DEVELOPING MEASUREMENTS AND METHODS FOR EFFECTIVE ABATEMENT OF METHANE ATMOSPHERIC EMISSIONS

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Introduction

Methane is an extremely useful molecule. It is a major source of the world's energy, with over 4 billion cubic meters (Bcm) providing 24% of the world's power generation needs in 2020 (1). It is a natural byproduct of biodegradation processes, whether through fossils, landfills, food waste, farm and crop waste, or wastewater. The relationship between methane generating soil bacteria and plant biology is only recently begun to be elucidated (2). Methane however, is also a powerful greenhouse gas (GHG). Studies now indicate that in its first 20 years of life as an emitted gas, it has 84 times the warming potential of carbon dioxide (CO2) (3). According to the IEA, the world emits more than 360 million metric tonnes (MMT) of methane each year through anthropogenic activities, i.e., food and energy production, the activities of providing energy and food for a growing world (4).

Within the energy industry, and in particular, the natural gas industry, a significant source of methane emittance is the millions of pneumatic devices being used along the natural gas supply chain. These devices, when powered using natural gas, constitute one of the largest sources of methane emissions in the natural gas value chain. Thus, the term 'bleeding' pneumatic devices. Bleeding pneumatic devices use natural gas to activate valves and pumps, mainly for process control and chemical injection. Familiar examples are pneumatically actuated valves, pressure, and level controllers. These devices vent spent gas, i.e. methane, directly into the air. The International Energy Agency (IEA) estimated that emissions from bleeding pneumatic devices exceed 11,000 kt of methane globally. This represents approximately 15% of the total global emissions of methane from oil and gas operations. It is comparable to approximately 300 million tonnes of CO2 equivalent (MTCO2e), which represents the emissions of nearly 60 million cars; undoubtedly a substantial number. Therefore, although each pneumatic device is a relatively small emitter, collectively they comprise a major source of methane emissions. Figure 1 shows a schema of the pneumatic controller challenge for the oil and gas industry.

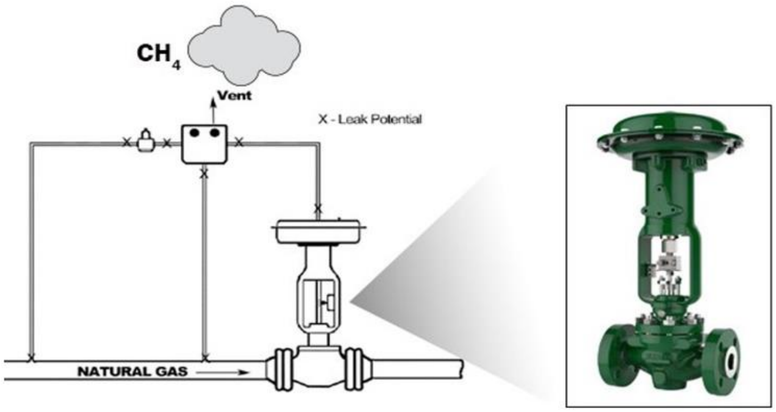


Figure 1. Depiction of the pneumatic controller challenge at oil and gas well pads. Historically, purposeful, passive venting of methane as the source of power for pneumatic valves was the method of choice for wells far from the electrical power grid. Left is system schema; right is example of a pneumatic valve. Substituting natural gas

with input dry instrument air via compressed air system eliminates methane venting while maintaining proper pipeline flow, pressure, and liquid levels.

Measurement & Mitigation

The requirement to eliminate emissions presents a technical challenge: how can we eliminate a large number of very small emitters that collectively accumulate to a substantial contribution to global greenhouse gas (GHG) emissions? The obvious plug and play solution is to replace natural gas as a source of power with compressed air. It is a simple and established construct which was proven to be the lowest cost and easiest to install. However, nearly half the sites in the US, a larger percentage in Canada, and an additional double-digit percentage globally, are not connected to a stable electrical grid. The reason that bleeding pneumatic devices are so ubiquitous is because most gas fields do not have a stable electrical grid, hence traditionally the choice has been to use pneumatic pressure as a source of power. Taking this into account, it is no surprise that the critical component that is needed to achieve net-zero at any off-grid site is grid-quality electricity.

In addition, the massive and sprawling infrastructure and many operators needed to deliver natural gas from field to final use lends itself to leaks due to random equipment failure and human error, so called 'fugitive methane.' In the United States alone there is an estimated 1 million oil and gas wells, and across North America, more than 2 million miles of transport pipe as well as thousands of boosting stations, processing, storage, and transport facilities. In totol, the IEA estimates that pneumatic control venting and fugitive methane contribute 45 MMT of methane release per year.

To mitigate what is odorless and colorless, one first needs to be able to detect and measure its presence to successfully know where and how to capture, and productively use methane. For fugitive methane, a variety of new technologies have arisen in recent years offering various levels of detection, ranging from interferometer carrying microsatellites, to spectrometer carrying airplanes and drones, to ground mounted optical gas imaging cameras and sensors of at-risk sites, and handheld flame ionization detectors for line and equipment inspections. Singly these techniques can detect and quantify local concentrations (at corresponding resolutions) from a leak source but not emission rates. Combining these technologies together along with time series analyses and imaging/quantitation software, leaks can be precisely pinpointed and repaired. Collectively these activities are referred to as LDAR for Leak Detection and Repair and are quickly becoming standardized within the natural gas and energy industry.

With respect to intended methane venting via pneumatic controllers the challenge has been as noted above, to deliver power to exploration and production locations far off the power grid and often in remote, rugged conditions. The approach has been and continues to be, replacing older high methane bleed devices with low bleed, and eventually no bleed solutions. In some cases, with high volume gas emittance at oil, not gas sites, flaring is pursued to destroy the methane as separating the gas from oil, especially in faraway, stranded fields is deemed more cost effective than trying to capture and transport the gas. These leading strategies are summarized in Table 1.

Strategy	**High bleed to Low**	**Electrification**	**Instrument air**	**Collection & destruction; flaring**
Flow (ft^3/min)	< 0.3	0.3-1	1-20	>20
Pareto (%)	23%	26%	48%	3%
Assets	Brownfield conversions	Single wells; typically green fields	Brown and green fields	Super pads; >12 wells & large facilities

Table 1. Predominant strategies for methane abatement. Pareto analysis of opportunity for each type of solution derives predominantly from Reference 4.

In approximately a quarter of the cases, companies are switching from high bleed to low bleed. This option is mainly relevant to legacy gas fields referred to as brownfields. One of the disadvantages of the high to low bleed approach is that it does not meet the zero emission criteria, and, secondly, it requires the replacement of many small emitters. Another strategy gaining momentum and applicable to approximately another quarter of the cases, especially in new gas fields, or greenfields, is electrification. The advantages are that it is a non-venting solution that consumes relatively low power and optimizes the amount of chemicals used in injection pumps. The downsides are the cost and the fact that it is not a plug and play type solution. Safety must also be considered when operating an electrical actuator. If the electrical actuator loses power, the valve in the actuator may default to an open state, which may become a safety hazard. Even grid connected electrical actuators require backup generator power to prevent this type of failure.

Therefore, several challenges remain to providing remote power reliably, effectively, and economically.

On the low power side, operators find that demand for high airflow and excess power relegate some of the familiar technologies uneconomical. These technologies include thermoelectric generators (TEG) and fuel cells in combination with a battery bank and off-grid photovoltaics. TEGs are relatively reliable but are low-power and inefficient (leading to high emissions). Fuel cells are efficient but require tanked fuel and have a short operational life. Both become prohibitively expensive when local power requirements require more than 1 kW. On the other end of the spectrum are microturbines, which are both efficient and reliable, but are oversized for most well pad applications and carry high capital costs, high maintenance costs, and high emissions. Operators have also historically experimented with conventional gas generators with internal combustion engines (ICE). These configurations lead to extensive maintenance visits for oil changes that contribute to the high total cost of ownership in addition to high NOx and CO emissions that pose environmental challenges.

What has emerged from this need for a low cost, environmentally friendly, robust solution for remote power is the resurrection and innovation of a more than 200-year-old technology, the Stirling engine (5). The novel engine operates on a simple principle: the expansion of gas when heated, followed by the compression of the gas when cooled. The Stirling engine contains a fixed amount of inert gas (typically Helium) that is transferred back and forth between a cold end and a hot end. The displacer piston moves the gas between the two ends and the power piston changes the internal volume as the gas expands and contracts. Once a magnet is attached to the moving power piston, one can create electricity (Figure 2).

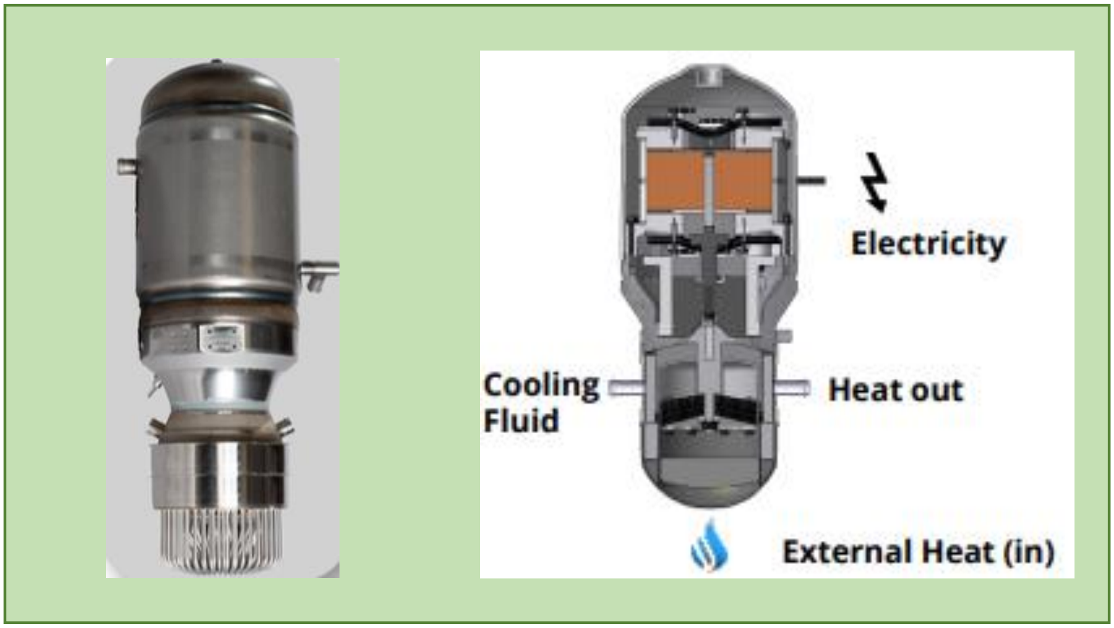


Figure 2. Free piston Stirling engine. On left is example of a free piston Stirling engine (Qnergy). On right is a cutaway diagram of the engine. Electronically controlled variable amplitude oscillation of the power piston within the solenoid (orange) generates electricity. As the engine is typically housed within a larger enclosure, useful heat is capturable.

A Stirling-based generator, using unprocessed wellhead gas, generates sufficient utility-grade power to drive a clean instrument air compressor system on-site. It can also produce useful and capturable heat. The Free Piston Stirling solution is emerging as the lowest total cost of ownership (TCO) in the industry. From the environmental performance standpoint, Stirling engines use no oil or lubricants and emits less than 1% of the NOx and CO of ICEs. A Stirling engine driven compressed air system includes a duplex configuration of low maintenance, robust compressors; an integrated air dryer; an HMI for local data review and control; gas flow measurement for mitigation reporting and carbon credit generation; a gas conditioning unit (GCU) to protect against liquids in the gas inlet, as well as an air receiver tank for air storage. Deployment of a fully functional skid is brought to the site and installed in just a few hours. Schema for a compressed air solution is shown in Figure 3.

The Stirling engine utilizes a fraction of the distributed methane that would have normally been venetd to the environmemt and functions as an energy and power platform to drive useful instrumentation, which in this case is air compressors to replace vented methane, and sensors for measuring gas displacement and measurement of actual methane abatement.

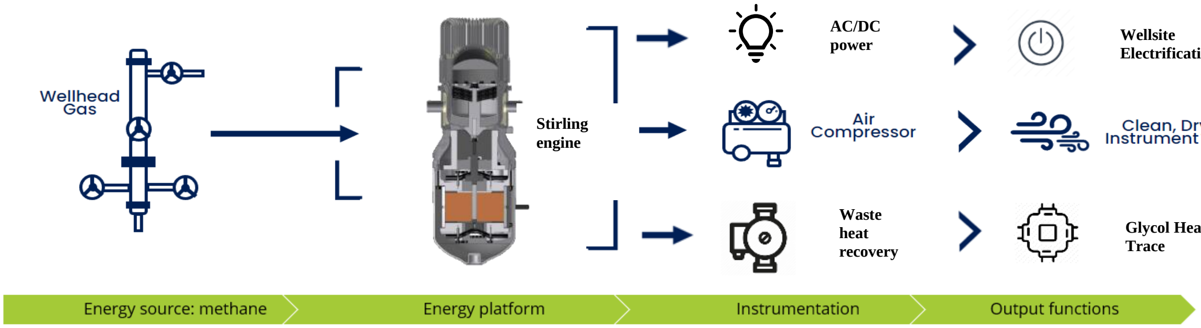


Figure 3. Schematic of a compressed air system at well pad. Compressed air solution system for wellhead gas pneumatic controller replacement. A small amount of well gas is diverted to run the Free Piston Stirling engine. The engine powers a connected air compressor system typically up to 5-10 HP or 3-7 kW to replace vented methane with clean dry instrument air. Effective electrification of remote well pads or sites is accomplished. Waste heat can be recovered for heating during cold climate conditions. The Stirling engine functions as a remote energy platform to convert methane into useful work. Compressed air solutions have been proven to save kilotons per year of methane venting per well pad.

An example field implementation is shown in Figure 4.

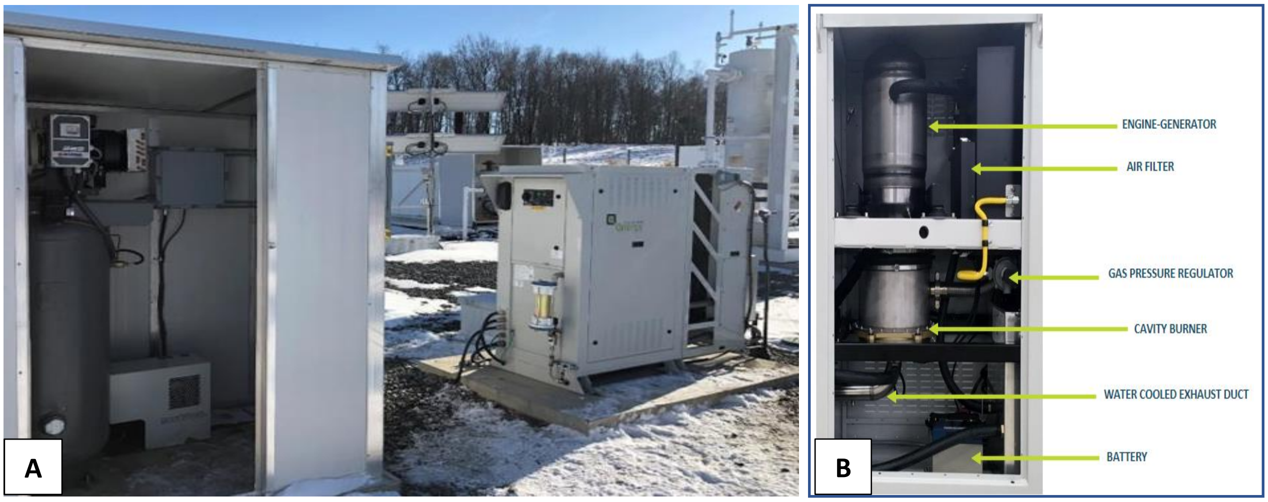
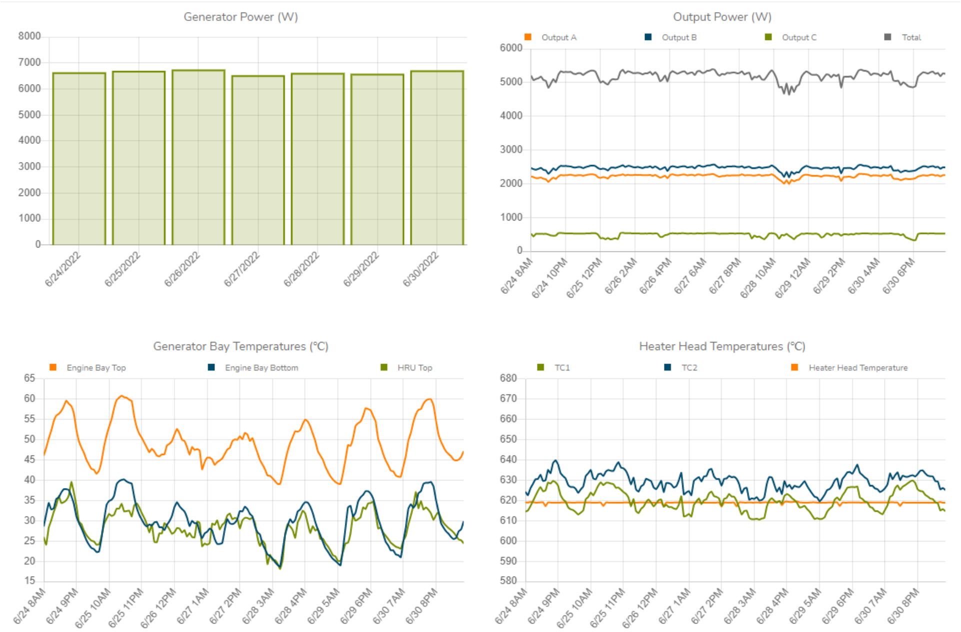


Figure 4. In field implementation of a Stirling engine driven air compressor system at a well site. (A) On left is cabinet housing compressor system with electrical power supplied by a cabinet (right) housing a Free Piston Stirling engine system connected to local natural gas. (B) shows the engine-generator internal housing.

Important to demonstrate as a solution is the measurement of actual methane abatement. On board instruments and sensors provide web-based access to real time flow data. Data is provided via standard TCP/IP protocol for cloud-based access and onboard modem powered by the unit itself for remote access and monitoring both for performance data as well as near real time system adjustments and troubleshooting.



Figures 5 shows example Stirling engine cabinet monitoring data and Figure 6 depicts gas and compressed airflow characteristics.

Figure 5. Stirling engine performance characteristics. Selected 7-day data set traces showing power generated (upper left), power distribution (upper right), generator bay temperatures (lower left; See Figure 3B), HRU is heat recovery unit, and heater head temperatures maintained around target 600C with additional thermocouple (TC) data.

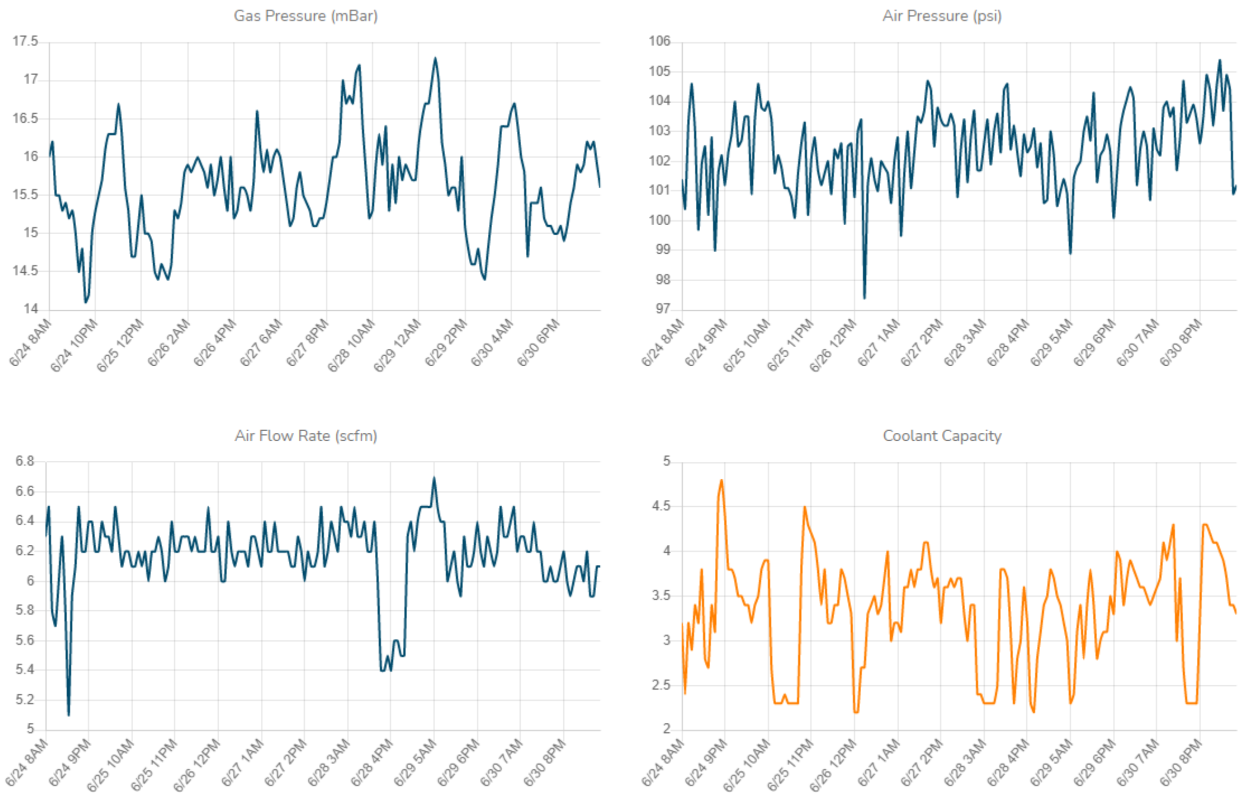


Figure 6. 7 day trace data of incoming gas pressure (upper left), maintained compressor air pressure at target 100 psi range (upper right), actual instrument air flow rate (lower left), and maintenance of coolant capacity (lower right). Monitoring and measuring the standard cubic feet per minute (scfm) flow of instrument air is a direct proxy for replacement of vented methane given certain approximations.

The ability to monitor Air Flow Rate along with both onboard instrument readings and manual calculations, e.g., accounting for differences in density of dry instrument air vs. “wet” natural gas and variable methane percentages, enables calculation of abated methane. Example of this approach is shown in Table 2.

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 2. Calculations of net methane abatement. Table 2 shows that Instrument Air (I/A) is suppled at 5 scfm 24/7/365 (maximum steady state system throughput) and accounting for density dry air and methane, and percentage of methane percentage per stream of abated natural gas emissions (for each particular wellsite and gas quality) and subtracting for methane consumed by the Stirling engine, that daily and annual net greenhouse gas (GHG) can be calculated for the purposes of scope emissions auditing as well as registration for carbon credits.

Table 2 shows that replacing vented methane with instrument air results in significant greenhouse gas (GHG) abatement. Results will vary depending on whether the pneumatic devices being modified are high or low bleed, and on volume/productivity of the well pad. However, recent announced data shows that such implementation and calculation as just described, can result in over 7,000 tons of direct methane abatement per year over just a few hundred such converted pneumatic devices.

In addition, monitoring of Air Flow Rate is an excellent way (in addition to the direct monitoring and visualization techniques described above) to monitor for upstream leaks in installed well pads. Figure 7 shows a particular example.

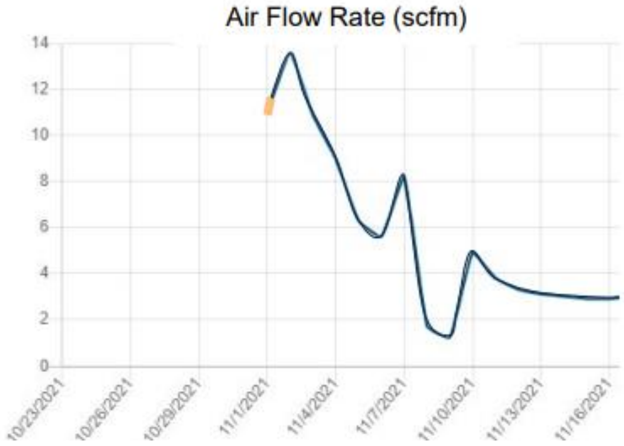


Figure 7. Drop in Air Flow Rate indicates possible presence of system leak. Drop in instrument air flow rate indicates the possibility of natural gas leak upstream of pneumatic controller. As less natural gas passes through the pneumatic controller path, less instrument air (relative to established baseline rate) is required for device regulation, indicating a drop in flow upstream to the device. In this particular case, the well pad operator did in fact investigate, and remediate the upstream leak, resulting in a significant rise and resumption of normal instrument air flow rate (not shown).

Ongoing and increasing deployment of instrumentation, sensors, and meters, along with cloud based analytics enable increasingly intelligent systems that enhance overall system performance for economic return to well pad operator and owner, as well as optimize for methane emittance and GHG management, as well as to calculate and capture additional economic returns via carbon credits or other such schema. Use of the robust Stirling engine, capable of using heat from any gaseous energy source such as methane creates an energy platform capable of delivering remote power to wherever methane (or propane and the like) occurs to provide local, *in situ* energy, power, sensing, monitoring, and useful work.

Conclusions:

The free piston Stirling engine is proving to be a very useful and powerful workhorse in the fight to abate methane. As an external combustion engine with no rotary movement and no lubrication, it has proven superior to internal combustion engines, diesel, or microturbines, both in terms of length of performance, conditions for performance, and total cost of ownership, or importantly, the total cost to abate methane and CO2e.

When combined with another technology such as compressed air, a useful solution platform is created, one that can be used in the over half a million estimated brown field well pads known to be in existence in North America to abate 9-10 estimated million metric tonnes of methane per year (the 20% of methane of the total 45 MMT attributable to the natural gas industry annually due to pneumatic devices). It is important to note in this context that methane is not just simply a GHG (84X more powerful in warming potential than CO2 in its first 20 years of existence), but also an extremely useful fuel and source of economic value. Being able to abate close to 9 MMT of methane also results in significant recapture of lost economic value. For this reason, these small, distributable platforms that capture and convert methane into useful work is a highly promising solution to both mitigating GHG and simultaneously creating immediate economic value and return.

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