Project Code	RDR/P1/L2/0212
Project Lead Organisation	CAGE Technologies Ltd (CTL)
Project Title	HGE Hybrid Gas Engine
Project Start Date	23 March 2022
Duration	11 months

CAGE Final Report (Redacted)

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Report Author: Paul Andrews

Objective
Final report to cover activities of BEIS funded Hybrid Gas Engine project (HGE)

Overview

The project conducted research and development to explore a pragmatic internal combustion engine innovation that allows an industrial engine to be powered by a range of gas fuels including hydrogen without any physical changes to the engine and deliver performance comparable with existing diesel product.

The project built and tested 3 hybrid gas engine platforms that proved the concept is viable using either LPG or Hydrogen fuel and developed, tested, and demonstrated the final engine product in working generators.

Contents

Table of Acronyms

Acronym	Description
BSFC	Brake Specific Fuel Consumption
CTL	CAGE Technologies Ltd
ECU	Electronic Control Unit
EU	European Union
g/kWhr	Grammes per Kilowatt hour
H2	Hydrogen
HC	Hydrocarbons
HGE	Hybrid Gas Engine
HP	Horse Power
kW	kilowatts
kWe	Kilowatts electrical
kWe	Peak kilo Watt electrical power output
LPG	Liquid Petroleum Gas
MCP	Multi Cylinder Pack
mS	milli seconds
NOx	Oxides of Nitrogen
OEM	Original Equipment Manufacturer
PEMS	Portable Emissions Measurement System
PPM	Parts Per Million
R&D	Research and Development
RDME	Renewable Dimethyl Ether
RPM	Revolutions Per Minute
VAC	Voltage Alternating Current
λ value	Lambda (air fuel ratio)

1. Executive summary

HGE, the Hybrid Gas Engine project, has developed an engine technology that enables internal combustion engines to use any gas fuel or mixtures of combustible gasses, including hydrogen by precisely controlling all elements of the combustion process. In doing so the project has optimised the low emissions potential of gas fuels to provide a pragmatic and cost-effective solution for the replacement of diesel in the construction, mining and quarrying sectors.

The project has delivered on all of its initial objectives.

These are as follows:

1. Set up hydrogen fuelling systems at OakTec and Helical technologies
2. Manufacture and run small Hybrid Gas Engine (HGE)
3. Manufacture and run large HGE
4. Developed and calibrated small and large HGE suited to transition to trial phase

In addition, the project developed a medium size Hybrid Gas Engine, forged a new relationship with an engine and generator OEM, and developed and trialled two new gas generators with large operators in the construction sector.

2. Project description

To provide a viable and cost-effective replacement for diesel in construction, CAGE Technologies Ltd and partners built on previous work in clean gas engine development and successful trials in the construction sector to develop a pragmatic technology solution that will both enable short term impacts in carbon reduction and improved air quality whilst demonstrating a realistic technology platform and roadmap for the longer term transition to net zero.

HGE harnesses knowledge gained over 7 years in the development of LPG, biogas, and hydrogen engines to develop a multi-gas engine technology that enables clean, efficient combustion of fossil gas, biogas, and renewable hydrogen independently or in any mixture ratio, paving the way for future wide scale availability of synthetic e-gasses and hydrogen. The product goal is an engine that can use most gas fuels simply by switching to an appropriate control strategy and plumbing the fuel supply into the relevant port.

HGE Phase 1 also investigated possible benefits of using blends of hydrogen and LPG precisely metered into the engine combustion process to reduce GHG emissions, engine-out NOx emissions with a target of increased efficiency and improved local air quality.

HGE will deliver benefits by:

- Providing a short-term practical replacement for diesel with a much cleaner and more cost-effective fuelling solution.
- Helping smooth the establishment and growth of a green hydrogen supply chain to the construction, mining and quarrying sectors.
- Developing a net zero pathway towards use of 100% hydrogen or e-gasses.

When green hydrogen is more widely available the technology will allow for a higher level of H_2 substitution of the fossil gas, ultimately with the capability of a 100% transition to hydrogen. The technology will equally accept synthetic gas fuels such as e-methane, alone or mixed with hydrogen.

The technology enables optimised reduction in emissions through precise combustion control and net zero capability when using hydrogen.

In the intended generator applications for the first engine products cross over sectors include agriculture, leisure, off-grid power and marine whilst the core engine concept can be used to replace any conventional liquid fuelled engine where provision of gas fuel is practical. Units developed within the project are in the 6-25kWe output range.

Assumptions and constraints

The project delivered its objectives around the following list of assumptions.

1. The CTL team had the capabilities and knowledge to deliver the project entirely in-house.
2. Unreliable supply chains could deliver the materials and hardware needed to complete the project, and if components were not available CTL would take from stock or adapt.
3. CTL had the inhouse testing and R&D facilities in place to deliver the project other than work carried out in the engine test labs at subcontractor Helical Technology.

The project could only be delivered within the constraints of the BEIS funding and the very significant benefits in kind offered by existing CTL partners including engine OEM's construction companies and the HS2 rail project.

3. Technical Report

HGE Phase 1 set out the following technical objectives.

1. Develop an engine platform that will combust most gas fuels or gas fuel mixtures efficiently, reliably and with ultra-low or zero emissions with a focus on hydrogen as a practical future fuel.
2. Investigate any benefits of using hydrogen as a combustion agent to enhance the lean combustion of LPG to benefit engine out NOx emissions and understand the full spectrum of LPG/hydrogen fuel mixtures in an engine.
3. Develop the CAGE engine control platforms and engine systems to achieve the above objectives.
4. Build and test the completed engine systems into working generators and demonstrate them to key players in the construction sector using LPG fuels.
5. Measure emissions of the complete engine systems both in the lab environment and on a working construction site with high profile construction partners.

Engine Platform Development

The project initially set out to develop 2 engine platforms (6HGE, 60HGE) with performance data shown based on design fuel. During the project a third platform was identified with full OEM support.

- **6HGE 6kWe @ 3,000 RPM**. A four-stroke petrol 420cc single cylinder based on a simple generic industrial petrol engine.
- **20HGE 15kWe @ 3,000 RPM or 12kWe @ 1,500 RPM.** A four stroke 1200cc spark ignition industrial engine 2 cylinders.
- **60HGE 30kWe @ 3,000RPM.** A four-stroke direct injection petrol 1500cc 3-cylinder unit based on a much more complex turbocharged automotive engine supplied to the project by the OEM.

6HGE

CTL uses OakTec's own in-house control platform to manage all elements of combustion in the 6HGE engine. This controller has been developed for gas engine management over a number of years and a new iteration is being developed for the HGE technology. The controller is designed to be robust and low cost yet incorporate every element of functionality needed to deliver optimised emissions, performance and fuel efficiency. A CTL designed digital throttle load control and fully variable ignition timing were developed for this engine to replace the centrifugal governor and fixed magneto type ignition.

The engine fuel supply was configured using a separate hydrogen and LPG feed system using individual fuel injectors ported into a common induction pipe. This allows for the fuels to be fed independently or together in variable quantities. The injector control uses two engine control ECU's one for each system with the LPG ECU being the master for the engine. Two laptops control the two ECU's and OakTec has designed and built fuel trimming boxes that integrate with the ECU's and allow trimming and calibration on the fly. Fuel supply is regulated at bottle output and is delivered at 1.5 bar to each injector. The fuel pressure is monitored by bespoke CTL designed sensors and a live pressure value supplied to the ECU so that it can be monitored at all times. This gives a fully variable control system for ease of R&D and data gathering. The final system harnessed R&D learning and incorporated all control logic into a single ECU to reduce cost and add simplicity.

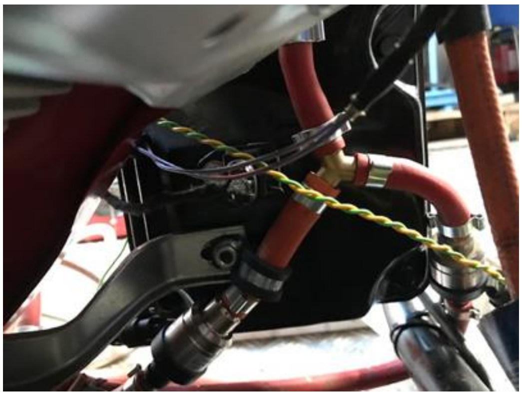


Figure 1: LPG and hydrogen injectors

Figure 2: 6HGE test cell and dynamometer

LPG fuelling. By controlling the engine with sophisticated electronic devices and optimising combustion these HGE has delivered an exceptionally sophisticated engine for this small capacity sector where a typical alternative uses a physical centrifugal speed/load governor, has no variance in ignition timing or spark intensity and as such is very heavily compromised in terms of performance efficiency and emissions. The HGE lean combustion operation allows much better light load efficiency as there is less restriction through throttling and it is realistic to claim an efficiency benefit of 22 -25% compared to a standard gasoline engine of the type used for development. This benefit is likely to be higher still when compared to the old type of gas conversions that are currently commercially available. These use crude regulators valves and carburettors. System providers often quote Brake Specific Fuel Consumption (BSFC) at above 350g/kW hr for this type of engine, and they are fickle in terms of set up, whereby a manual adjustment screw can destroy the fuelling efficiency of the engine and massively increase its emissions. The 6HGE has a BSFC at its rated operation output of 260g/kW hr.

Performance. The 6HGE engine delivers broadly the same power output as the OEM specification for the petrol engine. Its peak output is 10kW but its performance delivery is much smoother and more responsive than the OEM engine due to the fast action of the electronic control and the instantaneous reaction of the CTL designed digital throttle. CTL's calibration for the engine limits peak output to 7.5 kW in lean combustion mode and the calibration maintains the engine in a lean regime in order to greatly reduce engine-out NO_x emissions. This enables the engine to operate around 80% below the Stage V emissions standard and still deliver generator output similar to an OEM machine using the same engine.

Emission measurements for this HGE engine confirm it to be at least 80% below the EU Stage V standard and testing throughout the project has proven a very high level of reliability and consistency of performance.

Hydrogen fuelling. Hydrogen combustion presents many challenges compared to conventional fuels due to its extremely flammable nature. In an engine it combusts at about 10 times the speed of a conventional carbon fuel so requires markedly different combustion strategies to ensure safe and effective engine performance. The CTL/OakTec engine control platform allows continuous response to all the requirements of effective combustion including ignitions timing, intensity and duration, engine fuelling, fuel injection timing, air fuel ratio control and response ambient conditions and machine load requirements.

Challenges in the development of the hydrogen calibration include eliminating unwanted backfires, reliable starting and ensuring sufficient temperature in the engine oil at low loads as the engine tends to run cool compared to a fossil fuel.

When these elements are addressed the main challenge of a refined hydrogen engine calibration is the reduction/elimination of NO_x emissions during the combustion process. These can be very high especially in the initial lean AFR region, whereas with extreme lean mixtures the issue disappears. There can be a pronounced step in the engine calibration where the NO_x falls away whilst the engine still delivers good performance and efficiency, and this area is the target of operation for 6HGE. NO_x emission is very sensitive to ignition timing. The 6HGE engine has been calibrated to run at wide open throttle over its complete operating range in this extreme lean mode and can still deliver 5-5.5 kW continuous power with minimal NO_x emissions. Graphs of these conditions have been shown in previous reports.

The final calibration of the engine features lean combustion to minimise/eliminate NO_x emissions. This calibration allows the engine to produce a continuous 4kW from the generator of the type we will deploy as a commercial product. Peak BSFC at this output was measured at 96g/kW hr equating to circa 40% thermal efficiency from the engine, higher than expected but confirmed by very low levels of waste heat compared to a petrol or LPG equivalent.

Performance The peak output from the 6HGE using hydrogen is 7.5kW. This is lower than the LPG output partly because the high volume of port injected hydrogen needed to get the correct air-fuel ratio displaces induction air and reduces volumetric efficiency. At peak output the engine produces a lot of NO_x emissions so the engine is derated to eliminate this. In ultra-low NO_x mode, it can produce 5.5-6 kW depending on ambient temperature. This equates to a reliable 4 kWe from the generator and as it runs permanently with wide-open-throttle and very lean combustion it has excellent thermal efficiency.

6HGE Conclusions (460cc, 6kWe)

The 6HGE hybrid gas engine concept will consist of one ECU containing two calibration maps, one for hydrogen and one for LPG with no provision for blended gasses deemed appropriate at this stage. Final layout of the HGE fuelling system still needs to be determined as the selection of gas pipes and fittings to appropriate safety standards and material properties will dictate whether a single system can feed either fuel to the engine. Otherwise, a twin feed system is required with each fuel plugged into its own port and fed to the engine independently.

The way the fuel map is selected during change-over is also under consideration. This can easily be done with a manual switch but may be possible by automatic selection by sensors, but this will be determined in ongoing work.

60HGE development (1,500cc, 25kWe)

The 60HGE engine was developed at Helical Technology R&D centre near Preston. It uses an automotive industry standard test cell, with the engine coupled to a 200kW Schenck dyno. The lab has full emission measuring equipment by Horiba Mexa. Fuel is supplied from a remote LPG tank to an engine fuel tank and supplied to the engine as a liquid LPG feed. Hydrogen is supplied directly into the test cell by a piped network from a 12kg MCP.

The 60HGE engine had been built in an LPG format prior to the start of the project and initial calibrations established. This system uses direct liquid LPG injected into the engines combustion chambers at circa 100bar pressure.

These calibrations were used as the baseline for the new HGE set-up. A new fuel supply system was installed to enable port injection of gaseous hydrogen into the engine. Both fuelling systems are controlled by the OakTec engine controller with different calibration maps.

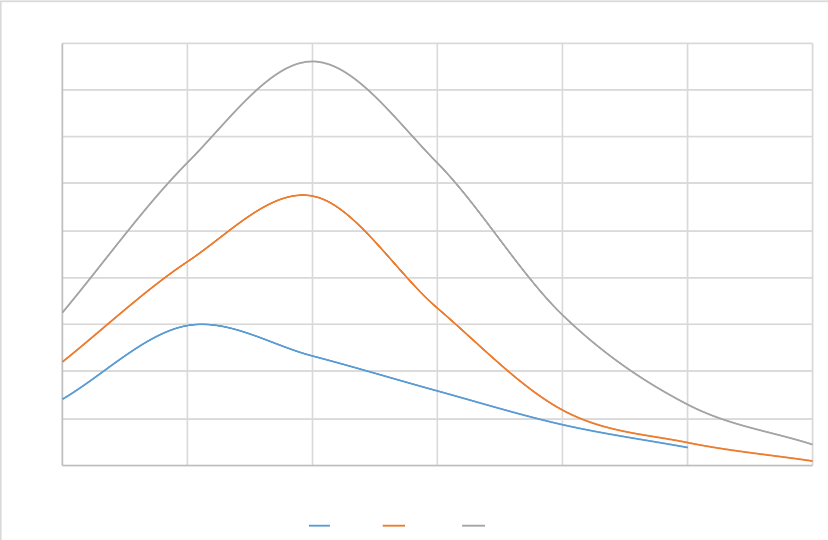
LPG. The project sought to understand the effects of lean combustion in this engine to mirror previous R&D on the single cylinder 6HGE where the LPG version of the engine uses extreme lean combustion mixtures to greatly reduce NO_x emission formation during the combustion process. This has been an area of extensive development to achieve a good compromise between engine efficiency and low emissions by running just inside the threshold of lean combustion misfire. Previous development of this engine had focussed on running at Lambda 1 the stoichiometric air fuel ratio that is used in automotive engines to balance power, efficiency and emissions by using exhaust aftertreatment. The lean thresholds had not been previously explored in this direct injection engine and several strategies could be experimented with that are not possible on the simpler 6HGE platform. This is due to the complex characteristics of 60HGE that enable both variable valve timing, variable EGR and variable turbo boost all under the control of the ECU. By establishing the lean thresholds, it becomes possible to then evaluate any benefit of dosing the combustion with hydrogen to further reduce NO_x at source.

Experimentation showed that very lean yet stable combustion can be achieved by focussing on valve timing strategies enabled by recalibrating the engines variable valve timing. This effect is enhanced by controlling the effective EGR (Exhaust Gas Recirculation) within the engine. A large database of test data has been transposed from a spreadsheet to graph form showing the trends and results at varying engine outputs. **Figure 3 shows a sample of test data.**

Brake specific fuel consumption (BSFC) was measured and graphed at the different conditions. Engine out and tailpipe emissions were recorded and compared giving a clear perspective on the effects of the exhaust after treatment system.

A well refined calibration has been developed with the engine operating around 1.5 Lambda (very lean) with the engine running on wide-open throttle for much of its operating cycle to maximise efficiency by reducing pumping losses. Engine out NOx emissions are very good in this condition, but part of the research is to establish any benefit from running with a dose of fast burning hydrogen to extend the lean combustion boundaries as with the much less complex 6HGE engine.

WP9 engine testing



Lean combustion of LPG effect on NOx emissions

Figure 3: LPG NO_x v fuel air mixture

Performance The 60HGE engine is rated at 200kW in its automotive application. Converted by CTL to run on directly injected liquid LPG it was configured in the genset to run at 3000 RPM and was tested at 1500RPM.

As a turbocharged unit with variable valve timing, it has the ability to be tuned to deliver a broad spectrum of performance depending on the application whilst maintaining efficiency and emissions at a high standard. Unlike the 6HGE it was developed to run at lambda 1 and to make use of the automotive after-treatment system. CTL conducted peak power tests at and above OEM spec boost pressure of 1.04 bar. At this level the engine delivered 87kW at 3000RPM and, when over-boosted, comfortably exceeded 100kW. For a generator application the engine runs constantly and at a relatively light load and the design specification for the generator was 25kWe so the engine was tuned to deliver around 32kW. Best BSFC was 242g/kWhr, a good efficiency for a spark ignited engine.

The engine was also tested extensively at 1500RPM and here it would deliver 36kW peak. It was harder to make it perform better at this speed as the turbocharger was too large and could be made to stall and loose boost causing the engine to lose power. A smaller, lower flow turbocharger would address this and will be investigated as part of the ongoing CAGE R&D process.

The CTL team believes that there is potential to use forced induction in HGE technology as our control system gives us the potential to manage boost accurately to suit different fuel types and power requirements. Turbocharging is not the norm in this type of engine but with sophisticated management allows a smaller engine and generator to be selected to provide a higher output with high levels of efficiency.

Hydrogen.
Learning from the development of the single cylinder 6HGE was applied during the development of the 60HGE and the 20HGE. On the fly calibration was enabled by CTL's mapping box that enables all parameters to be trimmed whilst the engine is running.

The 1,500cc CAGE 60HGE engine uses a port injected gaseous hydrogen supply controlled by the OakTec ECU. Initial baseline testing was conducted over a range of air fuel ratios, ignition timings and valve timings, injection timing etc. The engine has been calibrated to run at continuous power with minimal NOx emissions and can deliver about 20kW at 3000 RPM in this condition. It runs well and reliably.

Testing and development found that the exhaust temperature at these low loads is not sufficient to light off the catalytic converter, so it is important to run the engine lean to eliminate NO_x.

Further testing focused on running the engine with more turbo boost to understand the potential for higher outputs and how NO_x can be mitigated. A direction for further development has been established as the introduction of an electrically driven turbo/supercharger to enabled controlled boost pressure to deliver the required engine performance and emissions. **Photo Figure 4 shows 60HGE lab installation.**

Performance. 60HGE worked well with hydrogen but in some ways testing this engine highlighted the limitations of running a very clean hydrogen engine at high power without optimised forced induction. A problem with hydrogen combustion is that it tends to produce low exhaust gas temperatures especially in lean combustion states. This prevents a 3 way catalyst lighting off to clean up the gas and makes it not practical to run cleanly at lambda 1.
With this engine CTL concentrated on lean combustion low NO_x operation and this allowed a peak engine power at 3000 RPM of around 20kW in a very lightly boosted state. When higher boost rates were tried the injectors quickly reached their hydrogen flow limits so restricting power potential, but this has indicated a direction for future R&D.

Figure 4: 60HGE lab installation.

CAGE 20HGE

LPG and Hydrogen.

The 20HGE engine was formally introduced mid-way through the project following an agreement between CTL and an engine OEM. It is a dedicated industrial engine platform and will be both a focus for RDR2 and future commercial activities using the HGE concept.

The development engine was installed on a new dyno at OakTec and commissioned.

Initially the engine uses port injected gaseous LPG fed by 2 injectors and controlled by OakTec's development ECU. Later in the project a low pressure gas proportioning valve was developed to allow the injectors to be used for hydrogen, so in effect 2 separate fuelling systems.

The initial calibration of the engine has been quite straight forward as knowledge and data from previous engine development programmes has been transferred to the new engine.

The engine works very well and delivers around 22kW at the 3000RPM speed used in UK 50Hz generators.

During the calibration process emissions were measured both pre and post aftertreatment. It has been found that post engine emissions on this engine are poorer than either the 60HGE or the single cylinder 6HGE. Tailpipe emissions are still very clean when calibrated to use the catalytic convertor correctly, so this is not a problem if after-treatment is employed for commercial applications. CTL has ideas how to reduce engine out emissions and these are being fed back to the OEM to be incorporated on future engine iterations.

Performance. 20HGE development closely mirrored what had been learned from the earlier R&D.

On LPG the engine was developed around the ideal air fuel ratio, lambda 1, and was calibrated with after treatment using a 3 way catalytic convertor supplied by the OEM. It delivered peak power of 22kW at 3000 RPM and 14kW at 1500RPM with LPG fuelling. Generators have been developed to work with both these calibrations.

With hydrogen fuel running in the lowest emission regime the engine delivered 17.5kW at 3000RPM and 10.5 kW at 1500 RPM. 20HGE is the most likely platform for CTL to conduct R&D with forced induction and this is a likely activity for RDR2.

Hydrogen and LPG fuel mixtures

The following report discusses the findings of experimentation to evaluate any merits of blending hydrogen with LPG and the effect of this on emissions output. Similar tests were carried out on 6HGE and 60HGE and the findings concurred.

This document discusses the dynamometer test results listed in the spreadsheet 'LPG and H_2 base line runs.xls'. The spreadsheet contains three sets of data. The first is a base line run of Liquid Propane Gas (LPG). The second is a base line run of Hydrogen Gas (H_2). The third is a run of blended LPG and H_2.

The main object of the testing is to characterise the emissions of Hydro-Carbon (HC) and Nitrogen-Oxide (NOx) compounds with different combinations of throttle position, ignition timing and fuel blending.

The first LPG data set covered a set of power outputs from idle to 13HP. The engine was run rich enough to not have any lean burn misfire and all HC values were below 70PPM. The test speed was 3000RPM to represent the typical electrical generator speed required for 230VAC @ 50Hz.

The LPG NO_x vs power graph, shown in **Figure 5,** shows the increase of NO_x as power output increases. Up to 5HP the NO_x is low and then rapidly increases as the engine is driven to maximum power. The mixture was set lean to 1.22-1.31 lambda (λ) for power output 0 to 8 HP. The emissions are lowest within this λ range, and no HC misfire occurs. Above 8HP a richer fuel mix was used to achieve the higher power outputs but with the consequence of much higher NOx values.

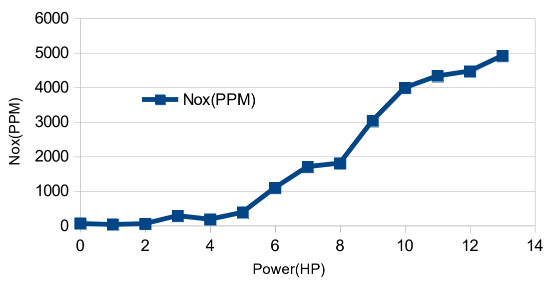


Figure 5, NO_x vs power, LPG

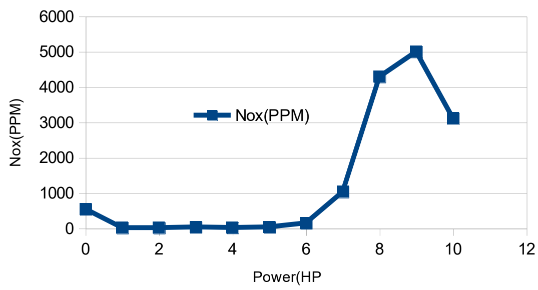


Figure 6, NOx vs power, H_2

The H_2 graph, **Figure 6, NO_x vs power**, shows the increase of NOx as power output increases. Up to 6HP the NOx is again low. The NOx then rapidly increases as the engine is driven to maximum power. The maximum power achieved was 10HP due to the density differences between LPG and H_2. At 10HP the NOx was reduced by retarding the ignition to 0deg. The λ at 10HP was 0.95.

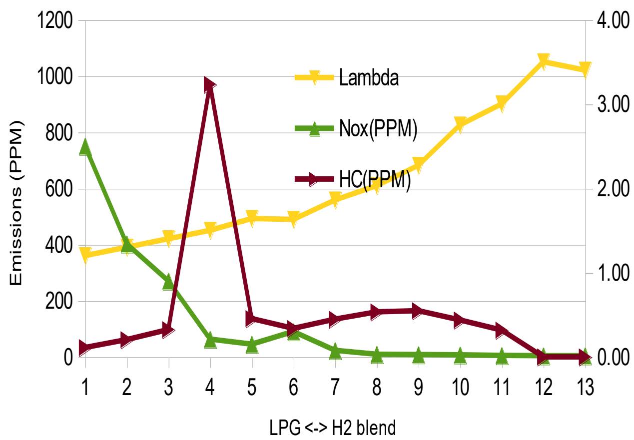


Figure 7 Effect of Lambda on emissions

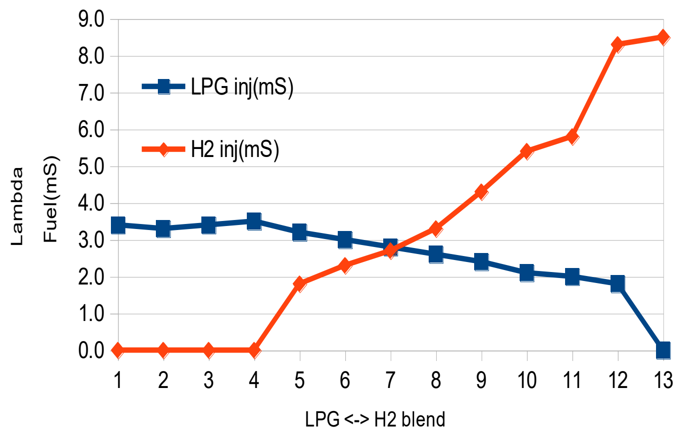


Figure 8 Injection duration with fuel blend

The blended test shown was at 3000RPM and 3HP power output.

The blended fuel data is displayed as two graphs. The LH graph**, Figure 7,** shows the emissions of HC and NOx together with the λ value. The high spike in HC demonstrates lean burn misfire occurring at a λ value of 1.50 with LPG-only fuelling. The HC emissions go to zero as the LPG ratio of fuelling goes to zero.

The second graph**, Figure 8,** shows the blending of the LPG and H_2. Initially the engine runs only on LPG and then H_2. Is introduced. At each point of the blending, the LPG amount is reduced to bring the power output back to 3HP. Both fuels were injected at the same pressure of 1.5bar above atmospheric. Running on only LPG required 3.3mS fuel injection. Running only on H_2. required 8.5mS of fuel for the same 3HP output.

The HC emissions drop to zero when there is a high ratio of H_2. to LPG but with a significant amount of LPG still present. The presence of small amounts of H_2. does not seem to reduce the amount of HC emissions. The λ value when operating on H_2. Goes above λ 1.50 all the way to 3.50. More work is required to see if this a true lambda reading or if the presence of H_2. is changing the calibration of the λ sensor.

4. Conclusions

There does not appear to be much benefit of blending LPG and H_2. as the optimal ignition timing is very different for each fuel and hence in blended format, one or other of the fuels will have non-optimal ignition timing. The testing has shown that it is relatively straight forward to have a dual fuel engine that can be easily switched for LPG to H_2.

5. Development of CAGE engine control platforms

Success of the HGE technology uses sophisticated control and management of engine combustion so that every aspect of the combustion process can be optimised at every combustion event.

This relies on continuous monitoring and feedback of the engine operating process and ability to instantaneously adjust to demands such as load and change in ambient conditions This enables exceptional control of emissions without compromising performance or efficiency.

CTL has two engine control platforms, one for larger complex engines and another designed specifically for smaller engines targeting lower cost applications. Both deliver the same levels of combustion control. The platforms have been developed over several years by OakTec and were both further optimised in the HGE project to allow for the complexity of running multiple fuels with different burn characteristics. The 6HGE controller is developed entirely in house and the 60HGE system in partnership with a leading ECU manufacturer but to CTL's specification.

A new controller is being designed with available components for high volume production to enable HGE technology to have volume commercial roll-out. **Figure 9** Photo shows CTL's bespoke small engine controllers in tandem to control two fuelling systems on prototype engine for development. One ECU controls both systems in final version.

Figure 9 CAGE small engine controllers

6. Generator build test and trials.

The final development of the 20HGE engine was a refined calibration to suit the requirements of a construction site genset. CTL had developed genset systems prior to the project so had knowledge of load response and speed control algorithms and these were applied in the calibration to ensure that no spikes in emission output occur during start-up, light load and sudden load demand. Two new generators were developed in the project producing 10kW and 15kW and supplied to major plant hire companies for trial with LPG fuel using standard gas take-off 47kg bottles.

Feedback forms were supplied, and feedback will be used for future developments. That said the feedback has been overwhelmingly positive. The existing 25kW machine that uses the 60HGE engine has also been trialled in the project initially with HS2 at Euston and latterly with a plant hire company. Photos below show the 15kW (**Figure 10**) and 25kW (**Figure 11**) ultra-low emission CAGE LPG gensets.

Figure 10 CAGE 15PG generator

Figure 11 CAGE 25PG generator

7. Exhaust Emissions test on site by Imperial College

Imperial visited CTL labs and measured engine test bed emissions in lab conditions and then the Euston site and undertook a 2 day test programme of the tailpipe emissions of the CAGE genset using their PEMS measuring system. They compared the two sets of results and corelated against the Horiba Mexa lab emissions measuring equipment.

This CAGE machine is fuelled by direct injected LPG from a tank in the undercarriage of the genset. The emission results exactly confirmed the targets set and levels achieved by the CTL engine development team.

The emissions were measured at various load points and compared against data previously gathered from diesel machines and against the European Stage V emission standard that was introduced as a legally binding standard in 2020.

The CAGE machine delivered 90-95% reduction in all toxic emissions compared to the Stage V standard for diesel. A full report from CLEC at Imperial College detailing this has been submitted to BEIS.

Later in the project Imperial visited CTL for a second time and measured emissions from the 60HGE running with hydrogen and the 20HGE running with LPG. These results align with the 60HGE measurements summarised below.

Figure 12 shows CAGE engine emissions compared with EU Stage V and Stage 3A.

The test results indicated

- 95% carbon monoxide (CO) reduction compared to Stage III-A and Stage V diesel emission standards and 94% CO reduction compared to spark ignition emission standards.
- 96% nitrogen oxides (NO_X) reduction compared to Stage III-A and Stage V diesel emission standards and 94% NO_X reduction compared to spark ignition emission standards.
- 98% particulate matter (PM) reduction compared to Stage III-A and 33% PM reduction compared to Stage V diesel emission standards; there are no spark ignition emission standards.
- 95% particle number (PN) reduction compared to Stage V diesel emission standards (there are no Stage III-A PN emission standards); there are no spark ignition emission standards.

Table 3 Summary of emissions measured from the CAGE-generator on-site HS2

Emission species	Stage IIIA Diesel standard (Cat. J)	Stage V Diesel standard (NRE-v/c-3)	Stage V SI standard (NRS-v-2b)	average working emissions measured	% difference		
	g/kWh			g/kWh	IIIA	V	SI
CO	5.0	5.0	4.4	0.27	-95%	-95%	-94%
NOx	4.7	4.7	2.7	0.17	-96%	-96%	-94%
PM	0.4	0.015	NA	0.01	-98%	-33%	NA
PN	NA	1E+12	NA	5.395E+10	NA	-95%	NA

Figure 12 Summary of emissions test by Imperial College at HS2 Euston

8. HGE Benefits and challenges

The project has demonstrated very clear benefits reflected by keen commercial interest from the sector. It has also clearly brought into focus several challenges faced by CTL and all other UK SME's developing power solutions using gas and alternative fuels.

Benefits. The HGE concept offers a workable and pragmatic technology whereby a power solution with the broad capability of a diesel equivalent can be used in the harsh working environments of the construction, quarrying and mining sectors in the immediate term with clear benefits to the environment through minimal emissions. Over time, and when a hydrogen or other net zero fuel supply chain becomes practical, the same machine can switch to the net zero fuel either on a permanent basis or selectively as the supply chain dictates. This means that the customer can make a net zero compliant investment now, users can become used to working with fuels other than diesel and an alternative fuel supply chain can be developed on a sound economic platform and with a clear net zero end game.

Incentives for the customers to switch are many fold and especially as the HGE solution offers economic benefits over the current incumbent diesel solution. Despite the exceptional emissions performance of the CAGE technology, it will be similar or lower cost than an emissions compliant diesel engine despite making the Stage V standard almost obsolete due to the achievable emissions standards.

Figure 12 gives an insight into the 2019 Stage V standard for diesel engines and spark ignition (petrol) engines. The CAGE tests were carried out over a spread of load points representative of the Stage V test process. Over the test cycle the allowable emissions of CO is 5.0 g/kWhr with CAGE aggregated at 0.27g/kWhr. Allowable NOx emissions are 4.7g/kWhr with CAGE recording 0.17g/kWhr. Hydrocarbon emission reduction is at a similar level. Although PM numbers are not a factor of the test for a spark ignition engine they were measured anyway against a diesel with a particulate filtration system, and the CAGE LPG engine showed a 33% reduction and a 98% reduction against the previous Stage 111A emission standard still widely used in the sector.

A further advantage is the cost benefit of many gas fuels especially bulk LPG, that is broadly 50% of the cost of diesel. Bulk LPG can currently be purchased at around £0.5/ litre with diesel at £1.55 per litre purchased in bulk by the construction sector. (Sunbelt)

In terms of energy density 1 litre of LPG weighs 0.5kg whereas 1 litre of diesel weighs 0.84 kg. This means that bulk LPG is 55-60% of the cost of bulk diesel and CAGE engines are broadly comparable with industrial diesel engines of the same size in terms of fuel efficiency at 250g/kWhr so the fuel cost savings can be realistically stated at 40%.

Whilst hydrogen is currently prohibitively expensive for many applications, considerable work and innovation is likely to reduce this cost over time. When widely available HGE can, at the flick of a switch, become a hydrogen engine. Calor currently estimate that green hydrogen is between 10 and 12 times the cost of LPG and it is well accepted that there needs to be a revolution in the delivery and production of green hydrogen to make it commercially viable in the sector.

Although CAGE engines and generators have multi-fuel capability there will be no provision for them to run on conventional petrol or diesel fuels as this would introduce some level of technology compromise and move away from CTL's gas is better message.

The CAGE generators developed in the project have further benefits in that they are quieter than diesel equivalents due to the more gentle combustion of gas, they will have longer service intervals and potentially longer useable life due to lower combustion pressures and the fact that gas does not have the issues with lubricant oil contamination that is prevalent in liquid fuelled engines.

The project has demonstrated that the solution is scalable to a wide variety of engines of different types and configurations. As the core IP is in the intelligent control platforms and dedicated combustion strategies that are fuel and application specific, the scale-up of the technology relies on replicating the R&D processes developed in the project on the selected engine platforms and working with OEM's to manufacture and market.

Challenges and risks

Scaling of the technology and other similar RDR solutions relies on products meeting certification standards and fuel supply chains being developed. These are currently the biggest hurdles to mass adoption of the HGE technology and present a risk to the roll-out of what is a very practical diesel replacement solution.

- **Emission certification** is a legal requirement for commercial sale of any NRMM combustion engine. The current standard is EU Stage V introduced in 2019. Many engines especially diesel fuelled struggle to meet this standard and there is a great shortage of certified engine products available in the industrial engine market. Certified diesel engines are very expensive, often more than twice the cost of previous non-Stage V products. These means that there are still thousands of non-certified machines being sold into the market as enforcement is weak and products are needed to keep business as usual.
  CTL's CAGE engines are so clean as to make Stage V obsolete, yet great barriers exist to an SME engine developer like CTL to certify as traditionally the costs are prohibitive the certification process is very long winded and geared to global OEM's whose objectives are to 'scrape through' the test with the lowest possible level of technology and cost. We believe that to enable certification of low emission alternative fuel engines made by SMEs in low volume a new process needs to be developed.
  This needs to be cost effective and pragmatic ideally mirroring the automotive IVA system for low volume vehicles OEM's. VCA and policy makers (including BEIS, DFT etc) need to be engaged to achieve this.

- **The alternative fuel supply chain.** Currently there are very great hurdles to the provision of gas fuels into the construction and other sectors. Whilst bottled gas is supplied to the sector and H&S protocols are in place for its use, the supply of gas fuels including LPG and RDME in bulk tanks to be used in liquid form is very difficult as there are not mature protocols in place. For any machine with a large power requirement bulk liquid gas supply is essential. Removal of these barriers is vital to make refuelling of gas engines a practical proposition in the construction sector. This requires a framework to be developed that includes the HSE, Liquid Gas UK and bodies representing the construction sector to develop viable solutions that will enable gas suppliers to provide portable site based bulk refuelling tanks that can be moved around the site to refuel equipment. Protocols and systems already exist for automotive (garage forecourts) and domestic heating tanks that could be adapted to solve this problem.

These problems almost certainly exist with other alternative fuel types and these could be considered within the same dialogue.

Generator trials

The 3 generators developed within the project have been loaned to major plant hire companies for trials along with construction companies Mace Dragados and Keir.

The generators were tested using LPG fuel only as the full solution is earmarked for more extensive trials in Phase 2.

The purpose of the trial was a basic assessment of the performance of the machines their ease of operation and subjective assessment of noise in terms of sound level and quality. Reassuringly the feedback from all parties broadly concurred in general there is wholehearted support for the direction of travel of the project and enthusiasm for the level of technical achievement and sophistication.

Figure 13 compares CAGE technologies to the incumbent and currently proposed solutions including hydrogen fuel cells, HVO diesel engines and most other current solutions.

CAGE vs COMPETITION

Technology	Technology Availability	Convenience compared to diesel	Equipment cost	Fuel cost	Energy density	Rare earth material use	Air quality benefits	Net Zero emissions potential
CAGE LPG	Now	Good	Low	Low	Good	No	Fair, Good vs diesel	No, but it is a transition fuel
CAGE bioLPG	Now	Good	Low	Medium	Good	No	Fair, Good vs diesel	Partial (biogas from waste)
CAGE hybrid multi-gas	Short term	Good	Low	Low-High	Good	No	Fair-Good	Yes
CAGE hydrogen	Now	Fair/Good	Low	High	Fair	No	Good	Yes
CAGE biogas	Now	Fair	Low	Very Low	Good	No	Good	Yes
CAGE solar hybrid	Now	Good	Medium	Very Low	Good	*No , Lead Acid*	Good	Yes
Battery Electric power	Now	Fair	High	Low	Poor	Yes	Good	Yes
Renewable electric power	Now	poor	Medium	Very Low	Poor	No	Good	Yes
HVO bio diesel engine	Now	Good	Low	High	Good	No	Poor-fair	Partial
Hydrogen fuel cell	Now	Fair	Very High	High	Fair	Yes	Good	Yes
Synthetic fuel engine	Medium/ Long term	Good	Low	Unknown *Likely High*	Good	No	Fair	Yes
Conventional biogas engines	Now	Poor	Low	Very Low	Poor	No	Poor	Yes (biogas from waste)
Conventional bio diesel	Now	Fair/Good	Low	Quite High	Good	No	Poor	Partial

Figure 13 Technology comparison table

9. HGE route to market

Within RDR1 demonstrations of the CAGE generator have been undertaken by some of the UK's major plant hire companies. CTL has learned that it is not practical to supply directly to major construction companies as they almost exclusively hire their machines of this type.

It is therefore important to engage with the plant hire sector to develop the market entry of the products using CAGE engines. Whilst all players in plant hire are seeking environmentally worthy and net zero products they will only engage with a new product if it is functional and reliable and fits within their existing business models. Key to success in this sector is competitive cost in terms of both capital equipment cost and operating running costs.

CTL believes we have a unique offering to this sector and can establish a significant disruption to the diesel status quo if issues of certification and provision of fuel to site can be overcome. One hire company has a stock of 600 x 35kW battery packs for construction sites but needs a clean generator solution to replace the diesels they currently use for charging. The charging power requirement is 10kW so ideal for the 20HGE and they have agreed to take some on trial.

10. Lessons learned and conclusions.

RDR1 has been a transformational project for CTL. It has enabled the development of a new technology offering built on work previously undertaken in the areas of gas engine development.

The HGE project has been able to achieve all of its objectives both from a technical and commercial perspective. Focussed development and testing of 3 separate hydrogen engines has furthered our expertise in this area and helped us develop a commercial direction for future CTL products. During the project we have gained knowledge in the following areas.

- **Technical.** From R&D using two engines of differing levels of sophistication it was clear that there is no obvious advantages to blending hydrogen with LPG as the different combustion characteristics of the two fuels mean that there is a compromise in the combustion process particularly in terms of spark ignition timing that eliminates any benefit. This is not to say that a fuel mixture does not work more that if hydrogen is available the engine should be run as a hydrogen engine and if not that it should use whatever other gas fuel is available. Furthermore, there was no significant advantage to dosing an LPG mix with a small quantity of hydrogen to extend its lean combustion threshold and so reduce or eliminate NOx emissions at source. It was found that other strategies, and in particular on the more complex engine where valve timing can be varied, can be used to optimise the lean combustion limit.
- **Emissions**. Levels of toxic emissions from LPG engines that the CTL engineers have been able to minimise in the lab can be replicated fully in a working environment. This sometimes requires a minor adjustment to the engine calibration at the product development stage. This results in a step change in 'the art of the possible' when compared even to the very best existing diesel hardware and makes the current emission standards obsolete.
- **Hydrogen engines** can be run at 'zero' emissions if the NOx level is controlled within the combustion process, but this results in a reduction in power output compared to a diesel product of the same capacity. The solution to this is to use larger engines or to develop forced induction systems and high-pressure direct injection of hydrogen into the combustion chamber.
- **Commercial.** The RDR1 project has emphasised the need for a rethink of how alternative fuelled engines are certified for emissions to allow their rapid deployment to market. In particular if an SME focussed standard can be developed for ultra-clean engines it would offer a commercial opportunity for innovative companies to take a lead over the global OEM's who tend to prefer a business-as-usual approach.
- **Fuel supply** to the construction sector has issues that needs to be resolved if alternative fuels are to be widely adopted. Bulk liquid gas fuel deployment has been a particular challenge within this project and bulk fuel supplies are needed if the industry is to move away from diesel.
  - For many technologies being developed within this programme the plant hire sector represents a key route to market and technologies will need to meet with the requirements of this sector if they are to enjoy commercial success.

11. Dissemination events attended during RDR1

CTL was active in attending events to promote HGE activity and CAGE technologies. The first hydrogen generator was used as a show piece and was universally well received.

CTL staff joined panels and made presentations at several events.

A log of events attended is shown below.

- **Futureworx Peterborough 2022** An event to showcase emission reduction technology for the sector. CTL was a panellist at this event and based on the HS2 stand. **Figure 18.**
- **CMDC showcase Portsmouth** An event showcasing technologies developed to decarbonise the maritime sector
- **All Energy Glasgow 2022** The national clean energy show. 2 presentations made by CTL
- **The UK Energy Forum Glasgow .** A government and utilities focussed energy conference, CTL were on the Innovate UK, BEIS, OFGEM stand.
- **India visit** CTL visited OEM partner in India to discuss commercial collaboration. Reciprocal visits by them to the CTL HQ
- **Kenya Innovation Week.** CTL invited by FCDO to represent UK innovation and attend this clean energy focussed event in Nairobi. British High Commission arranged for the CTL team to meet Kenyan President William Ruto at the event.

Figure 14. CAGE hydrogen generator on

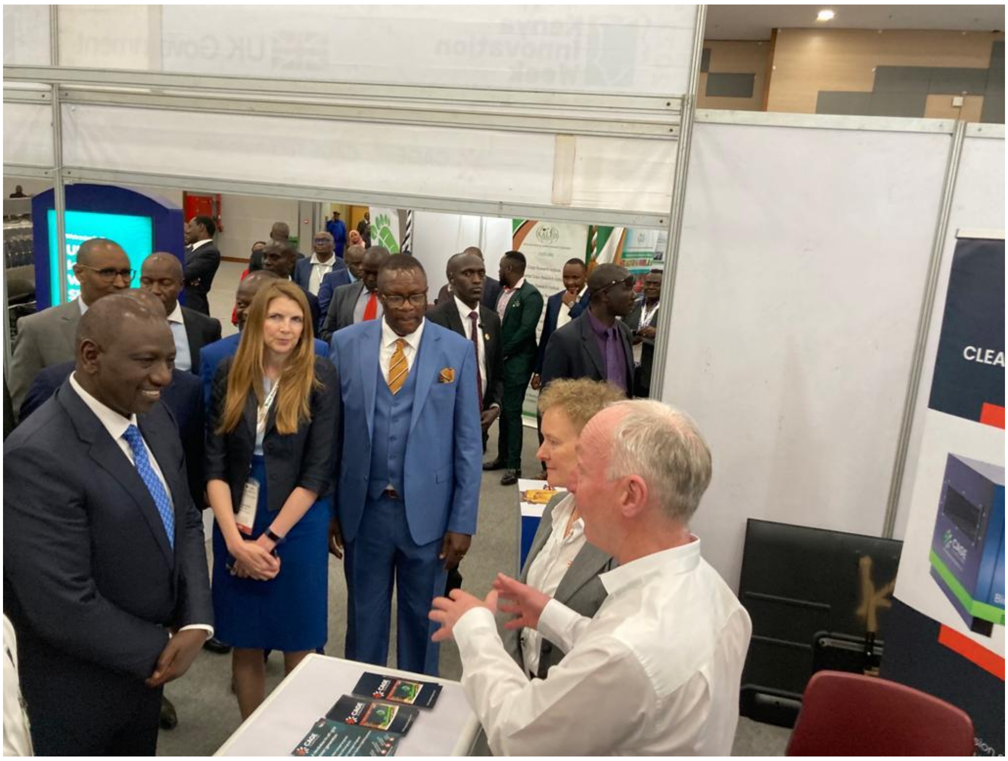


Figure 15. CTL visited by President William Ruto at Kenya Innovation Week

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