mail: pci@prime-pci.com

Price: Typical range of $85,000-$115,000 (based on Natural Gas STAR discussions with vendors)

More Information: FLIR GF320 24° Fixed Lens
[http://www.flir.com/uploadedFiles/Thermography_APAC/Products/Product_Literture/FLIR%20GF320%20Infrared%20Camera%20Datasheet_au.pdf]

Calibrated Bags

Description: Vent-bagging uses bags of known volume (e.g., 1 m^3, 2 m^3), made from antistatic plastic with a neck shaped for easy sealing around the vent. Measurement is made by timing the bag expansion to full capacity. The temperature of the gas is measured to allow correction of volume to standard conditions. Additionally, gas composition is also measured to verify that the vented gas is actually all natural gas, since in some cases air may also be vented, resulting in a mixture of gas and air. A key advantage of the bag expansion technique over rotameters is that it does not exert any significant back pressure on the vented component. This eliminates any potential interference with the vented operation.

Performance: Measure leaks >> 17 m^3/hour

Accuracy: ± 10%

Detector: Stop watch to record time to fill bag, and monitor to measure the gas temperature

Power Source: None.

Operating Conditions: 0 to 50 °C

Vendor: Heath Consultants [http://www.heathus.com/_hc/index.cfm/products/emissions]

Distributor Contact:
Milton Heath III
9030 Monroe Road
Houston, TX 77061
(713) 844-1304
milt.heath3@heathus.com

Price: US$50 per bag

Thermal Mass Flow Meter

Description: QED's Thermal Mass Flow meter is a portable, battery operated device that allows the user to measure and record gas flows. Using an insertion-style probe design, the flow meter can measure flows directly through docking ports in headers 1" diameter and larger. The flow meter boasts automatic data logging capability and uses a high contrast, photo-emissive graphical LED display that is readable in sunlight.

Accuracy: ± 0.5% of Full Scale ± 1% of Reading

Turn-down: 100 to 1

Resolution: Up to 1,000 to 1

Repeatability: ± 0.2%

Gas Temperature: -40°F to 200°F (-40°C to 93°C)

Ambient Temperature: -4°F to 125°F (-20°C to 52°C)

Pressure Rating: 500 psig (34.5 bar)

Response Time: 1 second (each time constant)

Data Logging: Up to 3,800 data points

Flow: 0-200 scfm (0-340 m3/h) in 2" diameter wellhead

Distributor Contact(s):
QED Environmental Systems
2355 Bishop Circle West
Dexter, MI 48130
Phone: 800-810-9908
International: 734-995-2547
Fax: 734-995-1170

Price: Approx. US $5,500 (International prices may vary)

More Information: http://www.qedenv.com/flowmeter

VPAC II Valve Leak Monitor

Description: The VPAC II unit determines leakage data for different valves. The device finds where and at what rate the valve is leaking. If the valve properties are uploaded, the unit will perform the leak rate calculations automatically and store the reading. The unit can store readings for up to 100 valves at a time and the data can be transferred via a Bluetooth interface.

Size: 4.75 x 5.75 x 1.4

Weight: 1 lb

Power Source: 4 – AA batteries

Preamplifier Gain: 20dB

Total Gain: 21 to 75 dB

Noise: ≤ 14 dBAE /with sensor

Backlight: 4 blue LEDs with diffuser

Operating Temperature: -15 – 158 ° F

Storage Temperature: -40 – 185 ° F

VPAC II Valve Leak Monitor
[http://www.mistrasgroup.com/products/company/Publications/2$Acoustic_Emission/VPAC_II_IS_Product_Bulletin.pdf]