Qnergy

Qnergy Zero Methane Slip

Abstract

Methane is a valuable fuel but also a potent greenhouse gas (GHG) with 84X the global warming potential of CO_2 over its first 20 years, when allowed to escape into the atmosphere. Productive utilization of methane is a global challenge given the many sources of methane emittance, from upstream wellpads in the energy industry, to farms, wastewater, municipal waste, and landfills, i.e., wherever organic waste accumulates, methane is generated. These diverse sources all require power to capture, store, and/or convert this valuable resource into useful energy. Interestingly the raw gas itself can provide the required onsite, local fuel for power, provided fluctuations in flow, purity, and the challenge of corrosive contaminants can be overcome.

Conventional generators based on internal combustion power cycles perform poorly in this type of environment, requiring frequent normal operating maintenance, suffering ongoing corrosion due to sulfuric impurities present in raw gas leading to high ongoing operating costs, frequent engine replacement, and incomplete methane combustion known or methane slip. In this paper, Qnergy describes environmental performance measurements of the unique generator built using an external combustion, metal-fiber matrix heat source for a proprietary power cycle, which has been deployed successfully in diverse and demanding environmental conditions.

Qnergy's PowerGen is based on an external combustion engine, with a clean-burning external combustor designed to work with any gaseous fuel, using power electronics and software to control for variable raw source fuel feedstocks. The tested PowerGen SN833 was tested with a natural gas fuel flow rate of 3500g/hr at a rated power of 5.65kW exported. This represents a fuel input flow of ~>600 g/kW.hr of methane at >95% methane purity natural gas, with a measured CxHy hydrocarbon export of only <1.5mg/kW.hr. Combustion resulted in >99.998% (~100%) methane destruction efficiency with PM, CO, and NOx emissions at 0.11, 0.30, and 1.1 g/kW.hr, levels respectively, levels that meet or exceed Environmental Protection Agency (EPA) proposed criteria for a Best System for Emissions Reduction (BSER)[1].

These results demonstrate that environmentally friendly utility-grade electrical power can be sourced from methane generation sites using combustion in a generator with zero methane slip.

> **"Qnergy releases new environmental performance data on its leading clean energy generator solution"**
>
> The results demonstrate complete methane destruction and orders of magnitude better environmental performance than EPA standards...
>
> **'Zero Slip: The superior environmental performance of Qnergy's PowerGen, a free piston Stirling engine.'**

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[1] Federal Register: Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review. federalregister.gov/documents/2022/12/06/2022-24675/standards-of-performance-for-new-reconstructed-and-modified-sources-and-emissions-guidelines-for

Keywords

Generator, methane, zero emissions, external combustion, metal fiber burner, renewable electricity, energy, GHG

Key results

A novel 5.6 kW generator uses a combustion system capable of cleanly burning methane, propane, or mixed gaseous fuel, and demonstrates superior environmental performance.	Independent third-party testing using EPA guidelines show zero methane slippage with CO, PM, VOC, others at levels 4-27X lower than EPA requirements.	A fuel flexible generator for reliable remote power exceeding EPA emissions standards by an order of magnitude and meeting the definition for Best System for Emissions Reduction (BSER) is now proven and commercially available.

Introduction

Methane is a valuable fuel as the key component of natural gas and in renewable energy sources, such as landfill and biogas. However, it is also increasingly recognized as a potent greenhouse gas (GHG) when allowed to vent or leak into the environment. Therefore, capturing and productively using these distributed sources of methane, in all its various source forms, accomplishes multiple goods; as an economic value capture for methane owners, as part of a larger strategy for energy resiliency and transition, and in abatement of GHG emissions. According to the International Energy Agency's (IEA) 2022 analysis of methane emissions, the Energy industry emits close to 135,000 kT of methane per year, with agriculture and waste (landfills) emitting 141,000 kT and 73,000 kT, respectively.[2] Capturing and converting 349 million tonnes (MT) of annual methane is a major negative emissions technology opportunity, taking a GHG and converting it into useful economic activity.

However, many of these emitting sites are small, remote, and perhaps off-grid. Many are of sufficiently small size that traditional collection, purification, and injection of gas into existing natural gas infrastructure is impractical. Indeed, U.S. Census, USDA, and EPA data show that the majority of methane emitters, i.e., farms, landfills, wastewater treatment facilities, etc., are small and widely distributed (data not shown). To address this distributed methane challenge, a new kind of small footprint, distributed solution is required to capture and convert venting methane into useful local power.

Well pads in the natural gas industry are an example of the need for reliable remote power generation from a raw methane source. In 2020 U.S. Energy Information Administration (EIA) report indicated >483,000 active natural gas wells in the U.S.[3] Due to horizontal drilling techniques, the number of well sites or well pads with multiple well holes

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[2] IEA Methane Tracker 2022: iea.org/data-and-statistics/data-tools/methane-tracker#iea-total-sources

[3] U.S. Energy Information Administration, Natural Gas: eia.gov/dnav/ng/ng_prod_wells_s1_a.htm

have proliferated. This is important as this increases the degree of required piping, flow, temperature, and pressure regulation at each well pad, and carrying concomitant risk of unwanted methane emissions. A 2018 study by Alvarez et al., indicated that close to 85,000 sites examined contained nearly 285,000 wells ranging from 2 to 7 wells per site.[4]

While precise numbers on the percentage of sites not tied to the electrical grid, i.e., "off-grid" is not known, both on and off-grid well sites make extensive use of pneumatic controllers for regulating temperature and pressure of fluid flow. A recent estimate of total pneumatic device use in the oil and natural gas sector numbers over 1.7 million, contributing to an estimated 2,000 kT of operationally vented methane per year in the U.S.[5] Globally this number is estimated to be 11,000 kT of annual methane venting from pneumatic device (controllers and pumps) use.[6,7]

A favored and leading solution for methane abatement on the well pad is the replacement of passive, operationally vented methane as the working pressure fluid with clean, dry instrument air provided by air compressors. This affords the ability to "plug and play" an air compression system into the sometimes extensive and complex piping for multi-well pads without extensive retooling and configuration.

In this study, Qnergy's PowerGen was tested for its ability to both effectively destroy methane and deliver electricity. The key to achieving effective 100% methane destruction is the PowerGen's external combustion radiant matrix metal fiber burner design. A critical design aspect of the PowerGen design is that the proprietary power conversion engine has no rotating parts, thus requires no lubrication, has a long life, and is very low maintenance. Another important aspect of the PowerGen is that combustion and heat exchange processes occur outside the engine, obviating exposure of corrosive gas contaminants to the piston and other internal components. Controlled combustion via the metal fiber matrix design ensures clean, complete destruction of methane, i.e., zero methane slippage, while delivering electricity.

In May 2022, the Canadian Emissions Reduction Innovation Consortium (CanERIC), focused on reducing upstream methane emissions, conducted testing demonstrating that of 6 commercially available gas to power generators, Qnergy's PowerGen was the only one to demonstrate 100% methane destruction.[8]

To corroborate the independent party results, and to expand the analysis to encompass other environmental agents of interest, Qnergy contracted an independent, third-party agency to measure and report on the environmental performance of the PowerGen. Alliance Technical Group (Decatur, AL, alliancetg.com), an EPA-certified recognized leader in environmental testing was selected to perform testing onsite at Qnergy. A representative PowerGen with designation "Serial Number 833" was used for testing.

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[4] Alvarez et. al., "Assessment of methane emissions from the U.S. oil and gas supply chain" SCIENCE, Vol 361, Issue 6398 (2018) science.org/doi/abs/10.1126/science.aar7204#supplementary-materials

[5] Kleinberg, Robert, EPA Methane Emission Controls, Obama vs Trump vs Biden: What Needs to Be Fixed and What Should be Left Alone (March 22, 2021). Available at SSRN: ssrn.com/abstract=3810337 or http://dx.doi.org/10.2139/ssrn.3810337

[6] Reducing Methane Emissions: Pneumatic Devices. Methane Guiding Principles: methaneguidingprinciples.org/wp-content/uploads/2019/11/Reducing-Methane-Emissions-Synopsis-Pneumatic-Devices.pdf

[7] International Energy Agency, Methane Tracker 2020: iea.org/reports/methane-tracker-2020

[8] Canada Emissions Reduction Innovation Network (CERIN) Public Report; Electrical Generation Technology Showdown, CanERIC. Report available at Qnergy's website, qnergy.com

The environmental agents of interest for this study include particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), and volatile organic compounds (VOC). Since the generator consumes well pad natural gas (and other landfill gas or biogas) as feedstock for heat generation, it is important to measure the environmental footprint as part of a solution to lower net methane emissions at various methane emission sources. In addition, to test for fuel flexibility, both propane and methane were tested in the Qnergy system.

PowerGen's external combustor requires zero to minimal gas processing or scrubbing and can accommodate variable flow, pressure, and methane content. Additionally, the external combustion design is ideal for variable fuel quality. This verification is important, given that the usual field case is the conversion of raw, unrefined gas into useful energy to reduce cost and increase ease of deployment at any methane-producing site.[9] Therefore, it is important to determine PowerGen's operational GHG and environmental footprint as a power plant delivering utility-grade electricity remotely.

Results

The generator enclosure and internal design are shown in **Figure 1.** The external combustion cavity burner is gaseous fuel flexible for C1-C4, methane, ethane, propane, butane, and hydrogen mixtures, but primarily optimized via power electronics for dry natural gas with typically >85% methane content. Electrical output is 120/240 VAC split phase to 5.65 kWe and a Wobbe Index range of 832-2,163 BTU/ft3 and a fuel consumption rate of 3,964 ft3/day natural gas.

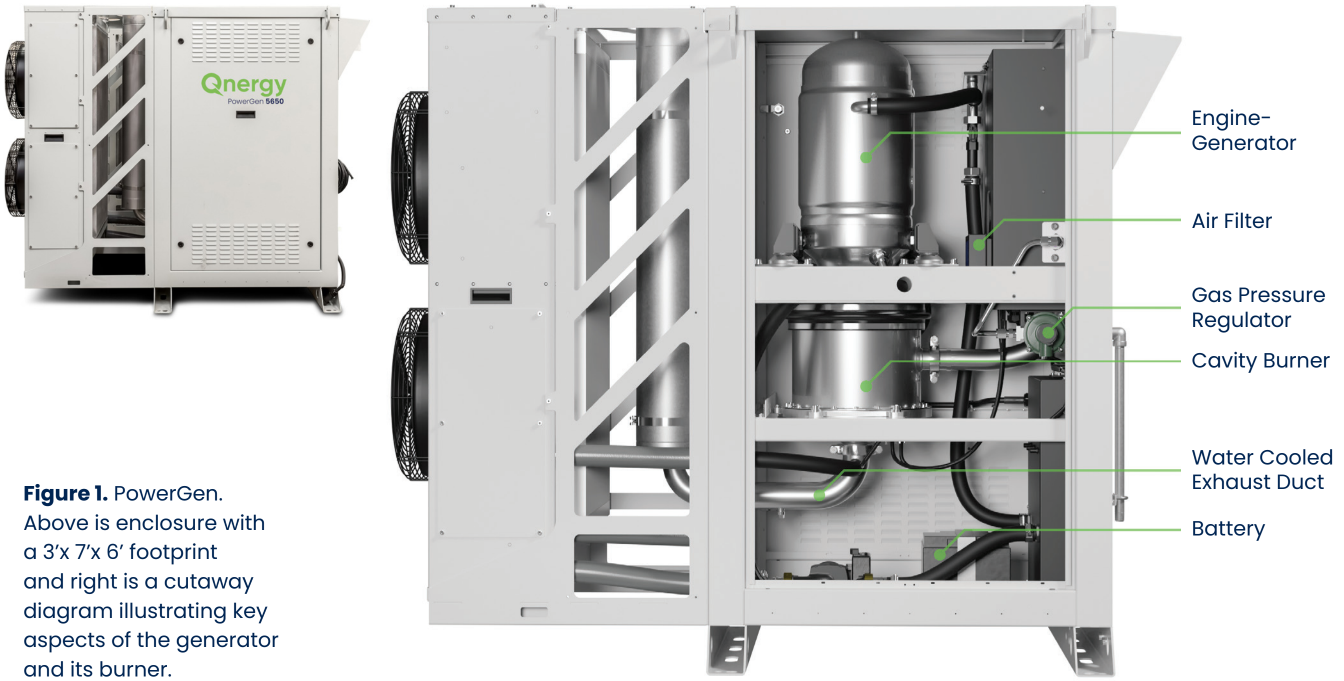

Figure 1. PowerGen. Above is enclosure with a 3'x 7'x 6' footprint and right is a cutaway diagram illustrating key aspects of the generator and its burner.

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[9] Garaway, I., & Pang, K., Compressed Air Pneumatics for Methane Mitigation, SPE Annual Technical Conference and Exhibition, 2022: onepetro.org/SPEATCE/proceedings-abstract/22ATCE/2-22ATCE/D022S088R002/509020

Table 1 contains the list of EPA approved testing protocols performed on SN833. PM, NOx as a key GHG component, CO as a proxy for overall combustion, direct measurement of completion of methane combustion ("slippage"), and VOCs were all tested for. Available standards by which results were read against and analyzed are shown in **Table 2,** which contains air quality standards from the EU, the US EPA, and the California Air Resources Board (CARB), generally regarded as currently the most stringent. Note, that as an external combustion process, the PowerGen engine does not fall into any of the three categories listed in Table 2, and these standards are used in direct comparison to internal combustion engines (ICE).

EPA TEST METHOD	DESCRIPTION	SOURCE
Method 1	Velocity and/or particulate survey method	epa.gov/emc/method-1 samplevelocity-traverses
Method 4	Measurement of stack gas moisture content	epa.gov/emc/method-4 moisture-content-0
Method 7e	Measuring NO(x) from stationary sources	epa.gov/emc/method-7e nitrogen-oxide-instrumental-analyzer
Method 10	Measuring CO from stationary sources	epa.gov/emc/method-10-carbon-monoxide-instrumental-analyzer
Method 18	Gaseous Organic Compounds by Direct Interface GC/MS (VOC)	epa.gov/emc/method-18-volatile-organic compounds-gas chromatography
Method 25A	Total gaseous organic concentration via flame ionization	epa.gov/emc/method-25a-gaseous-organic-concentration-flame-ionization

Table 1. Table of EPA-approved test methods employed. EPA approved methodologies for measurement were employed for each emission molecular entity of interest to compare engine performance with published standards (Table 2) as well as comparison to upcoming EPA final rulings regarding best standards for emissions reduction (BSER) for the oil and gas industry [ref]. Method 1 was first employed for the proper selection of sampling ports and traverse points for air pollutant sampling. Subsequent Methods were employed to measure moisture, nitrous oxides (NOx), carbon monoxide (CO), and volatile organic compounds (VOC) such as formaldehyde.

CARB – CI/SI 17 CCR, 3.1.8.3 Section 94203 Table 2, 2013 [10]	EU, nonroad, Stage V, Table 4, 2019, category NRE, P<8kW (CI) [11]	EPA NSPS for CI engines, Tier 4, <8kW [12]	EPA NSPS 40 CFR part 90 for Class 1 SI engines <19kW [13]	EPA NSPS 40 CFR part 1048 for SI engines, NG, LB, >500HP [14]	Individual Contaminant
NR	7.5	7.5	16.1	NR	Hydrocarbon
0.032				1.3	NO(x)
0.045	8	8	610	2.7	CO
NR	0.4	0.4	NR	NR	PM
0.009	NR	NR	NR	0.94	VOC
(CARB, 2022)	(DieselNet, 2022)	(EPA, 2016)	(EPA, 2008)		

Table 2. Table illustrating various emissions standards by emission engine/generator type and size. The California Air Resources Board (CARB, Column 1) provides the most stringent GHG baseline standards across the measured GHG elements (Column 6, right). All units are specified in g/kW-hr. NR = No Requirement specified, CI = Compression Ignition, SI = Spark Ignition.

[10] California Code Regulations Title 17, Section 94203; casetext.com/regulation/california-code-of-regulations/title-17-public-health/division-3-air-resources/chapter-1-air-resources-board/subchapter-8-compliance-with-nonvehicular-emission-standards/article-3-distributed-generation-certification-program/section-94203-requirements

[11] European Stage V Non-Road Emission Standards; theicct.org/sites/default/files/publications/EU-Stage-V_policy%20update_ICCT_nov2016.pdf

[12] New Source Performance Standards for Stationary Compression Ignition Internal Combustion Engines; epa.gov/stationary-engines/new-source-performance-standards-stationary-compression-ignition-internal-0

[13] Federal Register: Improvements for Heavy-Duty Engine and Vehicle Procedures, and Other Technical Amendments; federalregister.gov/documents/2021/06/29/2021-05306/improvements-for-heavy-duty-engine-and-vehicle-test-procedures-and-other-technical-amendments

[14] CFR Part 1048-Control of Emissions from New, Large Nonroad Spark-Ignition Engines; ecfr.gov/current/title-40/part-1048

Per determination by Method 1 (**Table 1**), all emissions measurements were taken at the top of the 6-inch diameter air/exhaust mixing duct. Volumetric dilution, cooling, and 'drying' by ambient air occurs within this duct where approximately four parts of ambient air is blended via induced draft with each part of hot exhaust to significantly lower the molar concentration. However, mass flow based on reacted fuel remains unchanged for all pollutant emissions measurements. To determine maximum PM emittance, testing was done via three consecutive full power runs with natural gas as shown in **Table 3**.

	Run 1	Run 2	Run 3	Average
Filterable PM				
Concentration, grain/dscf	0.00023	0.00024	0.00024	0.00024
Emission Rate, lb/hr	0.00036	0.00036	0.00036	0.00036
Emission Factor, g/kw-hr	0.028	0.028	0.028	0.028
Condensable PM				
Concentration, grain/dscf	0.00069	0.00049	0.00089	0.00069
Emission Rate, lb/hr	0.0011	0.00073	0.0013	0.0010
Emission Factor, g/kw-hr	0.082	0.057	0.10	0.08
Total PM				
Concentration, grain/dscf	0.00093	0.00073	0.0011	0.00093
Emission Rate, lb/hr	0.0014	0.0011	0.0017	0.0014
Emission Factor, g/kw-hr	0.11	0.085	0.13	0.11

Table 3. Particulate matter emissions. PM for both filterable (<2.5 uM) and condensable particles (typically 1 um size) collected at exhaust stack exit. Total PM is then calculated. Concentration is actual grains of PM per dscf, and Emission expressed in lb/hr of PM. Emission Factor is then calculated against power output, 5.65kW up to 5.82kW measured. Condensable PM is 1 uM or less sized particles captured when gas at stack exit is cooled to ambient temperature. Total PM is then calculated from filterable plus condensable PM. Dscf = dry standard cubic feet

Filterable PM is capturable as dry particles typically 30 um or less whereas condensable PM is typically 2.5 um or less in size and condense upon cooling. Filterable is captured in stack whereas Condensable is bag captured and cooled exhaust. The measured Emission Factor for Total PM is at 27% (1/4) of both EU and EPA allowable limits (Table 1).

Six types of emissions measurement tests were then run consecutively on SN833:

1. Full Power, Natural Gas Fuel [85% methane content]
2. Run 1 consecutive repeat
3. Run 1 additional, consecutive repeat
4. Half-Power operation, Natural Gas Fuel
5. Half-Power operation, Propane Fuel
6. Full Power repeat test, Propane Fuel

These half-power test configurations were chosen to mimic field conditions when not all power is consumed continuously, and therefore impact on g/kW-hr measurements, and in particular methane slippage as a function of power output and burn rate is desired to be measured. Propane, in addition to natural gas, was tested for fuel flexibility and GHG performance with the PowerGen given market interest in replacing diesel for backup power generation. Measurements for methane detection and slippage, VOCs, and other GHG components are shown in **Table 4**.

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Unburnt Hydrocarbon	NG	NG	NG	NG^{50}	Propane	Propane^{50}
Concentration, ppmvd	0.48	0.4	0.4	1.9	1.4	2.4
Emission rate, lb/hr	0.00021	0.00017	0.00017	0.00053	0.00071	0.00063
Emission Factor, g/kw-hr	0.017	0.014	0.013	0.083	0.056	0.096
Nitrogen Oxides						
Concentration, ppmvd	12.6	13.5	13.3	3.4	19.4	3.7
Emission rate, lb/hr	0.016	0.017	0.016	0.0027	0.028	0.0028
Emission Factor, g/kw-hr	1.3	1.3	1.3	0.43	2.1	0.43
Carbon Monoxide						
Concentration, ppmvd	5.3	5.7	5.7	2.3	7.3	2.2
Emission rate, lb/hr	0.0041	0.0043	0.0042	0.0011	0.0063	0.001
Emission Factor, g/kw-hr	0.32	0.34	0.33	0.18	0.49	0.15
Volatile Organic Compounds						
Concentration, ppmvd	3.0	2.6	3.2	2.0	2.0	1.5
Emission rate, lb/hr	0.0037	0.0032	0.0038	0.0015	0.0027	0.0011
Emission Factor, g/kw-hr	0.29	0.25	0.29	0.24	0.21	0.16
Formaldehyde						
Concentration, ppmvd	0.26	0.26	0.26	0.26	0.26	0.26
Emission rate, lb/hr	0.00022	0.00022	0.00021	0.00013	0.00024	0.00013
Emission Factor, g/kw-hr	0.017	0.017	0.016	0.021	0.019	0.019

Table 4. Measurement of effluent gas from six configured test runs. The series of six configured runs are as described in text above. Shown are the calculated figures from independent one hour runs per test configuration. Given instrument calibration for methane the unburnt hydrocarbon numbers for the two propane runs are likely high but still well below EPA limits and represent >99.9% propane destruction. ppmvd = parts per million, volume dry, NG = Natural Gas, NG50, Propane50 = testing at half power consumption for natural gas and propane, respectively.

Table 4 shows the results of the six runs. Formaldehyde was never detected in any runs. The uniform 0.26 ppmvd value shown for formaldehyde in Table 4 represents the maximum possible value given instrument resolution. The results *in toto* show superior emissions profile against EPA requirements for NOx, CO, and PM as defined in Table 2 and illustrated in **Figure 2**.

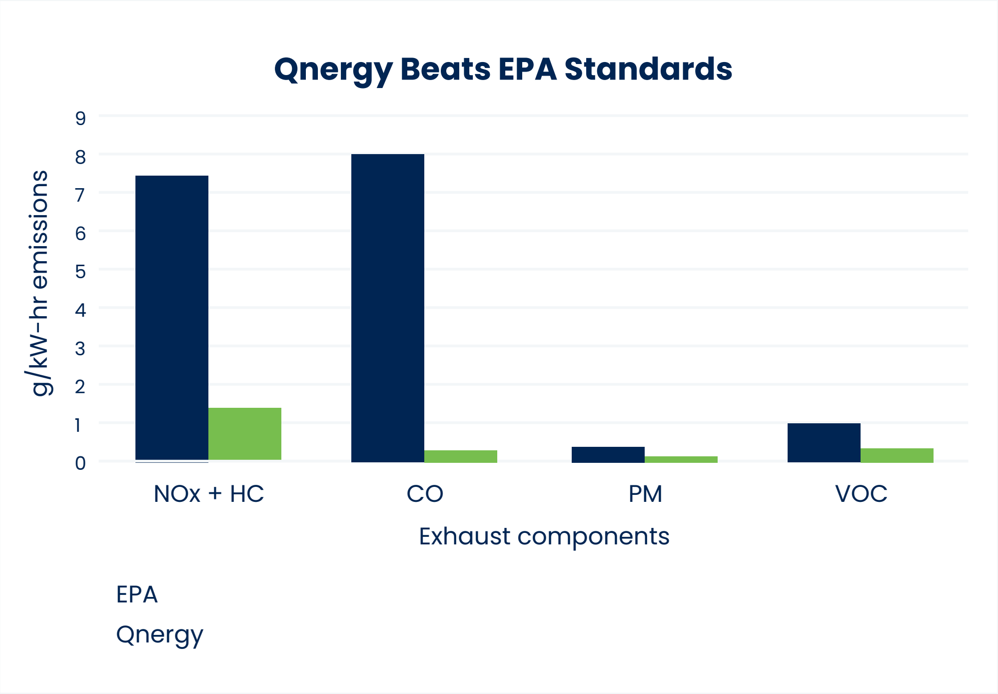

Figure 2. Comparison of PowerGen testing against specified EPA standards for non-road spark engines. Qnergy emissions for NOx, CO, and PM are all well below EPA specified maximum emissions on a gram per kW-h of operation basis. Both the EPA and EU combine unburnt hydrocarbons and emitted NOx into a single output number of 7.5 g/kW-h. Note that Qnergy stack exhaust is 7X lower for NOx, 27X lower for CO, and 4X lower for total particulate matter release against EPA specifications. Minimum levels of expression for CH4, CH2O (formaldehyde), and VOC are not EPA specified for <8 kW offroad CI engines. EPA VOC figure of 0.94 is for >500 HP CI engines and used for comparison. Qnergy emissions for methane and formaldehyde are essentially zero given the limits of detectability in instrumentation.

Figure 2 illustrates environmental performance of the SN833 against EPA specifications. Results show that environmental performance significantly exceeds required specifications. Given the demonstrated zero methane slippage (Table 2) the 1.31 figure is nearly all attributable to NOx and is still >5X lower than EPA standards. Qnergy's CO output is 24X lower, PM is nearly 4X lower, and VOC > 3X lower than EPA standards. Importantly, as indicated in Table 4, even when run at 50% load for both propane and methane, exhaust outputs remained significantly lower than EPA standards. Under variable load conditions as might be expected in field applications, PowerGen will provide ultra-low emissions performance that remain well below EPA guidelines.

Discussion

A key stratagem of mitigating climate change is reduction of the massive annual methane emissions globally.[15] The challenge in doing so is that methane is fundamentally distributed, from well sites, active or abandoned, to farms, wastewater facilities, and landfills, all of varying sizes with variable access to power. The ability to capture and use raw gas at the source and prevent emissions itself requires power. An ideal solution is to be able to use the raw gas itself to generate utility grade electricity for local use wherever methane is generated. This constitutes a sustainable solution only if the engine-generator itself can be assured to emit near zero methane emissions. If so, then the

[15] Removing methane from the atmosphere. Stanford Earth Matters magazine, September 2021. [link]

threat of methane as a GHG is abated and its utility and value as a fuel is capitalized on. This makes capture and conversion of otherwise emitted methane a perfect negative emissions energy source, as a harmful GHG is now converted into ultra-low emission energy.[16]

The results generated from the independent, third-party evaluation demonstrate an ultra-low methane emission profile for Qnergy's PowerGen. These results also corroborate earlier, similar testing conducted by the Canadian Emissions Reduction Innovation Center (CanERIC) that certified the PowerGen as the only generator tested to achieve 100% methane destruction.

These two independent tests, along with Qnergy's own internal testing shows conclusively that the PowerGen is capable of 100% methane destruction and zero methane slippage performance. Further, given the identical EPA and EU emissions specifications (Table 2), the PowerGen is an ideal generator for use in both geographies with limited GHG footprint.

These tests are critical as the EPA is close to final ruling on historically stringent regulations to steer the energy industry towards a near net zero methane emissions future.[17] In this ruling, the EPA is calling for the replacement of all natural gas driven pneumatic controllers that vent to the atmosphere with zero emissions controllers. Designated as "BSER" or Best System for Emissions Reduction, such a ruling would mandate zero tolerance of any methane slippage as well as VOCs. Systems and solutions intended to replace pneumatic controllers must themselves certify their environmental performance to qualify for BSER status.

Qnergy believes that once passed, the BSER standard of thinking will be applied to all sources of methane, including biogas and landfill gas. The need for a zero methane emissions world will demand this. Thus, the Qnergy PowerGen solution with its superior environmental performance profile is a central part of the solution for the capture and conversion of distributed methane into useful power.

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[16] The case for negative emissions. The Coalition for Negative Emissions, June, 2021. coalitionfornegativeemissions.org/wp-content/uploads/2021/06/The-Case-for-Negative-Emissions-Coalition-for-Negative-Emissions-report-FINAL-2021-06-30

[17] EPA's Supplemental Proposal to Reduce Pollution from Oil and Natural Gas Operations to Fight the Climate Crisis and Protect Public Health. epa.gov/system/files/documents/2022-11/Oil%20and%20Gas%20Supplemental%20Proposal.%20Summary%20of%20Proposed%20Technical%20Requirements.pdf