Title: Compressed Air Pneumatics for Methane Mitigation

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Abstract

Objectives/Scope: With the challenge of reaching carbon neutrality, the energy industry will need to be transformed. One of the key challenges facing the industry is eliminating Scope 1 emissions from the pneumatic devices used in wellpad automation and control. This practice accounts for roughly 45 million tons of CO2E/yr in the United States alone. Eliminating these emissions from existing brown-field sites is a significant challenge given that many of these well pads are in remote locations and suffer from a lack of reliable and sustainable electric power.

Methods, Procedures, Process: Compressed Air Pneumatics (CAP) is an innovative technology that replaces the methane emissions of pneumatic devices with clean, dry, compressed air. By employing highly reliable free-piston Stirling engine technology the end-user utilizes a small fraction of the normally vented methane to efficiently generate continuous and reliable electric power and clean, dry, compressed instrument air. CAP systems conserve valuable instrument gas and entirely eliminate methane venting at the well pad. They also eliminate the "wet-gas" issues associated with low-bleed pneumatic device contamination. In addition to compressed air for well pad automation, CAP technology is able to further provide additional utility grade electric power for additional well pad loads. Operators are able to further reduce their carbon footprint by harnessing the reject heat of the Stirling engine to keep process lines warm, further displacing the emissions of low-efficiency gas fired heaters. Another advantage that Stirling engine based CAP solutions gives upstream producers is the option to commission their instrument air system on tanked fuels like propane and readily switch over to instrument gas once wells are operational.

Results, Observations, Conclusions: A deployed CAP system on a multi-well pad in the Barnett Shale formation in Texas mitigated the vented emissions of 42,000 SCF of Methane in a 30-day period, which is equivalent to the removal of over 1,000 tCO2E on an annual basis, equivalent to removing 200 cars of the road. This same wellpad had zero downtime due to lack of pneumatic control or vent contamination across the same period. In addition to pneumatic control the CAP technology provided the wellpad prime power electricity, eliminating the need for large solar panels and cycling battery banks.

Novel/Additive Information: This technology when rightsized can maximize system value, driving down the cost of methane abatement below $2/tCO2e

Introduction:

Methane is second only to carbon dioxide (CO2) in contributing to global warming. Growing evidence indicates that the global warming factor of methane over CO2 is much larger than originally believed. We now know that atmospheric methane, while shorter lived than its CO2 counterpart, in its first 20 years of existence methane possesses eighty-four times the warming potential of CO2. We therefore need to aggressively address methane emissions as our primary strategy to achieve the IPCC recommended goal of containing global warming within 1.5°C (1). This mounting recognition is galvanizing action to contain methane emissions across the globe.

According to the International Energy Association (IEA), anthropogenic emissions of methane totaled more than 360 million metric tonnes (MMT) in 2020 (2). With rising global population and rising incomes this number can only increase without active mitigation. The challenge is, as the IEA points out, that the sources of methane are many and varied. Figure 1 shows the distribution of attributable methane sources.

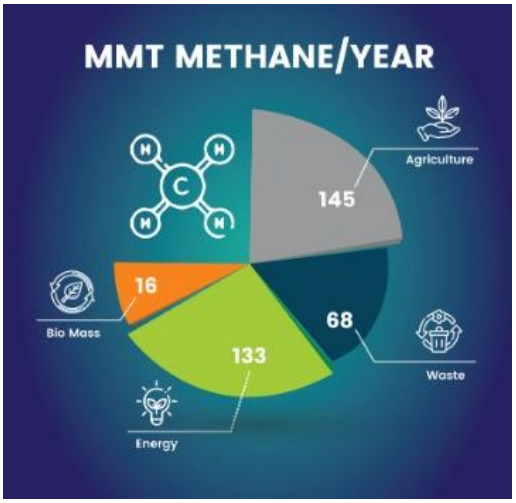

Figure 1. Global MMT of methane emitted per year. Adapted from IEA 2020 Methane Tracker

At 37% the energy industry constitutes a significant source of methane emissions.

This industry with its vast sprawling infrastructure covering more than 1.7 million oil and gas well sites and 2 million miles of pipe in North America alone, releases methane along any number of points of production, processing, and delivery. Figure 2 illustrates the natural gas infrastructure, along which at any point methane can and is released. Methane emissions occur in two major ways. The first, termed, “fugitive emissions,” occurs through random leaks due to equipment failure and human error. The other predominant avenue is through purposeful venting of gas, predominantly through pneumatic controllers (Figure 3) often used in remote, off-grid areas. Fugitive emissions require leak detection and repair (LDAR) technologies to detect, visualize, and pinpoint random leaks expected to arise from such massive infrastructure. Purposeful venting, however, is known, and requires new technologies to replace “last generation” methods for controlling well pad and pipeline pressure.

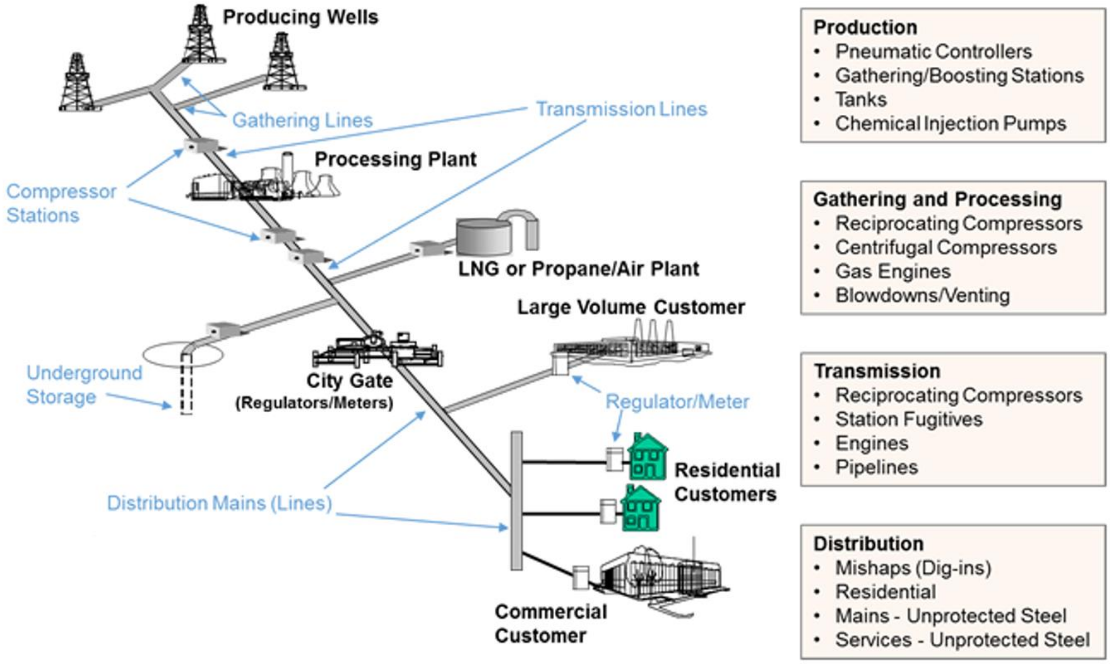

Figure 2. Illustration of natural gas infrastructure (Source: AGA and EPA) Pneumatic valves and controllers are used throughout the natural gas pipeline.

Natural gas driven pneumatic controllers are such last generation devices and utilized to control temperature, liquid levels, and pressure all along the production, processing, transmission, and storage pathway. According to the EPA (3), pneumatic controllers account for 25% of the 45 MMT of annual emissions attributable to the natural gas industry.

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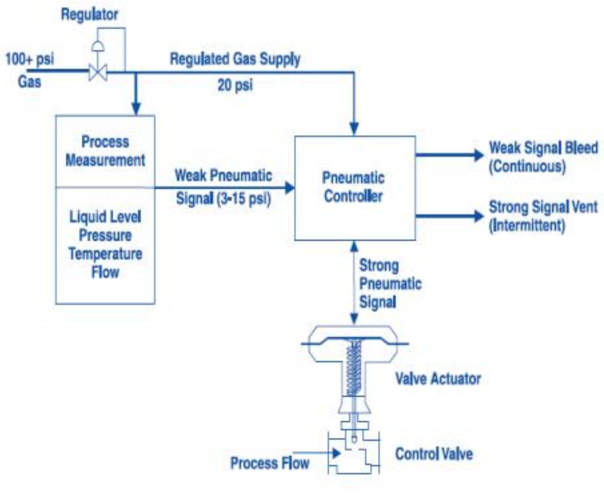

Figure 3. **Example pneumatic controller system** (Source: EPA). In a CAP technology modified system, instrument air is substituted for methane gas.

Well pads contain any number of controllers depending on the number of wells in operation. In 2006 the EPA estimated over 400,000 pneumatic controllers at production centers, 13,000 at processing stations, and 85,000 in use for transmission regulation (4). These numbers might be significantly higher today due to growth of the industry and our estimates of over 1 million pneumatic devices in use at well sites (Qnergy, internal data). Therefore, the replacement or technological supplementation of pneumatic controllers to prevent methane emissions is a significant and promising area for solution.

Statement of Theory and Definitions:

Sources of natural gas are often located in remote areas far from the electrical grid. Pneumatic controllers have historically been the technology of choice for providing power via natural gas pressure. Replacement of vented methane with a cost effective, robust, low to no maintenance remote power solution with clean, compressed instrument air is an ideal solution. To this end a free piston Stirling engine capable of utilizing raw, unprocessed methane for fuel was coupled to power a reliable, oil-less compressed air system to replace unprocessed natural gas (primarily methane) with dry instrument air.

Test conditions and challenges included ability of the free piston Stirling engine to function continually under remote, harsh environmental conditions, effectively utilize varying methane fuel conditions, including contaminants such as H_2S, CO_2, NO_x, H_2O, and to sufficiently power a compressed air system to provide required standard cubic feet (scf) of instrument air to completely replace and eliminate methane venting. A further challenge given remoteness of test sites was powering a web-based communications module for 24/7/365 monitoring, control, and adjustment of instrumentation.

Key measurement goals included system performance, degree of methane abatement using instrument air consumption as proxy, and overall measurable impact on greenhouse gas emissions.

Description and Application of Equipment and Processes

Figure 4 shows an in-field installation of a CAP (Compressed Air Pneumatics) system. Each system is comprised of a dual redundant compressed air system electrically powered by a Free Piston Stirling 5650 Watt generation unit. Key operating characteristics of the compressed air system is shown below in Table 1. Housing of each generator unit comprises the Stirling engine, electrical and onboard controls, fuel, cooling, and communication systems. Example aspects of the configurable system are shown in Table 2.

Figure 4. Field implementation of the CAPtechnology. On left is reach-in housing for compressed air storage. In middle is the 5650 Watt Stirling generator unit. On right is connection into a pneumatic controller structure

Instrument Air System Specifications

	Standard	High pressure	High Temperature
Compressor	Duplex oil-free	Duplex oil-free	Duplex oil cooled
Compressor CFM	15.2 @ 100 psi	12.5 @ 145 psi	11 @ 150 psi
Maximum pressure	116 psi	145 psi	150 psi

Maximum temperature	40C	40C	40C
Dry tank capacity	80 gal/303lt	80 gal/303lt	132 gal/500lt
Air Dryer	Dessicant dryer – minimum 25C dew point suppression		
Air meter	Thermal mass flow sensor		
Maintenance interval	Once per year		
Emergency power	Manual transfer switch		

Table 1. Various operational specifications for configured CAP systems.

Example Stirling generator system operational data

Configuration	Output	Phase angle	Connection	Max power @ 85F | 120F
120/240 VAC Split phase	120 Vac 60 Hz	A: 0° B 180°	3 wire: L1, L2 & Common/Neut.	5.65 kW | 5.1 kW
Fuel operational specifications				
Fuel consumption		Natural gas (min/max)		1,433/3,964 ft^3/day
Fuel pressure range		Natural gas		3-50 PSI
Wobbe index		Min/Max		832 BTU/ft^3/2,163/ft^3
Caloric index		Min/Max		751 BTU/ft^3 / 3,382 BTU/ft3
Emissions				
NOx @ 5% O2		30.0 ppm		66 mg/kWh
CO @ 5%)2		9.0 ppm		12 mg/kWh
VOC		--		Negligible, Lean Combustion
HRU Operational Specifications				
Thermal Heat Rejection		Max Available		x2.5-3.5 of Electrical Power Output
Environmental Condition Specifications				
Sound		Max dBA		<75 dBA @ 1m
Ambient Temp Continuous Operation		Min / Max		-13°F / 122°F (configurable to -40°F)
Ambient Temperature Rated (Startup)		Min / Max		5F° / 122°F (configurable to -40°F)
Altitude		Derate		5% per 1,000 ft above 5,000 ft

Table 2. Example Stirling Generator specifications used for implementations.

Power generation for the system is driven by a methane burning, externally heated Stirling engine (6) housed within the middle cabinet seen above. The engine operates using the Stirling cycle, which can theoretically reach the maximal thermal efficiency known as Carnot efficiency. The efficiency achieved in practice is less due to pressure and thermal losses in the engine. The Stirling cycle operates on a closed regenerative thermodynamic cycle, with cyclic compression and expansion of a working fluid at different temperature and pressure levels. Heat is transferred to the engine's working gas through the walls of the primary heater. The engine is a completely closed system. The working gas (typically air or an inert gas such as helium or hydrogen) forces the pistons in the engine to move, compressing and expanding the working fluid, thus producing mechanical energy that can be used to drive a frictionless, linear electric generator and produce electricity.

The Stirling generator shown is a sealed external combustion system comprised of a linear free piston frictionless Stirling engine that for the majority of these field implementations was configured to deliver 5.65 kW of electrical energy at maximum output with an additional stream of capturable waste heat. The engine is contactless, i.e., no contact between moving parts, fully sealed and requires no lubrication or oil changes. At maximum continuous output the unit consumes 3,964 scfu of natural gas (methane) per day with 14% electrical efficiency. The unit powers a 5 hp dual redundant oil-less air compressor system.

Waste heat recovery from standard installs increase the fuel efficiency up to an average of 58% efficiency (with up to 93% possible) with optional glycol heat trace loop for installations in areas with severe winter conditions.

Figure 5 shows a Stirling engine and a cutaway diagram.

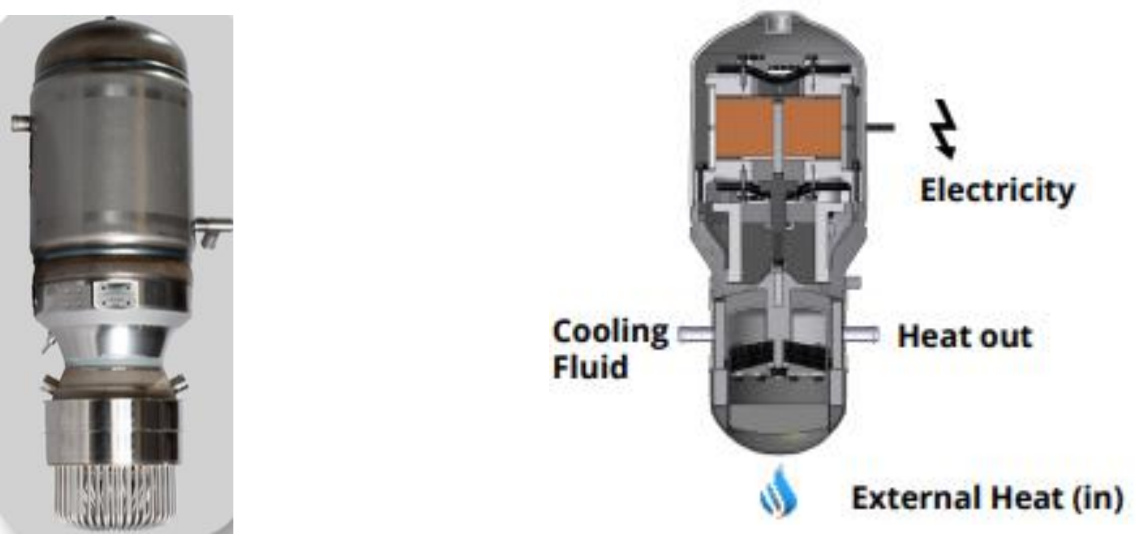

Figure 5. Left is a free piston Stirling engine. Each engine is approximately 242 pounds in weight and 33 x 14.5 inches in dimension. On right is a cutaway diagram of the engine. Field methane is used as external heat source. Free piston system generates electrical power via electronically controlled, spring flexure mediated amplitude of oscillation within a solenoid (orange).

Presentation of Data and Results:

To date, more than 900 systems have been deployed throughout North and South America, with emphasis in the Marcellus and Barnett shale basins, but ranging from Alaska, Alberta (Canada), and into South America. Systems have accumulated over > 10M hours of runtime with roughly a continuous 1,800 KW of power generated utilizing well pad gas. Installations focused primarily on brown field, off-grid well pads utilizing low bleed and intermittent pneumatic controllers. Individual machines (data not shown) have surpassed 40,000 hours of continuous operation with zero maintenance.

Utilizing IOT and remote monitoring technologies onboard software with TCP/IP cloud-based access, instrument and system performance were monitored and measured in near real time. An example view over a 7 day trace period of engine performance is shown below in Figure 6.

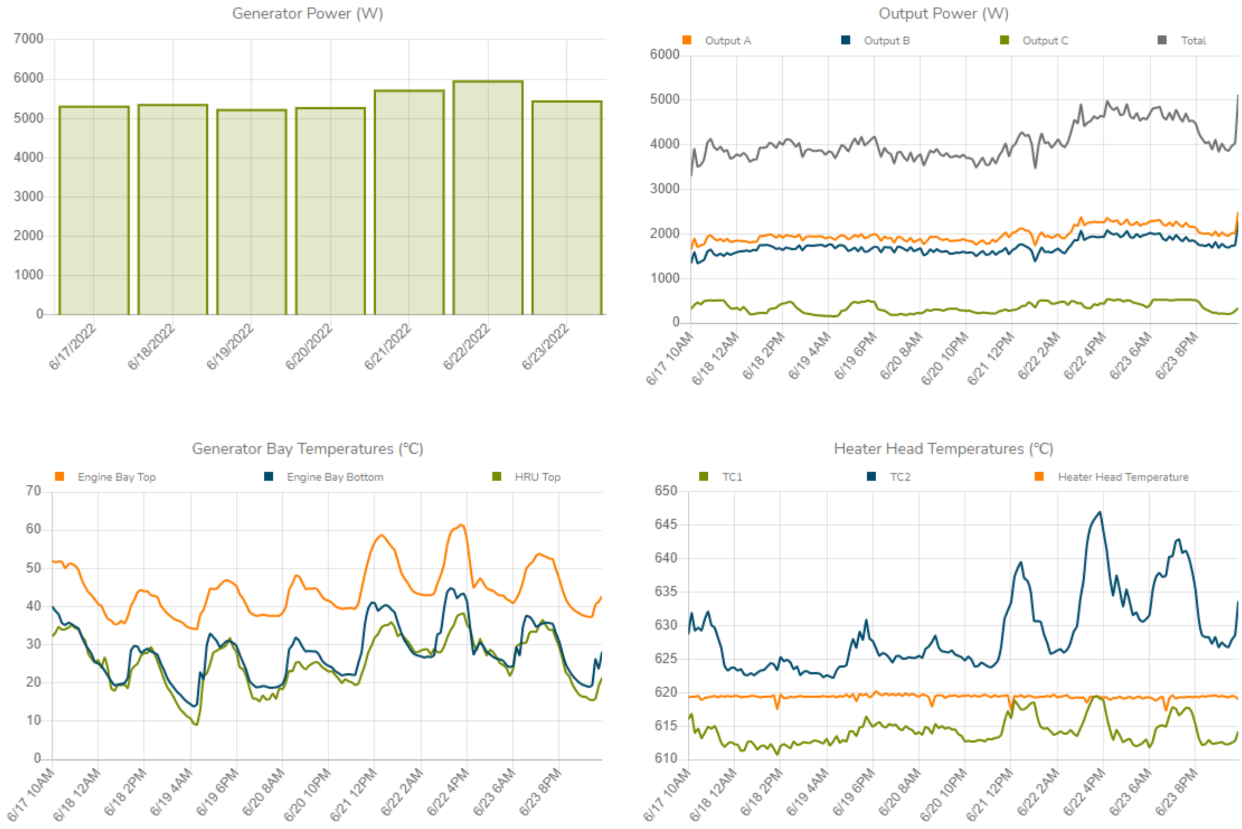

Figure 6. Example continuous 7 day trace in 14 hour intervals of engine performance located in the Marcellus Shale region. Overall generator power is shown in upper left. Various power outputs shown in upper right. Monitoring of generator bay temperatures is shown lower left. Generator bay temperatures (lower left) are monitored for heat control across the engine and lower right shows maintained heater head temperature and output from two variably placed thermocouples.

Data from the same system showing variable measured gas pressure and maintained air pressure and flow rates are shown in Figure 7.

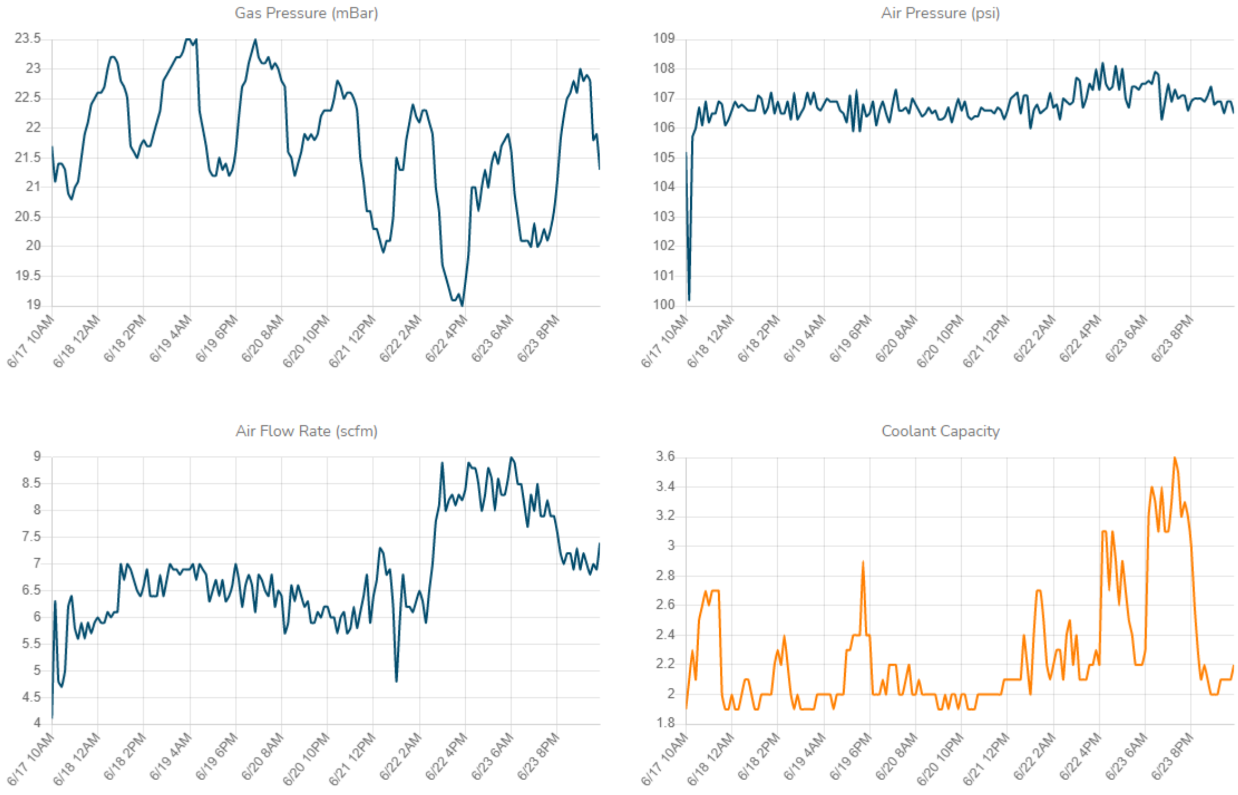

Figure 7. Sample 7 day trace from the same time period shown in Figure 6. Variable inlet gas pressure is shown in upper left. Maintained instrument air pressure in compressor system is shown upper right. Measured air flow rate (lower left) shows callable air to replace vented methane. Lower right shows utilization of coolant capacity.

Constant monitoring of air pressure and air flow rate are suitable indirect proxies for monitoring wellpad instrument leaks. Larger than expected airflow with concomitant drops in air pressure can be used to detect the presence of instrument leaks at sites. An example is shown in Figure 8.

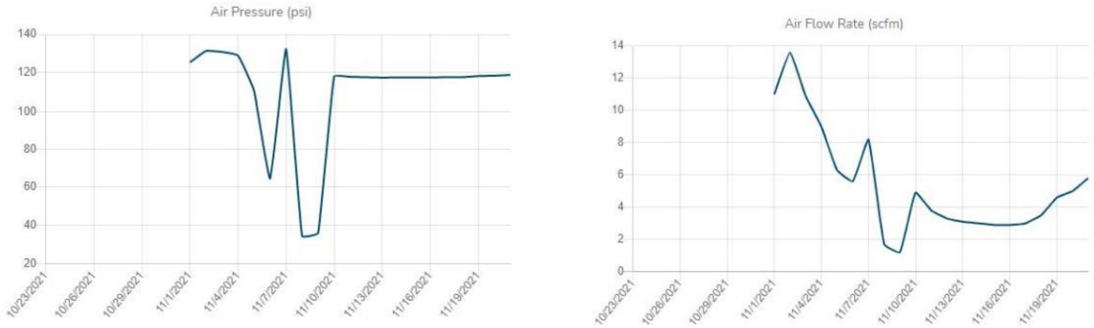

Figure 8. Example 1 month trace from an installed CAP system. Air pressure is maintained at targeted 120 PSI. Sudden drops in pressure accompanied by spikes in air flow detected by onboard sensors indicates presence of methane leak. Upon leak repair by customer, air pressure and flow resumed steady state rates of measurement.

Case study of abated emissions

Table 3 shows measured and calculated avoided emissions of vented fuel gas. In the case presented of a system utilized at full potential, 2.7 million scf of instrument air replaced vented methane over a year of operation. Calculated results indicate 1,500 CO2 equivalents (tCO2e) per year abated from this site. Other sites depending on processed volume and wellpad configuration and equipment status will vary.

Parameter	Value	Units
I/A supply (U.S. units)	5	Scfm
I/A consumption	2,628,000	Scf/yr
Gas equivalency ratio	1.2977	
% CH4	94%	
Density of methane	0.01889	Kg/scf
Global warming potential	25	tCO2e/CH4
Vented instrument gas	1,514	tCO2e/yr
Annual gas consumed	355	MCF
Operating hours	8,760	Hours
PowerGen electricity emission factor	1.10	$tCO2e/MWh_e$
Emissions air compression	13	tCO2e
Net annual GHG abatement	**1,500**	tCO2e

Table 3. Key performance characteristics of a maximally utilized CAP system.

Generalized use of a global warming potential factor of 25 of CH4 over CO2 utilizes the 100-year horizon. More recent data indicating a warming potential of 84 for the first 20-year horizon for emitted methane would give a figure of 5,073 tCO2e abated at this particular site regulated by a CAP technology system. Independent calculations by a CAP client yield similar abatement results. See news release ‘TotalEnergies and Qnergy deploy an innovative technology to reduce methane emissions on the Barnett field’ (7).

Emissions analysis

Table 4 shows average system emission results.

	Units (gr/kWh)	**PowerGen 5650 (CAP3)**	**EPA regulation 1039**	**Ratio**
Exhaust air	NOx	0.066	7.5	99.1%
	CO	0.012	8	99.9%
	PM	0	0.4	100%

Table 4. CAP system emissions from Stirling generator. Measurement and comparison of exhaust air against EPA 2014 regulations for nonroad compression ignition engines (8).

Conclusions

Methane abatement is now the number one priority in fighting global climate change. Given its 20-year 84X over CO2 warming potential, 25X over 100 years, methane, poses the greatest threat to not achieving the IPCC's recommended goal of 1.5°C temperature rise containment. Solutions that can replace passive methane venting pneumatic valves, whether through electrification via the grid or remote power provided by systems like the CAP system are required to replace the estimated greater than 1.5 million such devices now in use throughout the natural gas supply chain.

The 5650 Watt CAP system and other configurations (not shown) have, over 900 installations, shown to be a viable solution for the replacement of low bleed and intermittent pneumatic valves in brown fields. Not discussed is use of Qnergy system as backup to grid connected solutions in case of grid power outages, though this too has been proven.

Our results show that a single site operating at full capacity with our system can effectively abate up to 1,500 tCO2e (25X warming potential factor). Thus a powerful GHG gas is effectively abated and the economic value of otherwise vented methane is captured.

In response to the rising environmental challenge of methane release from distributed sources and devices, particularly in the energy industry, in 2021 the EPA issued a new call for a proposed best system of emission reductions (BSER) (9).

Now in deliberation, the Proposed Rule is intended to strengthen the Clean Air Act to encompass all new exploration and production configurations as well as retrofit and remediation of existing sites. Specifically, the Proposed Rule is intended to strengthen Section 111(a)1 of the Clean Air Act which requires the EPA to *"…impose performance standards that reflect the degree of emission limitation achievable through the application of the best system of emission reduction which (taking into account the cost of achieving such reduction and any non-air quality health and environmental impact and energy requirement)…"* This is also intended to include secondary impacts such as formaldehyde release along with other volatile organic compounds (VOCs) common with diesel and internal combustion engines.

The solution described herein also addresses the EPA concern of cost of achievement as internal calculations show effective methane abatement at <$2/tCO2e (not shown). Successful promulgation of the BSER would eliminate up to 95% of emissions from pneumatic controllers in the production, transmission, and storage segments of the natural gas industry and provide a strong economic return to the energy industry via the capture of up to 13 MMT of methane per year.

Our results show that this desired result is already achievable today.

- **Acknowledgments.**

Authors are grateful for support of colleagues and engineers who contributed to the data used in this paper.

- **Nomenclature**

CAP	Compressed Air Pneumatics
CH4	Methane
CO	Carbon Monoxide
CO2	Carbon dioxide
GHG	Green House Gas
I/A	Instrument Air
MMT	Million Metric Tonnes
Scfm	Standard cubic feet per minute
tCO2e	Tonnes of CO2 equivalent
VOC	Volatile Organic Compounds

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