The impact of Electric Turbo Compounding on Gas Genset CO_2, VOC and greenhouse emissions

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1.0 Abstract

This paper explores the ramifications from the current increase in wide scale adoption of gas powered gensets for power generation, including the associated rise in greenhouse gas (GHG) emissions.

By exploring the use of a novel waste heat recovery system, we demonstrate how reducing Volatile Organic Compound (VOC) emissions can reduce fuel costs, reduce GHG emissions and prepare organisations for forthcoming legislation. This includes an analysis of the four main sources of VOC emissions on gas gensets, their effects and how these can be reduced through adoption of Electric Turbo Compounding (ETC) technology (see figure 1).

Further supporting evidence is shown covering the results of field measurements from trials of the waste heat recovery system across three gensets running three different fuel types. A feasible operating map is included to help guide the reader on where the system can be applied and future potential for the technology.

Figure 1: Cutaway of the ETC system

2.0 Introduction

Ever tightening NOx emissions legislation has led to an increased market share for lean burn gas gensets in the power generation market in recent years. This has primarily been due to the combustion process of lean burn gas engines resulting in much lower in-cylinder peak temperatures, lower in-cylinder NOx formation and therefore no need to employ expensive after treatment systems to meet emissions limits.

These lower investment costs, together with lower fuel prices, have made it cheaper for the customer to operate gas instead of diesel gensets through the life of their power generation plant.

Unlike diesel engines, a proportion of the fuel supplied to lean burn gas engines is not burnt during the combustion process and is expelled out the exhaust pipe. This could be anywhere between 1–4% of the fuel depending on the engine design. Unburnt fuel from alternate fuel engines such as biogas or landfill gas can be of even higher proportions, due to the effects of both CO_2 and power cylinder deposits on combustion.

The unburnt fuel or VOC emissions are a wasted opportunity and an environmental risk. Any methods to reduce them can directly reduce fuel costs and greatly reduce both the local environment and the global GHG emissions impact of the genset.

Until now, VOC emissions from lean burn gas engines have largely been overlooked, but the growing market share of gas engines has led Environmental agencies across Europe to increase their focus, with the introduction of legislation on VOCs in recent years (such as the Medium Combustion Plant Directive) with tighter legislation due in the near term (TALuft).

For 16 years, Bowman Power Group (Bowman) has designed, developed, installed and maintained electrified turbomachinery products for improving internal combustion engines through reducing fuel consumption, reducing GHG emissions, and improving responsiveness.

Our ETC technology has been refined over this time and is now in its third generation, with over 800 systems in operation. To date, we have generated in excess of 710GWh of extra power, saved over 350,000 tonnes of CO_2 and removed the need for over $100 million of fuel to be burnt. The ETC system is comprised of a turbine and generator that are placed in the exhaust stream downstream of the engine (see figure 2).

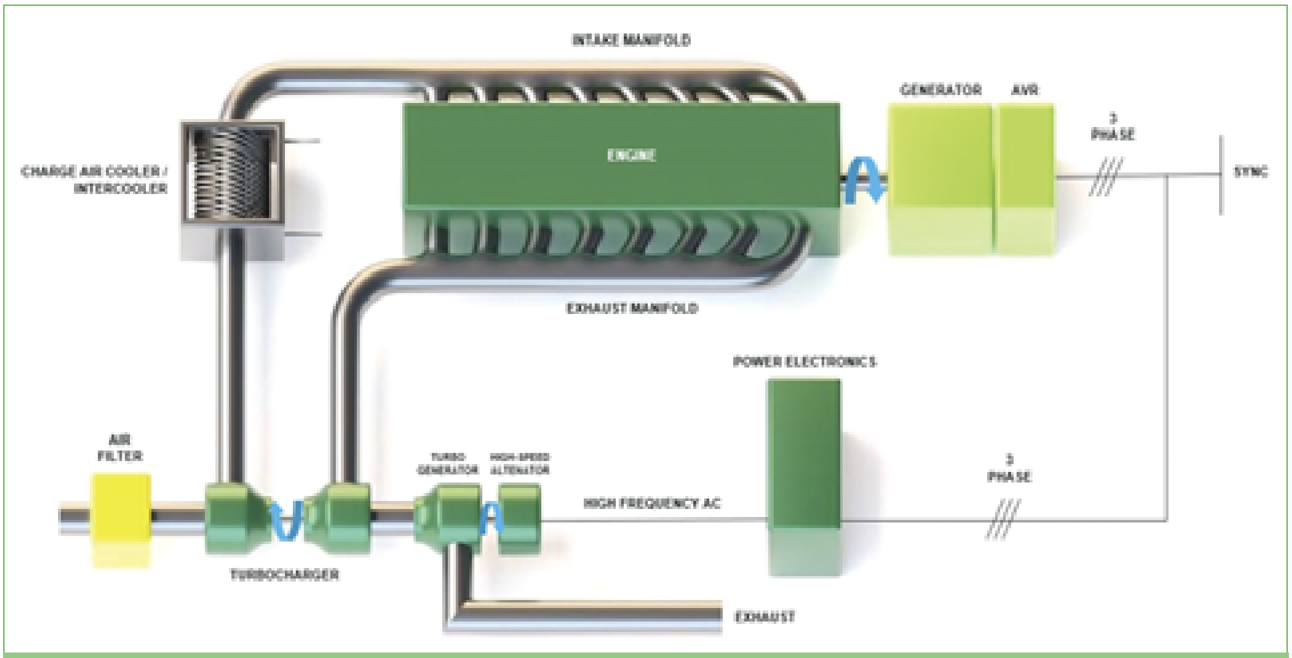

Figure 2: Example installation of ETC system

Bowman's technology recuperates some of the exhaust heat normally lost to atmosphere into additional electrical power which is then converted via a power electronics unit and added to the local or national grid. This then improves the efficiency and/or electrical power of the host genset, whilst reducing emissions. This benefit is typically 4–7% specific fuel consumption reduction on both gas and diesel engine platforms. On gas engines this reduction in fuel consumption also includes a reduction of the VOC emissions directly lost to exhaust. A recent installation can be seen in figure 3.

2.1 The need for change

OEM emissions datasheets indicate that methane (CH_4) makes up approximately 80% of the total VOC emissions on lean burn gas engines. It is a stable molecule requiring high activation temperatures before oxidation reactions will initiate. With the low exhaust temperatures seen downstream of lean burn gas engine turbochargers, there is currently little potential to economically reduce CH_4 emissions using traditional aftertreatment solutions.

Figure 3: ETC installed in containerised genset

Until now, reducing VOC, and more specifically CH_4 emissions, has been the responsibility of original equipment manufacturers (OEMs) through improving the base engine design. This normally involves expensive and lengthy development programmes focusing on the sources of the emissions. ETC technology represents a new and unique opportunity for both the OEM and customers in the field to reduce these VOC emissions without base engine changes.

3.0 Main sources of VOC emissions

VOC emissions primarily come from four main sources, three of which the ETC system has a significant effect on.

3.1 Fuel short circuiting – ETC effect High

Fuel short circuiting occurs due to two fundamental reasons on gas engines.

Firstly, in order for the lean burn concept to achieve high power densities, high air to fuel ratios (AFR) need to be achieved. This means turbochargers with high efficiencies must be utilised, resulting in high scavenging pressures (where the Intake Manifold Pressure (IMP) is much higher than the Exhaust Manifold Pressure (EMP) normally in the 0.3 to 0.8 bar range.

Secondly, the most cost-effective method of introducing fuel to a gas engine is the pre-mixed concept. This means gas is introduced within the intake system by means of a mixer before the main engine cylinders, much like a carburetted petrol engine in a 1980s car. Therefore, pre-mixed air and fuel flow into the cylinder during the intake stroke.

At the end of the exhaust stroke/beginning of the intake stroke there is a moment when the piston is at Top Dead

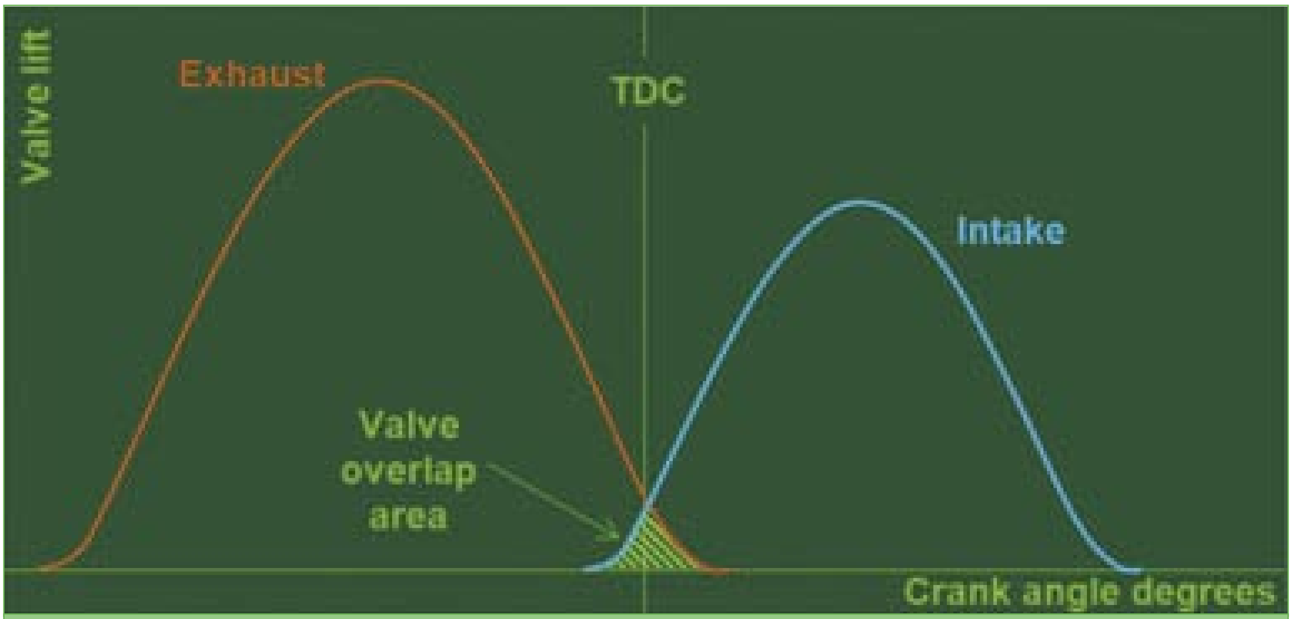

Figure 4: Typical gas engine valve lift profiles - Illustration of valve overlap at piston TDC

Centre (TDC) and both intake and exhaust valves are concurrently open, as shown in figure 4. The high scavenging pressure forces a volume of the pre-mixed air/fuel to flow directly from the intake port, through the cylinder to the exhaust manifold without taking part in the cylinder combustion process (as shown in figure 5). This process is commonly known as fuel short circuiting, or fuel slip.

The effect that scavenging pressure has on gas engine VOC emissions can be seen in figure 5. The most significant influence of scavenging pressures is seen above approximately 0.2 bar, below this fuel short circuiting due to the valve overlap period is believed to be negligible.

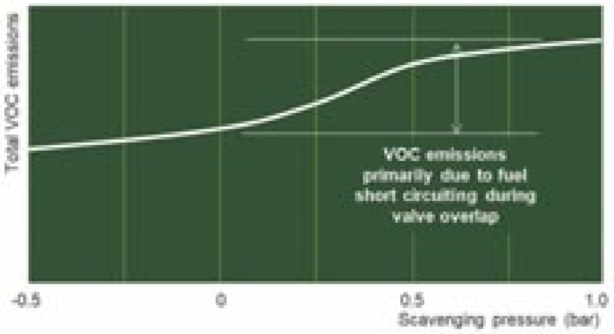

Figure 5: Illustration of the effect of scavenging pressure on the VOC emissions of a typical gas engine

3.2 Fuel storage in crevices – ETC effect Medium

Crevices are the spaces or volumes within the power cylinder where the flame cannot propagate, and combustion does not occur. These volumes are even more significant on lean burn gas engines when compared to rich burn or Lambda 1 engines as the quenching distance (minimum gap between surfaces through which a flame can propagate) is much larger. Table 1 shows the typical locations of crevices within a gas engine with an indication to their significance and contribution to VOC emissions.

Depending on the engine design and AFR, crevice volumes for spark ignition (SI) engines are normally in the region of 1-3% of the total cylinder volume when the piston is at TDC.

Figure 6 shows the most significant crevice volumes between the piston top land and liner and between the cylinder head, liner and gasket, which contribute the most to VOC emissions. During the combustion process a high proportion of unburnt fuel is squeezed into the piston top land and liner/gasket crevices as the flame front

Table 1: Significance of crevice volume on VOC emissions

Typical crevice volumes	Significance by location	Significance by volume
Spark plug threads	**Low** Typically in a hot location - good opportunity for oxidation	**Low** Typically account for ~10% of total crevice volume
Prechamber clearances		
Inspection/instrumentation bores		
Valve pockets		
Piston	**High** Typically by cool cylinder walls - poor opportunity for oxidisation	**High** Typically account for ~90% of total crevice volume
Liner/gasket		

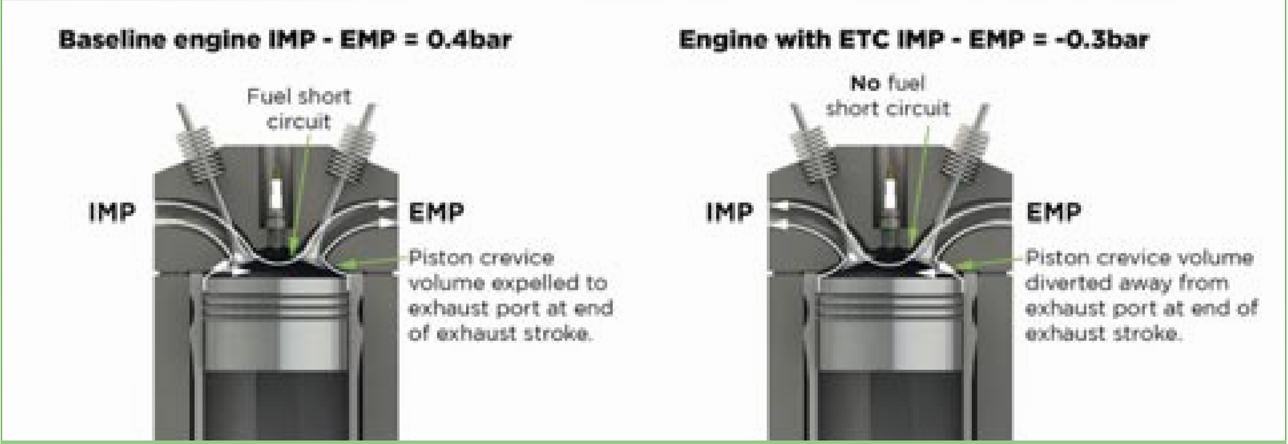

Figure 7: Illustration of scavenging pressure effect on fuel short circuiting and crevice volume VOC emissions at the end of the exhaust stroke, during valve overlap period

propagates through the cylinder. The high pressure and relatively low temperature of the gas in these zones during the combustion process results in a high density and higher proportion of fuel in the crevice than geometric volume suggests.

As the piston moves down during the expansion process, the unburnt fuel exits these volumes as the pressure decreases, depositing the unburnt fuel along the cool liner wall, minimising any opportunity for oxidation of the fuel to occur.

As the piston reverses and moves up during the exhaust stroke, the unburnt fuel is then picked up by the piston and expelled out of the exhaust port as the piston reaches TDC. A high proportion of the VOCs leave the cylinder at the very end of the exhaust stroke, during the valve overlap period.

3.3 Flame quenching – ETC effect high

Lean burn gas engines operate at high AFR, close to the lean or misfiring limit. This means that the flame will often extinguish (due to the high proportion of air in the cylinder over-stretching the flame front) before it can propagate fully across the cylinder. This becomes even more significant close to the cylinder walls (quench layer), where the temperature of the air fuel mixture is much lower, reducing the opportunity for the air fuel mixture to fully oxidise. This phenomenon results in incomplete combustion on every engine cycle and is more significant at lower NOx emissions settings where much higher VOC emissions are seen (eg 250 versus 500mg/Nm_3@5%O_2 NOx emissions setting).

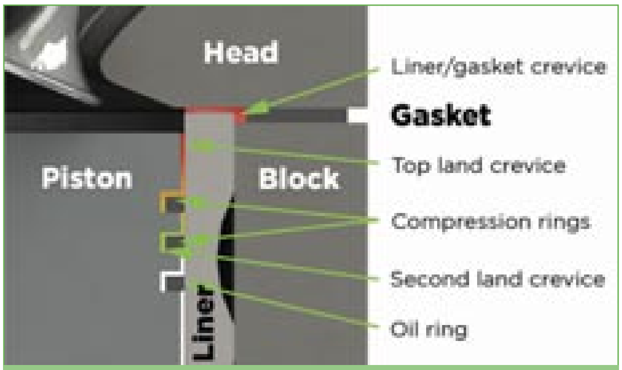

Figure 6: Most significant crevice volumes within a gas engine power cylinder

3.4 Fuel trapped in engine deposits – ETC effect low

Deposits have the effect of absorbing and trapping fuel during the combustion process and insulating them from the normal combustion event (increasing the quench layer thickness). This is more significant when running high ash oils, or fuels derived from sewage or landfill where deposit formation and thickness over time can be significant.

3.5 ETC effect on VOC

When the ETC system is applied to a genset the backpressure on the engine's turbocharger increases, effectively slowing the turbocharger down. This means it is necessary to modify the turbocharger by reducing the turbine nozzle area, to maintain the turbocharger speed, engine load and AFR. In doing so the exhaust manifold pressure increases, affecting the scavenging pressure of the host engine.

Applying ETC typically reduces the scavenging pressure by between 0.6 and 1.0 bar versus the baseline engine, normally changing it from a positive scavenging pressure to a negative one. This effectively eliminates VOC emissions resulting from fuel short circuiting during valve overlap (3.1) and partially reduces the VOC emissions coming from the crevice volumes at the end of the exhaust stroke (3.2).

Figure 7 shows an illustration of these effects from an engine before and after ETC is installed.

The reduction in scavenging pressure when fitting ETC additionally increases the trapped exhaust gas at the end of the exhaust stroke. This increase in exhaust gas has a

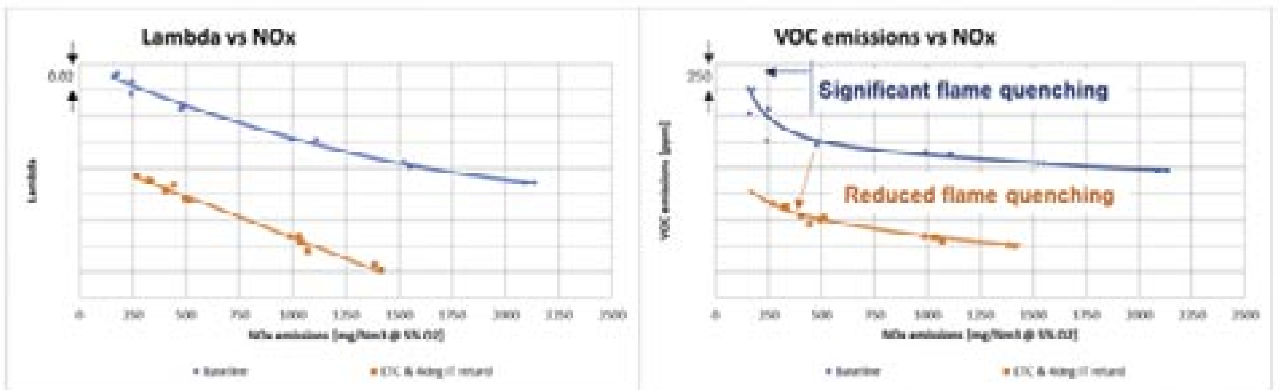

Figure 8: Comparison of Lambda and VOC emissions on baseline engine and engine with ETC fitted adjusted to constant knock margin

negative impact on the combustion process driving up endgas temperatures and the knocking tendency of the engine.

On engines that do not have sufficient margin between the Methane Number (MN) of the gas being burnt and the datasheet MN, adjustments need to be made when ETC is fitted to ensure knock free operation. This can be done by reducing piston compression ratio or retarding the Ignition Timing (IT). Both of these actions reduce combustion temperatures allowing the engine fuel settings to be adjusted to run lower lambda when ETC is fitted in order to achieve the same NOx emissions as the baseline engine.

Reducing in-cylinder lambda significantly reduces the flame quenching effects as described in section (3.3) and thus reduces the VOC emissions resulting from incomplete combustion. Figure 8 shows the change in lambda and VOC emissions when ETC was fitted to an engine with the IT retarded to achieve constant MN margin.

4.0 Field measurements

VOC emissions measurements have been conducted before and after the ETC system was fitted on three different gensets running three different gaseous fuels: Landfill Gas (LFG), Biogas (BG) and Natural Gas (NG), see Table 2. The VOC reduction measured when applying ETC ranged from between 29 and 42%. This directly related to fuel savings of between 0.3 and 0.6% versus the baseline genset (the total ETC system fuel saving when also including the power generated from the heat recovery system was between 3.6 and 5.7% of fuel saved).

The global warming potential (GWP) of CH4 is considerably higher than CO_2, with multipliers between 20 and 100 times commonly used. The Intergovernmental Panel for Climate Change's latest report published in 2013, AR5 Appendix 8A states that CH_4 has a GWP 84 times that of CO_2, when taking a 20-year time horizon into account. Assuming that 80% of the VOC measured is CH_4 then when combined with the CO_2 reduction seen from the fuel savings, impressive GHG savings have been calculated of between 15 and 24% when applying ETC. This equates to between 1,058 and 1,815 ton GHG/year saved for a 1MWe genset.

Note: In the case of the natural gas engine tests, two different turbocharger and ETC matching configurations were tested. The 'more aggressive' matching demonstrated that it is feasible that VOCs can be further reduced when applying ETC. This less aggressive layout however resulted in a better fuel saving and was chosen for the application as this was the target for the customer.

Figure 9 shows an estimation of the feasible operating map that it is envisaged all lean burn gas gensets could achieve when ETC is applied. It contains the field measurements described above and estimated curves for different engine designs:

Table 2: VOC emissions measurements per genset rating

Genset rating (kWe)	Fuel	Turbo & ETC match	VOC baseline (ppm)	VOC with ETC (ppm)	VOC reduction (%)	VOC Equiv fuel saving (%)	GHG saving (%) *
1065	LFG	-	1,100	750	32	0.3	15.3
625	BG	-	1,620	1,150	29	0.5	18.1
1,000	NG	More aggressive	2,260	1,306	42	0.6	24.3
1,000	NG	Less aggressive	2,260	1,500	34	0.5	20.0

* CO_2 Equivalent (includes CO_2 and CH_4). Assumes CH_4 = 80% VOC & CH4 GWP = 84 x CO_2

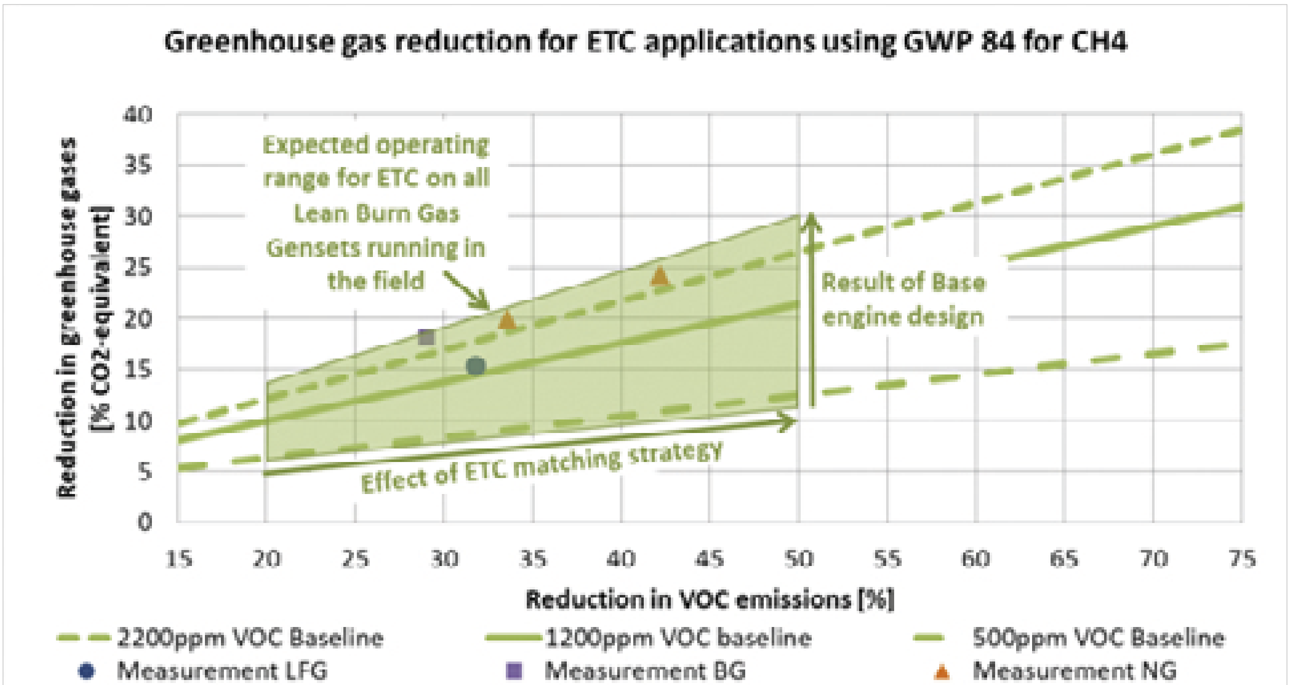

Figure 9: GHG reduction for ETC applications using GWP 84 for CH_4

- 500ppm VOC curve (modern gas engine optimised for low HC emissions)
- 1,200ppm VOC curve (typical gas engine running 250-500mg/Nm_3 NOx)
- 2,200ppm VOC curve (legacy gas engine running in field)

In all cases the ETC system can have a significant impact on VOC and GHG emissions depending on the strategy for matching the ETC to the host genset. VOC emissions reductions of between 20 and 50% and GHG reductions of between 6 and 30% are expected when fitting ETC to all types and vintages of lean burn natural gas gensets operating in the market today.

5.0 Conclusion

It has been proven that applying ETC to lean burn gas gensets results in significant reductions in emissions, with decreases in emissions of between 29–42% VOC and 15–24% GHG measured.

We estimate there are approximately 50,000 gas engines in the field that could benefit from these improvements, with annual running hours estimated at 698TWh. If all of these engines were to switch to ETC technology (and assuming a 4% reduction in fuel consumption (CO_2) and 33% reduction in VOC emissions from 1,500ppm is typical), this would result in an annual reduction of global CO_2 emissions by 12.9Mt and GHG emissions (equivalent CO_2 including CH4) of 95.5Mt.

With the number of gas engines expected to rise to 80-90,000 by 2021 the potential improvements to global warming from using ETC are hugely significant. ■

Further reading/references

1 - Intergovernmental Panel on Climate Change, IPCC 2013 – AR5

The author

Keith Douglas is Head of Performance Engineering at Bowman Power in Southampton, UK. Keith is responsible for the performance engineering team and leads efforts to identify and optimise applications for Bowman's high-speed electrical machine based energy efficiency products. He serves as a vital customer interface, working directly with the company's growing client base to enhance the performance of their engines and generators.

Prior to joining Bowman, Keith worked for two engine and genset original equipment manufacturers. Most recently he worked as Senior Performance Engineer at GE Jenbacher and before that, Technical Advisor for Gas Engine Performance at Cummins.