UK Government

Hybrid Gas Engine 2 (HGE2)

Red Diesel Replacement Phase 2 (RDR2)

Final Report

This project was supported by the Department for Energy Security & Net Zero through the Net Zero Innovation Portfolio (NZIP)

1 Executive Summary

This report explains the HGE2 project which provides an alternative power solution to the construction sector as a low emission and net zero alternative to diesel fuel, that is currently the de facto fuel for construction power. It covers the rationale behind the concept of the Hybrid Gas Engine (HGE) technology developed within the project, the work carried out by partners to develop, test and evaluate the new technology, and conclusions found from testing and the working trial conducted at the end of the project.

It also covers the future commercialisation of HGE technology and the next steps to ensure that the technology can provide value as part of the roadmap to de-carbonise the construction sector. The report covers the valuable contribution of project partners Calor, Imperial college London, Speedy Services, the HS2 rail project, and EKFB.

The project was supported through the Red Diesel Replacement Phase 2 Programme as part of the Department for Energy Security & Net Zero's Net Zero Innovation Portfolio (NZIP) and match funded by the extensive support from the HS2 rail project, their delivery partners and Speedy Services who were not funded by the project.

1.1 Project Overview

HGE technology offers a practical end-to-end solution to the replacement of diesel power in the construction and associated sectors. It focusses on the direct replacement of diesel generators with ultra-clean gas equivalents. It sought to prove performance and reliability at least on a par with incumbent solutions, and emissions performance an order of magnitude better.

By introducing flexible gas fuelling to power construction equipment, it aimed to show a cost-effective roadmap for net zero power by removing the dependency on immediate supply of net zero fuels. Through an intensive period of R&D to develop a flexible Hybrid Gas Engine, the HGE2 project demonstrated a solution by introducing a generator capable of switching between gas fuels, including LPG, bioLPG and hydrogen, then trialled this solution on construction sites. It also sought to overcome challenges of supply and operation of gas fuels on construction sites and the supply of gas to the generator from bulk storage tanks.

Speedy Services has worked with all partners to enable the introduction of the new technology to site and supported management of the trials from a delivery, logistics and service perspective.

The project meets RDR objectives in the following ways:

1. It developed commercially viable and globally applicable low-carbon, long term alternatives to red diesel.
2. It demonstrated an integrated, low-carbon solution at a moderate scale on site for use in the quarrying, mining and construction sectors.

3. It disseminated the learnings and results of the Red Diesel Replacement programme to international stakeholders, industry and other diesel-using sectors.
4. It helped inform policy teams on the potential of these low-carbon alternatives and create awareness of the spin-off opportunities for other sectors including maritime, agriculture and leisure.
5. It delivered match funding from industry and provided a platform for growth and investment.
6. It accelerated the commercialisation of low-carbon red diesel alternatives

1.2 Key Findings and Results

The HGE2 project successfully demonstrated a practical, ultra-low emission alternative to diesel fuels. The generators produced and trialled have run many hours of development time, both in testing and in trials, and have shown that gas fuels, including hydrogen, can offer a practical alternative to diesel. The caveat to this practicality is the current very high cost and low volumetric energy density of hydrogen and there needs to be considerable progress in its production, storage and end-user cost to enable it to fulfil its potential as a fuel of the future. Whilst not the focus of the project, LPG fuel has proven to be an easy to use, reliable, and very clean alternative to diesel with some carbon benefits, and if net-zero LPG-type fuels can be produced in future it has great potential. DME was also tested as a blended fuel with LPG and proved to be a route to practical carbon reduction when a secure supply chain of renewable (r)DME is established.

The project faced many challenges including technical, management, site access, and logistics, and most of these were successfully overcome during the project. Technical challenges included:

- Extreme difficulties in achieving absolute combustion stability with hydrogen, but a good, compromised combustion configuration enabled successful hydrogen and LPG operation.
- The realisation part way through the project that rDME would not be available within the timescale of the project caused a significant delay whilst a change request was processed and approved.
- Complexities of delivering novel technology on a busy live site and the associated personnel, training and logistics proved challenging but were ultimately overcome by a great delivery team.
- Hydrogen delivery posed many problems partly because of a mismatch of policies and procedures between the supplier and the contractor. Fuel was also delivered to the wrong area of the site so stranding the fuel and preventing operation on the machines it was ordered for.

1.3 Conclusions

Despite the challenges in delivering this complex project the team has great pride in the product delivered and how it has validated the concept of a multi-gas engine with very significant air quality benefits and net zero capabilities. The trial and subsequent demonstration has been very well received by all stakeholders, and this is borne out by real commercial interest in an HGE product both from within the project partners and for external applications.

1.4 Graphical Abstract

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Table 1. Acronym List

Acronym	Meaning
AD	Anaerobic Digestion (biomethane)
BOC	British Oxygen Company (gas supplier)
BSFC	Brake Specific Fuel Consumption
CG	Calor Gas (Gantt)
CLEC	Centre for Low Emission Construction (Imperial College London)
CO_2	Carbon Dioxide
CTL	CAGE Technologies Ltd (project shorthand in Gantt chart)
DME	Dimethyl Ether
ECU	Engine Control Unit
EKFB	Eiffage–Kier–Ferrovial–BAM Joint Venture
HC	Hydrocarbons
HGE	Hybrid Gas Engine
HGE2	Hybrid Gas Engine – Phase 2
HS2	High Speed 2 (UK Rail Project)
LPG	Liquefied Petroleum Gas
MCP	Manifolded Cylinder Pack (hydrogen supply)
NOx	Nitrogen Oxides
NZ	Net Zero
NZIP	Net Zero Innovation Portfolio
OEM	Original Equipment Manufacturer
PDI	Pre-Delivery Inspection
PM	Particulate Mass
PN	Particle Number
RDR / RDR2	Red Diesel Replacement (Phase 2)
rDME	Renewable Dimethyl Ether
RPM	Revolutions Per Minute
SS	Speedy Services (Gantt)
VCA	Vehicle Certification Agency (UK)

2 Background

2.1 Project Consortium

The HGE2 project was created and led by the innovation partner CAGE Technologies Ltd. Based in Lancashire with a team of 17 full and part time staff, CAGE has a history of innovation in clean energy technologies with a focus on ultra-low emission gas engines, and a secondary expertise in hybridisation with batteries and other energy renewables. Technology highlights previously developed by the team include a novel gas engine concept developed to TRL6, extensively prototyped and trialled, and patented in 8 countries.

CAGE has benefitted from very strong industrial partnerships and previous funding from Innovate UK, BEIS and others to develop world-leading small gas engine technologies and hybrid systems and developed engines to use a range of gas fuels including biogas, hydrogen, LPG, natural gas and blended gases from recycling processes.

Efficient clean gas combustion is enabled by use of bespoke engine control platforms that enable optimised combustion management. The engine technology has been developed by an internal engine design team who have had long successful careers running automotive OEM and global motorsport engine design and development projects, including several clean sheet designs of high-performance engines. CAGE has in-house electrical engineering expertise provided by former senior control engineers from the local military aircraft industry who have designed seven versions of our own engine management Engine Control Units (ECUs), plus data harvesting and telemetry systems.

The delivery consortium for the project included 5 partners. These were: gas supplier, Calor; construction emissions specialists from Imperial College London; the HS2 rail project; their delivery partner EKFB; and construction supply specialist, Speedy Services.

2.1.1 Calor Gas

A long-term supporter of CAGE innovation, Calor's role in the project involved addressing logistical issues and regulations to enable gas fuels to be safely used to replace diesel on construction sites. They supplied DME fuel to assist CAGE in development of the novel engine, and the supply of fuelling systems and fuel for R&D, generator endurance testing, and the trial phase.

Based in Warwick, Calor Gas is a leading supplier of LPG (Liquefied Petroleum Gas) in the UK, primarily serving homes and businesses that are not connected to the mains gas grid. They offer a variety of services, including providing LPG for heating, cooking, and hot water, as well as solutions for businesses and rural homes. Calor Gas is a part of SHV Energy, the world's largest dedicated LPG distributor. The company has over 2000 staff and in 2023 turned over £550M.

As a distribution company, energy efficiency is very important from an environmental and a cost perspective. Calor is actively investing in alternative fuels - such as BioLPG, rLPG and eLPG - and alternative vehicles to reduce impact on the environment and local air quality. They are sponsors of Air Quality News, and vocal participants at events focused on cleaner air such as Freight in the City and the Air Quality Awards. Their involvement in the HGE2 project had partial funding from DESNZ.

2.1.2 Imperial College London - Centre for Low Emission Construction (CLEC)

In this project, CLEC followed on from previous project work measuring diesel emissions on a wide range of construction applications along with other alternative fuel solutions including earlier CAGE engines to measure exhaust emissions from HGE technology at both lab scale and over the site trial period. This testing allows direct comparison of the clean gas fuels with an extensive database of site diesel emissions and against the latest UK and EU Stage V off-highway emission standard.

The Centre for Low Emission Construction (CLEC) is a research group within the Environmental Research Group at Imperial College London. CLEC focuses on conducting research to create scientific evidence for reducing emissions in the construction industry, with the goal of minimizing the impact on worker exposure, local air quality, and the environment. They collaborate with various stakeholders, including contractors, plant manufacturers, and supply chain partners, to develop and implement low emission technologies and practices.

They have been involved in projects related to chemical dust suppressants, diesel fuel additives, alternative fuels, and other technologies to reduce emissions from construction activities. The group has been working on low emission construction since 2004. CLEC is a funded partner in the HGE2 project.

2.1.3 High Speed 2 (HS2) Rail Project

HS2 sponsored the project by enabling the trial of HGE2 generators on their construction sites in Phase 1, the London to Birmingham section of the rail line. They facilitated the agreement with construction delivery partner EKFB and managed the complex structuring of the wider collaboration and trial. This activity aligns with their policies for improving air quality in the construction process, introducing innovations to assist the transition away from carbon fuels and leaving a legacy of benefits for the sector from the construction process that can be adopted for future generations.

The HS2 project is a high-speed railway under construction in the UK, designed to connect London and Birmingham. It aims to improve rail capacity, reduce journey times, and boost the economy by creating jobs and connecting major cities.

Environmental Benefits: trains will run on zero-carbon electricity, contributing to the decarbonization of the rail network.

Economic Impact: The project has generated numerous jobs, stimulated economic growth, and will improve connectivity for businesses and individuals.

2.1.4 EKFB

HS2 brokered the agreement with EKFB to facilitate the trials of the HGE generators. They sponsored the project by putting in place a management team to enable the trial process to take place. They compiled a detailed business case with HS2 management to ensure the project had potential to deliver both environmental and economic benefits to the construction process. As part of this they funded the onsite use of LPG as a baseline gas fuel. They addressed all the health and safety and logistics challenges working closely with Speedy, CAGE, Calor and Imperial College.

EKFB employs 4500 staff in a joint venture that brings together international, market leading expertise from four leading civil engineering and construction companies: Eiffage, Kier, Ferrovial Construction and BAM Nuttall. All four partners bring specialist expertise in the design, construction, operation, financing and maintenance of railway networks, including some of Europe’s largest high speed rail projects.

EKFB was appointed by HS2 to deliver civil engineering works across an 80km section of the new high speed rail link between the Chiltern Tunnel and Long Itchington Wood. The scope of the works includes 15 viaducts, 6.9km of green tunnels, 22km of road diversions, 81 bridges and around 30 million cubic metres of excavation.

2.1.5 Speedy Services

A long-term supporter of CAGE, Speedy sponsored the project by undertaking the task of managing the equipment trials on the HS2/EKFB sites.

Access to manage technical operations on complex, highly regulated construction sites is a major challenge and can only be delivered by organisations that meet very strict operating criteria including staff training, health and safety protocols and environmental credentials. The supplier needs the logistic mechanisms in place to ensure that the delivery and work process exactly adheres to the operational policies of the construction project, and CAGE, as technology developer, has none of these functions and systems in place. Delivery of the trials would have been impossible without the full collaboration of a major equipment supplier such as Speedy.

Speedy Hire is based near Manchester and employs around 3,300 people. This includes staff across various departments like customer service, technical roles, finance, HR, and logistics. They have a large network with over 180 depots across the UK and Ireland, as well as international operations.

Speedy Hire is a UK company specializing in the hire of tools, equipment, and plant machinery, primarily serving the construction, infrastructure, and industrial sectors. They provide comprehensive hire solutions and support services to enable their customers' projects. Speedy Hire also offers digital services, including online ordering and account management through their website and app.

Sustainability Focus: Speedy Hire emphasizes sustainability, aiming to minimize environmental impact and contribute to stronger communities.

2.2 Project Background

The CAGE HGE solution built on previous work with partners including HS2, Calor Gas and Speedy where prototype generators had been developed for both LPG and hydrogen as single fuel engines. The sophistication of CAGE engine control systems and the depth of knowledge in the team enabled development of a concept engine that enabled switching between different gas fuels with different combustion characteristics.

As a concept this was proposed to Speedy and others with the rationale that a generator that can switch between conventional and net zero gas fuels will allow a progressive move away from diesel and allow net zero products to be deployed ahead of a mature fuel supply chain enabling fuel use choices to be made around availability, cost and environmental benefit. This concept was seen as a solution to enable the transition away from diesel to NZ fuel options and as such was used as the technology development theme for Phase 1 and 2 of the RDR initiative.

Figure 1. HGE2 project organogram

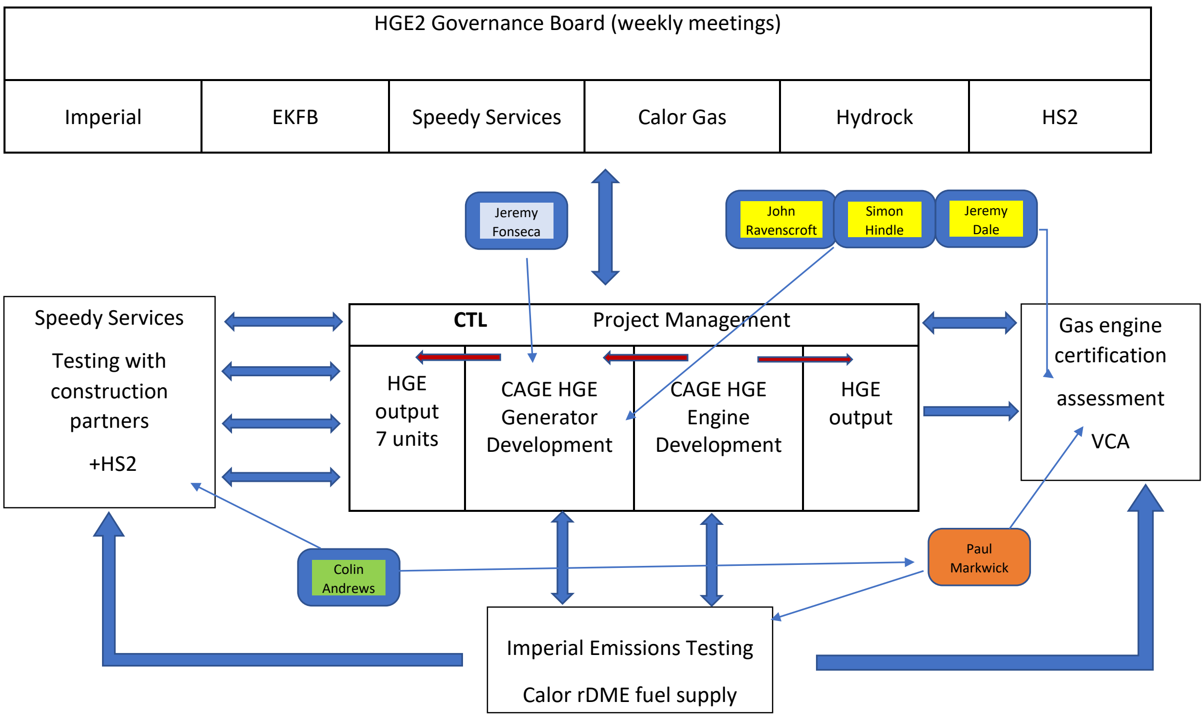


Table 2. Proposed Project Finance Table

Payment Milestone ID	Invoice Due Date *dd/mm/yy*	Planned Deliverable	Financial Year Work Done	Original Planned Invoice Amount (exc VAT)	Final Planned Invoice Amount (exc VAT)	Actual Final Invoice Amount (exc VAT)
1	31/08/2023	1.15, 2.01, 2.02	2023/24	£232,000.00	£100,661.10	£100,661.10
2	30/11/2023	1.01, 2.03, 2.04, 4.011	2023/24	£370,000.44	£177,333.23	£177,333.23
3	31/03/2024	1.02, 2.05, 2.11, 4.012	2023/24	£247,500.00	£165,841.04	£165,841.04
4	15/06/2024	1.03, 1.13, 2.061, 2.071, 5.01	2024/25	£222,000.00	£89,942.71	£89,942.71
5	31/10/2024	1.04, 1.08, 1.1, 1.11, 1.16, 2.062, 2.072, 2.081, 4.07, 4.08, 4.13	2024/25	£102,820.00	£181,008.09	£181,008.09
6	23/12/2024	1.05, 2.082, 2.09, 2.14	2024/25	£143,500.00	£103,322.17	£103,322.17
7	14/03/2025	1.06, 1.12, 1.14, 2.1, 2.12, 3.04, 4.013, 4.02, 4.03, 4.04, 4.06, 4.09, 4.14, 5.021, 5.061	2024/25	£116,500.00	£266,852.77	£266,852.77
8	31/05/2025	1.07, 2.13, 4.1, 5.022	2024/25	£166,500.00	£110,137.55	£110,137.55
9	31/07/2025	1.09, 1.17, 1.18, 1.19, 1.2, 3.05, 3.06, 3.07, 4.11, 4.12, 4.15, 5.03, 5.04, 5.05, 5.062	2025/26	No MS9 in original plan	£201,250.47	£199,415.34

3 Project Overview

The text below describes the objectives set out in the application prior to the start of the project.

Table 3. Project Cost Breakdown Form

	Partner Name	Original total organisation proposed cost (£)	Final total organisation proposed cost (£)	Original proposed total funding Amount for organisation (£)	Final proposed total funding Amount for organisation (£)
1	CAGE Technologies Ltd	£1,506,771	£1,548,342	£1,064,323	£1,093,687
2	Calor Gas Ltd	£556,670	£111,307	£292,252	£58,436
3	CLEC Imperial	£444,083	£444,048	£244,245	£244,227
Total		£2,507,524	£2,103,697	£1,600,820	£1,396,349

HGE technology is a practical and pragmatic solution to replace diesel engines in construction. It offers the use of widely available, cost-effective, ultra-clean fuels as a short-term replacement yet can transition to net zero fuels such as hydrogen and rDME as soon as these are commercially available. HGE engines have similar performance and efficiency capability to diesel, can use lower cost fuels and are robust, long-life propositions.

The HGE2 project follows from the successful HGE project that delivered three working prototype gas engine platforms that can use hydrogen, LPG or other gas fuels. Using LPG fuel, the engines were installed in generators and demonstrated to key operators in the construction sector, including major plant hire and construction companies. They were received with great enthusiasm. In the HGE2 project, the technology has been trialled in generators on construction sites demonstrating its full multi-fuel and net-zero capabilities. The engine platform was also developed to accept rDME, a net zero fuel with similar properties to LPG in terms of storage and transportation, though rDME could not be used for trials due to supply not being possible within the timescale of the project.

The HGE2 project also aimed to address two of the barriers to wide adoption of alternative fuel engines in the off-highway sector. The first of these was the certification to meet emission standards to allow legal commercial supply. Secondly, it considered measures to ease the safe supply of alternative fuels to the construction sector at the point of use where currently there are few protocols in place and many restrictions.

4 Design Considerations, Technical Development and Challenge

4.1 Initial HGE2 Design and Development

The project built on the successful execution of the initial HGE project, an R&D focused RDR Phase 1 project that experimented with combusting multiple gas fuels in the same single cylinder research engine with a particular focus on LPG (propane and butane) and hydrogen. At the same time during the HGE project plans were laid out to transition to a Phase 2 application with the partners that joined the HGE2 project. During Phase 1 a suitable engine platform and supply OEM, Cooper Corporation, was selected for Phase 2. Coopers were selected as they manufacture an appropriately sized, Ricardo UK designed, industrial engine for the target output and were prepared to build bespoke iterations of their spark ignition model to allow optimisation of the HGE concept. They also manufacture a range of generators for the higher end of the India market including military and they could supply full generator kits to allow prototype HGE products to be developed.

To help CAGE meet the ambitious project timelines generator kits were supplied to the UK prior to the project so that they could be purchased and delivered to CAGE during the early development phase, so cutting long lead times for the hardware and potential R&D delays.

Using information from Phase 1 the engine was configured in a CAGE test cell to begin development of the HGE concept engine. The concept engine was developed to accept 3 fuel types: LPG, Hydrogen and rDME (renewable Dimethyl Ether).

The generator kits were assembled at CAGE with the prototype engines and allow testing to begin quickly. Throughout the development process iterations of the CAGE engine control unit (ECU) were developed to allow it to respond to the combustion of the very different fuel types and a new ECU platform was developed with our UK manufacturing partner.

The CAGE team had previously attended HAZID/HAZOP training around the use of hydrogen in engines and generators and safety protocols developed during this process were adopted and enhanced within RDR2.

Using different iterations of the HGE engine system, three generators were built and tested during the early process and adapted to work with a Speedy BSU (Battery Storage Unit) of the type proposed for use on the trial phase. The hybrid system was subject to different load and duty cycles including powering work buildings and charging EV’s. Endurance testing of the engine then ran throughout the project on this BSU.

Extensive running of the Cooper generator began to expose a few weaknesses in the design and manufacture that would deem it inappropriate for use on a UK construction site at the standards expected within the HS2 project. In particular, the electrical outputs, whilst of acceptable quality, would not comply with the UK standard.

This prompted a change request for the project to transition to a bespoke UK-manufactured generator using the Cooper based HGE engine and as many components that could be salvaged from the Cooper machines.

Generators for the trial process were manufactured by Sutton Power based near Scunthorpe and meet all UK standards with a CE certification.

4.2 Technology Development

WP2 was the process of engine and generator development, testing and calibration using the Coopers base engine as a platform for the HGE generator product. It was split into the deliverables listed below and includes procurement, engine development, testing and generator design and build.

Table 4. Project Deliverables

2.01	HGE Define engine technical specifications
2.02	HGE procurement of development items
2.03	HGE Engine calibration - rDME and hydrogen
2.04	HGE procurement of testing items and long-lead items for first batch of trial generators
2.05	HGE engine build (in generator) for testing - looms, ECUs, fuelling systems
2.06	HGE generator development and testing including endurance emissions pt 1 - Hydrogen generator development
2.07	HGE generator development and testing including endurance emissions pt 2 - Hydrogen generator testing, refinement and finalised design.
2.08	HGE generator development and testing including endurance emissions pt 3 - rDME generator development
2.09	HGE generator development and testing including endurance emissions pt 4 - rDME generator testing, refinement and finalised design.
2.10	HGE generator development and testing including endurance emissions pt 5 - In-house endurance testing of developed generators.
2.11	HGE procurement of long-lead items for second batch of trial generators
2.12	First batch of 5 build for trial
2.13	Second batch of 5 build for trial

A summary of the work packages that included R&D is described below and these have been explained in more detail in previous reports submitted as claim evidence.

Table 5. Gantt Chart

					M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20
		Task		Support	Jul-23			Oct-23			Jan-24			Apr-24			Jul-24			Oct-24			Jan-25	
WP1		Project management, governance, finance	CTL	All partners																				
WP2		HGE engine and generator development	CTL	SS/CG/ CLEC																				
2.01-2.02	2a	HGE define technical specifications & procurement	CTL	SS/CG		MS1 ◊																		
2.03-2.04	2b	HGE Engine calibration RDME and hydrogen	CTL	CG/CLEC					MS2 ◊															
2.05	2c	HGE engine build (in generator) for testing - looms, ECUs, fuelling systems	CTL									MS3 ◊												
2.06-2.10	2d	HGE generator development and testing including endurance, emissions	CTL	CG								MS3 ◊		MS4 ◊			MS5 ◊	MS6 ◊					MS7 ◊	
2.11-2.12	2e	First batch of 5 build for trial	CTL												MS4 ◊									
2.13	2f	Second batch of 5 build for trial	CTL															MS5 ◊						
WP3		Fuelling. Development of rDME supply and supply to trials	CG	CTL																				
3.01	3a	Develop rDME delivery plan and bottling solution,	CG			MS1 ◊																		

		procurement																						
3.02	3b	rDME Filling station order placed	CG		**UNABLE TO COMPLETE.** **SEE REPORT**																			
3.03	3c	rDME Filling Station Installed & Commissioned	CG																					
3.04	3d	rDME cylinders delivered & certified	CG																					
3.05	3e	First Supply of rDME to Trial Site	CG	All partners											MS5 ◊									
3.06	3f	Delivery of Field Trials	CG	All partners																				MS8 ◊
3.07	3g	Bulk storage solution assessment	CG	All partners																	MS6 ◊			
WP4		Emissions, testing and certification	CLEC	All partners																				
4.01	4a	Engage stake holders to create certification plan	CLEC	CTL/VCA		MS1 ◊																		

The engine selected for the project is described below and is used in all iterations with all fuels.

- Engine OEM Cooper Corporation, Satara, India
- Capacity 1200 cc in parallel twin-cylinder format.
- Liquid cooling.
- Layout - Overhead camshafts and 4 valves per cylinder
- Air induction. V1 naturally aspirated, V2 (final) turbocharged with intercooler
- Operating speed 3000RPM to allow 50hz power generation
- Fuelling:
  - Hydrogen/LPG/LPG+rDME blend. Port injection at 1.5bar pressure
- Engine Control: CAGE gas engine ECU controls ignition and fuelling functions with control maps that can be switched externally to allow the fuel type to be selected.
- Sensors feeding information to the ECU include air inlet and cooling temperature, barometric pressure, boost pressure, fuel temperature and pressure, exhaust gas lambda, engine speed
- Engine loading is managed by drive-by-wire throttle controlled by the ECU.
- Emissions control uses wide band lambda closed loop control and 3-way platinum coated catalytic convertor.

D2.03 was the baseline experimentation and calibration of the engine on the two renewable fuels, hydrogen and rDME. Previous work in Phase 1 had developed a refined engine calibration using a low-pressure LPG gas supply and this was used as a benchmark for engine performance during Phase2.

The CAGE HGE engine was developed at CAGE Technologies. The testbed is an automotive specification Schenck 200kW engine dynamometer and control functions. Hydrogen was supplied from a MCP gas store from 9 vertical gas take-off bottles with outlets manifolded together. DME was supplied from a bank of bottles provided to the project by Calor through supplier BOC.

The calibration of the engine was carried out by two engineers. Every test run was logged on the test cell computer and all critical functions recorded including: power; torque; temperatures, including inlet air and exhaust gas; engine out emissions; post cat emissions when fitted; ambient and fuel pressures.

Figure 2. Test cell hydrogen store and control room

4.3 Hydrogen Testing

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.

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

When these elements were addressed the main challenge of a refined hydrogen engine calibration was the reduction/elimination of NOx 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.

The HGE engine uses a port injected gaseous hydrogen supply controlled by the CAGE ECU. Baseline testing was conducted over a range of air fuel ratios, ignition timings, valve timings, injection timing etc. The engine was then calibrated to run at continuous power with minimal NOx emissions and can deliver 16-17kW at 3000 RPM in this condition.

NOx production in a combustion engine is a chemical reaction that is a function of high temperature and pressure during the combustion event. It is particularly prevalent with limited amounts of excess air when combustion transitions from stoichiometric (Lambda 1 = ideal air/fuel ratio) to lean combustion where there is a small amount of excess air. With larger amounts of excess air (leaner combustion) hydrogen combusts very well and there is a point in the cycle where the engine delivers good performance, yet the NOx emissions fall away to zero. This is the band of operation that we targeted in this calibration. The engine was tested between Lambda 1 and Lambda 4+, a condition that is ultra-lean and delivers no useable power. With very lean mixtures the engine can operate at ‘open throttle’ with load controlled by fuel supply and this benefits the efficiency of the engine by reducing pumping losses.

The V1 naturally aspirated engine produced 16kW at 300RPM and 12 kW at 1500 RPM compared to 25kW on LPG at 3000RPM so it proved not possible to match LPG performance with target levels of NOx emissions with a naturally aspirated engine.

It was clear that there was potential to use forced induction to increase performance with a low NOx, lean burn regime and a decision was made to introduce a turbocharger system.

A calibration of the HGE generators was developed around these parameters for direct transfer to a generator application. This calibration requires the engine to respond instantly to load demand and be stable at its operating speed to ensure steady voltage output.

4.4 DME Engine Development

DME was supplied to the project by BOC. This was the first time that CTL had experimented with DME in an engine, and there was little resource available about its use in IC engines.

The potential advantages of rDME as a fuel are its ability to be created from recycled plastic waste and its liquid/gas properties that are similar to LPG in that it can be stored as a liquid in the same vessels as used for LPG, with similar properties in its transition from liquid to gaseous state, so enabling its use within the LPG infrastructure.

Whilst DME is a gas rather than a heavy oil, it has combustion characteristics similar to diesel and has been tested previously in compression ignition engines as part of academic research. It has also been blended with LPG to run in spark ignition engines and this has always been recognised by the CAGE team as a likely direction for commercial development.

When a DME supply was secured, CTL commenced experimentation and testing in the Coopers engine. It became apparent that performance of the engine in this specification would be restricted by a tendency of the fuel to detonate at high loads. The engine could run at lighter loads, but at 1500 RPM its output was restricted to around 5kW insufficient for this application. Engine out emissions were broadly similar to LPG engines previously developed so not an issue

4.4.1 Learnings and Next Steps

During MS3 a development programme further investigated the combustion of rDME (renewable dimethyl ether) in a single cylinder research engine. There were 2 pieces of work:

1. Experimentation of DME blended with LPG over a broad range of mixtures. The purpose of this was to establish optimal mixtures of the two fuels and investigate the practicality of moving this to a trial phase. This was successful at 50-50% blends and lower in an optimised engine.
2. Experimentation using a range of lower compression ratios to establish a safe specification for a DME fuelled spark ignition engine. It was concluded that 100% DME would not work satisfactorily in a conventional spark ignition piston engine.

The use of rDME in the project became impossible when the supply company ceased trading and Calor were unable to source sufficient rDME within the project timescales The project developed a perfectly functional engine using the LPG/DME blend ratio of 88%/12% that is being sanctioned by the UN as a partially renewable fuel.

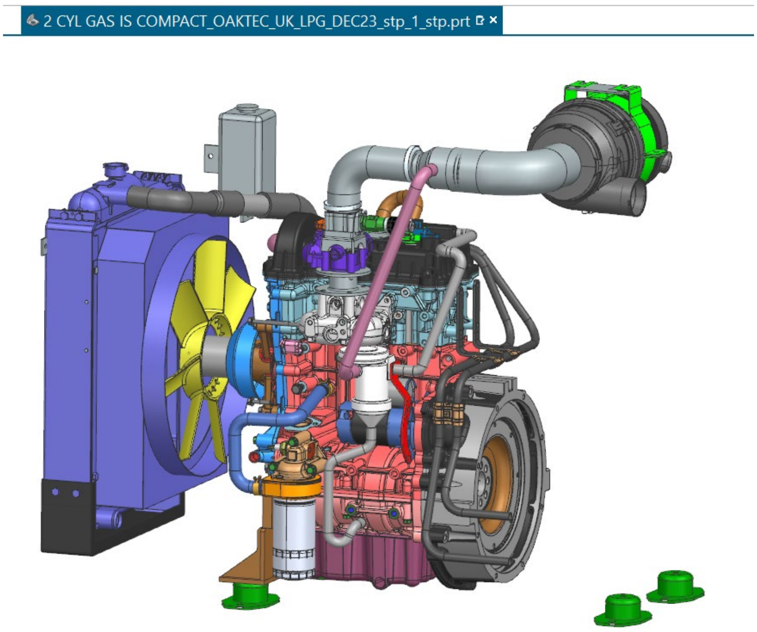
4.5 Background to Genset Build

CTL has been working with UK generator OEM Sutton Power on another project. Sutton has a diesel generator product that could be adapted for HGE as a replacement for the Cooper design. It is of a higher quality, more suited to UK construction and has UK standard wiring. It could also form the basis of a UK manufactured commercial product at the conclusion of the project. A PCR was submitted to allow adoption of this Sutton canopy. CTL used this base machine to build the HGE prototype.

4.5.1 Genset Build: Engine Installation

This required some modifications to the panels for the engine radiator and the engine mounts to ensure correct positioning within the canopy, but the basic dimensions of the engine were a good fit for the generator. Important criteria are access to service point, acoustic systems and cooling pathways. In a production version, any modifications can be translated from CAD into manufactured parts.

Figure 3. Engine system CAD model



When canopy modifications were made, the basic hardware was installed in the canopy and transfer of the subsystems was undertaken. These parts include, wiring harness, ECU, fuel systems, Cooling system (picture above), new design of exhaust and emissions systems.

4.5.2 Engine Control Unit (ECU)

During RDR phase 1 CTL began the design of a new engine controller specifically for the HGE technology. ECUs used in previous iterations and in the prototypes built so far have been expensive, and overly complex for the application. Additionally, they use microprocessor components that are hard to source since the recent supply crisis and very costly.

The new ECU design was led by CAGE and is contract manufactured by a UK OEM. Our ECU is specifically configured for CAGE gas engines with dedicated functionality to enable CAGE combustion control IP to be optimised. It will be 25% of the cost of the previous ECU when built in volumes and enables the HGE dual map system to allow a genset to run on hydrogen and other gas fuels.

4.5.3 Wiring Harness

To marry the ECU to the engine and the generator Deep Sea controller a new wiring harness has been designed and manufactured in-house. This incorporated all the protection systems to prevent the ECU from damage if there is a system fault.

Figure 4. Initial installation and testing of new HGE ECU

4.5.4 Fuelling Systems

The fuelling systems developed in the lab are transferred to the generator prototype.

The Hydrogen and LPG feeds gas to injectors located in the inlet manifold through a CAGE designed fuel rail. Dual fuel supply systems for the two fuel types are fitted with a switch over and non-return valves. A hydrogen safety system detects minimal leakage and shuts the fuel supply at both tank and in the generator enclosure.

Figure 5. Hydrogen/LPG fuel injectors installed in inlet manifold

4.5.5 Exhaust and Emissions

CTL has designed the exhaust to be robust, resistant to corrosion, and have a low noise signature. CTL engineers designed the full system using automotive expertise and mounting principles to achieve an effective design that incorporated the emissions reduction systems developed during M2. Due to the moisture from hydrogen combustion, the exhaust is manufactured from stainless steel to prevent corrosion.

Figure 6. Exhaust CAD model

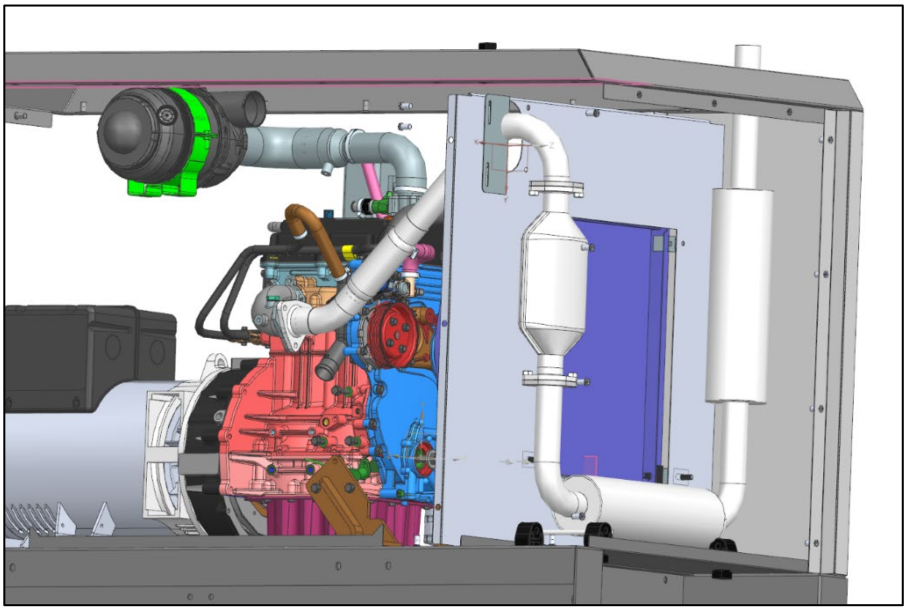


Figure 7. Manufacturing jig

Figure 8 Exhaust installed in genset

Figure 9. Catalytic convertor is in a cloth thermal shield

4.5.6 Testing

The Genset was commissioned and tested and was the first machine to run the new HGE ECU. The machine had refinements to the calibration and ran several shakedown tests with measurement of load response and acoustic benchmarking tests were measured against a Pramac ‘super silent’ diesel with favourable results.

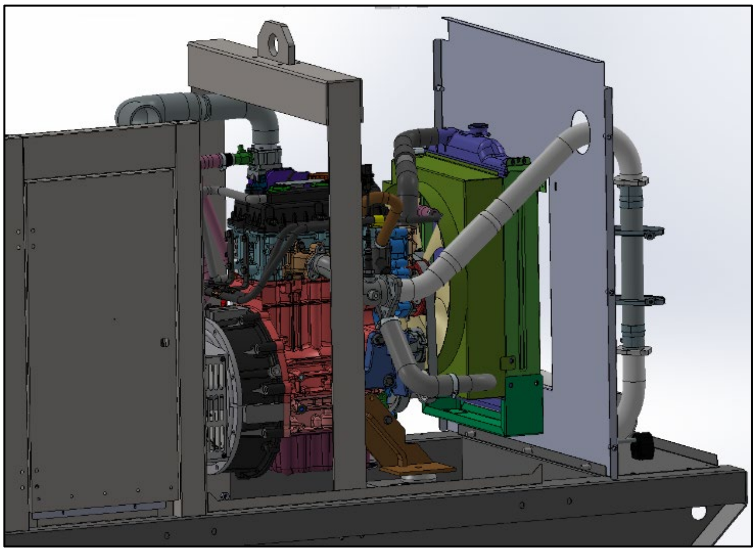
4.6 HGE Generator Development and Testing, including Endurance Emissions: (PT1) Hydrogen Generator Development & (PT2) Hydrogen Generator Testing, Refinement and Finalised Design

4.6.1 Overview

D2.06 The CAGE HGE prototype Coopers platform was of insufficient quality for harsh environment use on UK construction sites. At the time the project was configured these shortcomings were not apparent and machines had to be ordered early to enable progress with the project. A decision was made that the original machines would be replaced by a new machine made by UK OEM Sutton Power using the Cooper's as the parts suppliers for engines and other suitable components. This change was submitted to DESNZ as a PCR.

The generator design is based on an existing Sutton Power machine that uses diesel engines of a similar size to the Coopers 1.2 selected for this project. Acoustic systems, electrical outputs and human interfaces are adopted from the standard product.

Figure 10. Generator Design CAD



Modifications have been made to the internal panels of the system to accommodate the HGE system. CAGE designed these modifications in CAD and collaborated with the Sutton design team to interface the new systems. The generator uses a turbocharged version of the Cooper engine developed by CAGE to ensure that the hydrogen performance is equivalent to the output from LPG. A BOM (Bill of Materials) has been generated for the CAGE components supplied to Sutton Power for the generator build. The generator design was modelled in CAD prior to manufacture.

Figure 11. Generator prototype

Two prototypes were manufactured of this design. Sutton supplied the panel set and electrical 3 phase output hardware to CAGE for the machines to be assembled. Assembly instructions were documented to enable Suttons to build the 7 trial units.

4.6.2 Telematics

A bespoke telemetry system has been designed by CAGE engineer Steve Roe. Steve formerly led data gathering at the military aircraft BAE wind tunnel facility at Warton Preston.

A dedicated system is required in order to gather data from both the generator controller and the CAGE ECU to remotely track the generator use profile, the engine use profile and to analyse the engine performance of all machines in the field including the capability of fault diagnosis and failure prediction. This is important from a product development and commercial perspective. The module designed processes CAN data from the engine ECU and the Deep Sea generator controller and streams to a user interface by a mobile SIM network.

Figure 12. Telemetry system unit

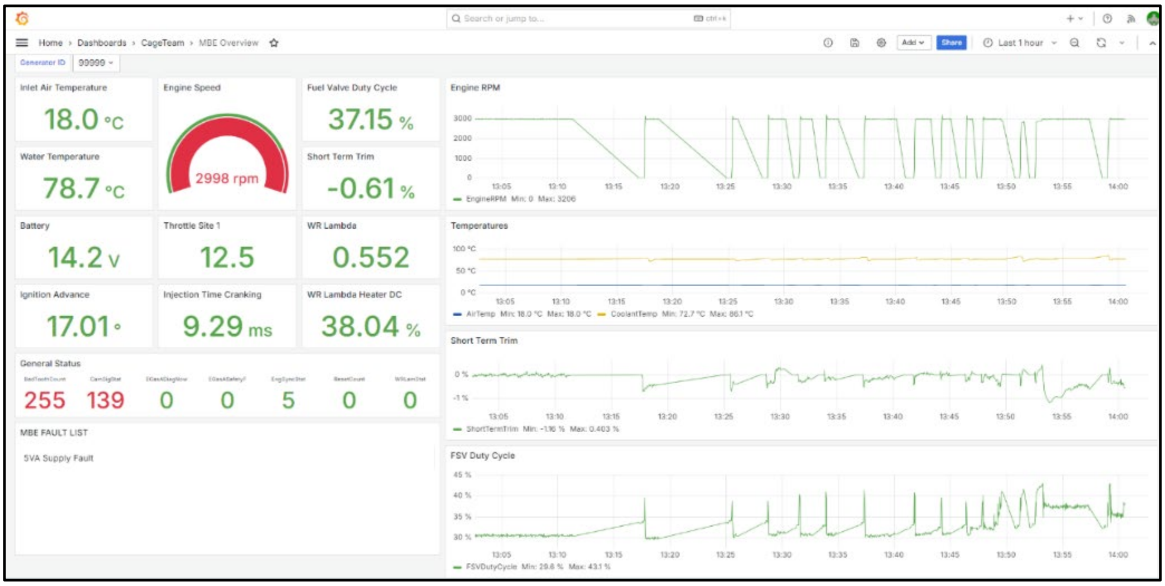
The unit is incorporated on the seven HS2/EKFB trial machines and development iterations produced throughout the project.

4.6.3 Safety Systems

Sophisticated safety systems are needed for hydrogen applications of this type. CAGE has previously implemented a hydrogen generator for trial and undertaken HAZID/HAZOP processes to ensure safe operation. This includes dual system shut down at the fuel tank supply and at the inlet to the generator if leaks are detected at sub combustion air/fuel ratios. Appropriate sensors have been sourced and previously tested. The system is installed in all generators within this project.

All components in the system are hydrogen compatible including the pipe work, fixings and valves. Hydrogen regulated at the supply to 2.5 bar inlets the generator through a different port to LPG and then joins the plumbing system for the LPG at a Y junction. One way flow valves are fitted in the fuel lines before the junction to prevent reversal of flow of hydrogen into the LPG feed and vice versa. Shut-off valves are fitted at the inlet of the fuel feed and connected to the highly sensitive leak detector system.

Figure 13. Engine data output



The leak detection system is operated using a Hydroknowz sensor made by Neodym in Canada. It detects and warns at 1% contamination of air with hydrogen and is wired to shut down the whole 12V system at 2% contamination well below the lower explosive limit of 4%. This includes activating the safety shut-off valves to isolate the fuel supply. Photos below show the sensor.

Further safety systems were designed to release pressure in case of an explosive event inside the engine and generator. These take the form of ‘blow-off’ valves. Several concepts were considered and a mushroom vent on the genset canopy was tested and approved.

The generator uses an industry-standard Deep Sea platform controller. CAGE has developed control files for use with battery systems. Deep Sea offers multiple functionalities and is configurable for user needs. It can include remote starting, curfew operation, outputs of all critical functions and CAN feed that is used for the CAGE telemetry.

Figure 14. Generator control

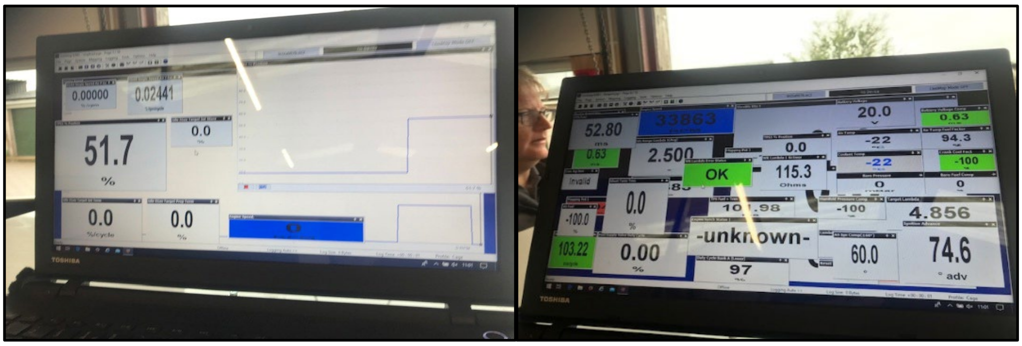
4.7 HGE Generator Testing, including Endurance Emissions: (PT2) - Hydrogen Generator Testing, Refinement and Finalised Design

On completion of the build, the prototype was commissioned and tested using LPG and then in a second phase with the hydrogen system installed. Testing of the hydrogen system in the generator delivered good results. Using the turbocharged engine system 20+kW electrical output is easily achievable but the machines will be supplied with a rating of 15kW for either hydrogen or LPG and LPG/rDME blend to give consistent performance. At this stage a hydrogen combustion instability was detected, and a programme of work started to identify its cause and eliminate it.

4.7.1 Calibration

The engine was initially calibrated in the test cell using a fixed speed 3000RPM control regime to allow stable 50hz output. The engine uses an electronic throttle controlled by the ECU to control these factors. The generator will produce a reliable 10kW at 1500 RPM and 15kW at 3000 RPM on all fuels. Emissions were monitored and optimised during this commissioning phase to ensure that they meet targets. The genset was run for a series of tests using load banks to make sure it operates correctly across its full operating range and minor calibration changes made.

Figure 15. Hydrogen/LPG engine calibrations



4.7.2 Noise Emission

Tests were carried out to industry standard and HGE was benchmarked against a commercial Pramac diesel machine and has competitive noise emissions.

Figure 16. Commercial Pramac diesel machine

4.7.3 Endurance Testing

To prepare for trial use the new generator has been extensively run at CAGE charging a battery pack provided by Speedy. The battery feeds power to the site buildings. The machine has run daily for around 8 months without problem.

Figure 17. CAGE generator

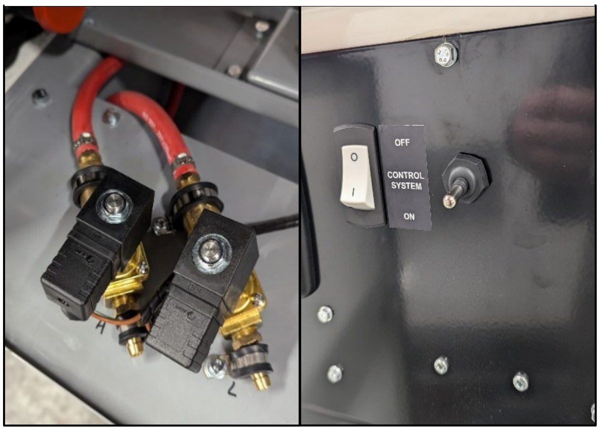
4.8 Hydrogen Fuel System Installation

The installation uses a port mounted fuel injection system. The inlet manifold is machined to press fit the injectors via a connecting pipe and hose and the same injectors supply both H2 and LPG to the engine with fuel regulated at the bottle. Separate fuel lines (Fig18) supply H2 and LPG with independent safety shut-down circuits/safety valves (Fig19) and one-way valves to prevent back flow of either fuel. At the same time the turbocharger, induction pipework and intercooler are fitted.

The system is all controlled by the HGE ECU which contains separate calibrations for H2 and LPG. A circuit is added to the wiring harness to switch between the different ECU functions.

Figure 18. H2 feed-pipe red, LPG pipe

Figure 19 H2 and LPG Shut-down valves and fuel changeover switch



4.9 Generator Testing and Development with Hydrogen (WP 2.14)

The extended generator testing with hydrogen encountered several issues causing delays to the development. Testing experienced an ongoing issue with misfires ranging from uncontrolled combustion that were known about from the lab development to very minor unpredictable misfires that are only detectable when closely monitored. The serious misfires can be prevented by set-up and calibration, but the minor misfires continue to be a challenge to resolve. These could be caused by thermal ’hotspots’, residual hot gasses, in cylinder air motion or ghost sparks. The misfires of this type or in these conditions have not been experienced on other hydrogen engines developed at CAGE.

The resolution of this issue required intensive R&D involving many tests with gas flows, fuelling strategies, spark plugs, ignition coils and control software and hardware. A detailed report was presented explaining this work and a satisfactory resolution reached to allow successful trials of the engines and generators. Further research is required to understand why this engine combusts hydrogen differently to others previously developed by the team.

4.9.1 Emission Testing

As part of the testing and development phases CLEC/Imperial College visited CAGE to carry out a series of emission tests on the generator engines to measure them against the EU Stage V emission standards on all fuel types including the rDME/LPG blend. The report from CLEC is appended to this report.

4.10 HGE Generator Development and Testing including Endurance Emissions: (PT5) In-house Endurance Testing of Developed Generators & First Batch of 5 Build for Trial (WP2.10 & 2.12)

The seven generators for the trial phase were carefully assembled and individually tested on both fuel types ensuring that they complied with the CE marking status. Collaboration between CAGE and Sutton ensured that CE/UKCA conformity was met by the generators as built by Sutton. The modifications by CAGE to incorporate the hydrogen systems fell outside this formal certification but met the standards in principle.

The generators then had final systems checks and a PDI (Pre Delivery Inspection) before dispatch to Speedy for the trials. (photo below)

Figure 20. Generators Pre Delivery Inspection

4.11 HGE Engine Calibration: rDME and Hydrogen - CALOR (WP3)

Led by Niall Parkin Calor delivered WP3 with 3 core functions. These were;

- to support the development of DME in the engine for the planned delivery of rDME to the project trials,
- supporting the project with the methodologies and supply of gas to the trial phase in bulk tanks
- support CAGE with the supply of LPG for development and endurance testing of the new generators.

As documented elsewhere the rDME supply JV that Calor was part of failed prior to fuel being supplied for trial and other possible supply avenues could not deliver within the timeframes. DME was delivered through Calor to CAGE for the R&D programme and engine development and the other deliverables ensured that Calor provided good value to the project.

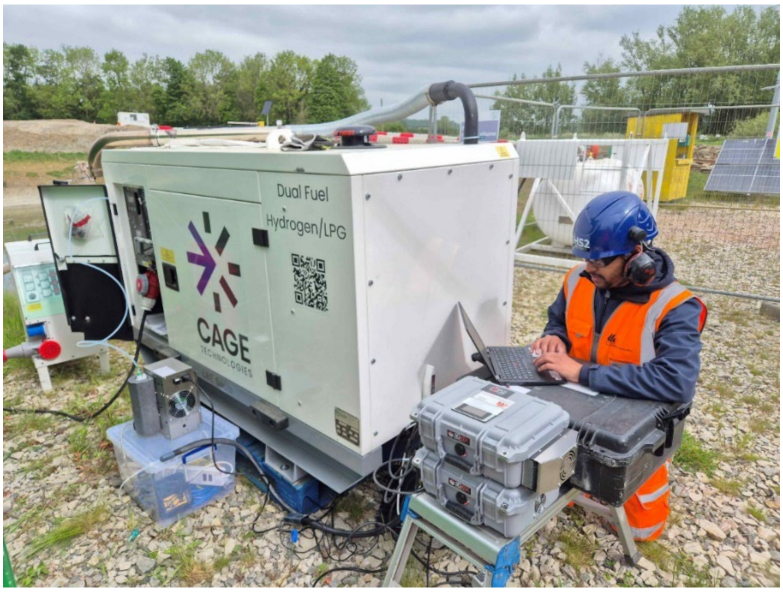
4.12 Imperial College Emissions Testing

Imperial College London Centre for Low Emission Construction (CLEC) managed WP4 within the project and this focussed on all aspects relating to emission measurement from engines and generators, and the legislative framework around adoption and use of gas engines on construction sites. This major piece of work included;

- Emissions certification frameworks and investigation of possible routes to certification in the UK for equivalent of EU Stage V
- Engaging stakeholders to create a certification plan
- Lab testing of CAGE engines using hydrogen, DME and LPG and measuring emissions against EU Stage V standards for diesel
- Conducting the same emission tests during the trial to ensure parity with lab results
- Conducting further site emission tests at the close of the trial to detect any change
- Supporting the trial with site H&S and logistics expertise to approve the trial permits

These deliveries were successfully completed and added a very valuable insight to the air quality benefits of gas engines when compared to diesel. CLEC engaged in further dissemination work and lobbying for change through the Construction Leadership Council.

Figure 21. The site emissions test of the HGE generator



5 Comparing the Tailpipe Emissions from Different Fuels used in CAGE Technologies Limited's Hybrid Gas Engine 2 – Imperial Report

Imperial College London conducted a mid-stage emissions assessment on the Hybrid Gas Engine 2 (HGE2) as part of the project's technical development. The objective of the testing was to evaluate the emissions performance of the engine when operating on three gaseous fuels: hydrogen (H_2), liquefied petroleum gas (LPG), and an LPG blend containing 12% renewable dimethyl ether (rDME). The complete assessment was carried out under controlled laboratory conditions using a 12 kW HGE2 unit on a dynamometer, following the ISO 8178 G2 test cycle

5.1 Test Method Summary

The engine was tested at five load points (1.2 kW, 3 kW, 6 kW, 9 kW and 12 kW), with each test sequence repeated three times to ensure repeatability. Concentrations of CO, CO_2, NO, NO_2, particulate mass (PM) and particle number (PN) were measured using a combination of advanced emissions analysers. Emissions were converted into g/kWh or #/kWh to enable comparison with EU Stage IIIA and Stage V non-road engine standards.

Figure 22. Test cycle performed on the CAGE-HGE2 generator/engine at CTL's test-cell. Taken from: (Desouza, 2025)

Engine load	Duration	Test cycle	Fuel
Warm-up	15 minutes		Day 1: LPG Day 2: Hydrogen Day 3: rDME blend
Idle	10 minutes	Test run 1	
1.2kW	10 minutes		
3.0kW	10 minutes		
6.0kW	10 minutes		
9.0kW	10 minutes		
12kW	10 minutes		
Idle	10 minutes	Test run 2	
1.2kW	10 minutes		
3.0kW	10 minutes		
6.0kW	10 minutes		
9.0kW	10 minutes		
12kW	10 minutes		
Idle	10 minutes	Test run 3	
1.2kW	10 minutes		
3.0kW	10 minutes		
6.0kW	10 minutes		
9.0kW	10 minutes		
12kW	10 minutes		

5.2 Main Findings

- **Hydrogen (H_2)**

Hydrogen consistently achieved the lowest emissions across all pollutants. CO, HC+NOx and PM were significantly below the relevant EU Stage V reference values across all load points. PN emissions were also comparatively low. Overall, hydrogen operation delivered the cleanest emissions profile of all fuels tested.

- **LPG**

LPG delivered strong performance with emissions well within the Stage IIIA and Stage V limits for HC+NOx and PM. CO emissions were below diesel-equivalent standards. LPG therefore remains a compliant and reliable fuel option for the HGE2.

- **LPG + rDME blend**

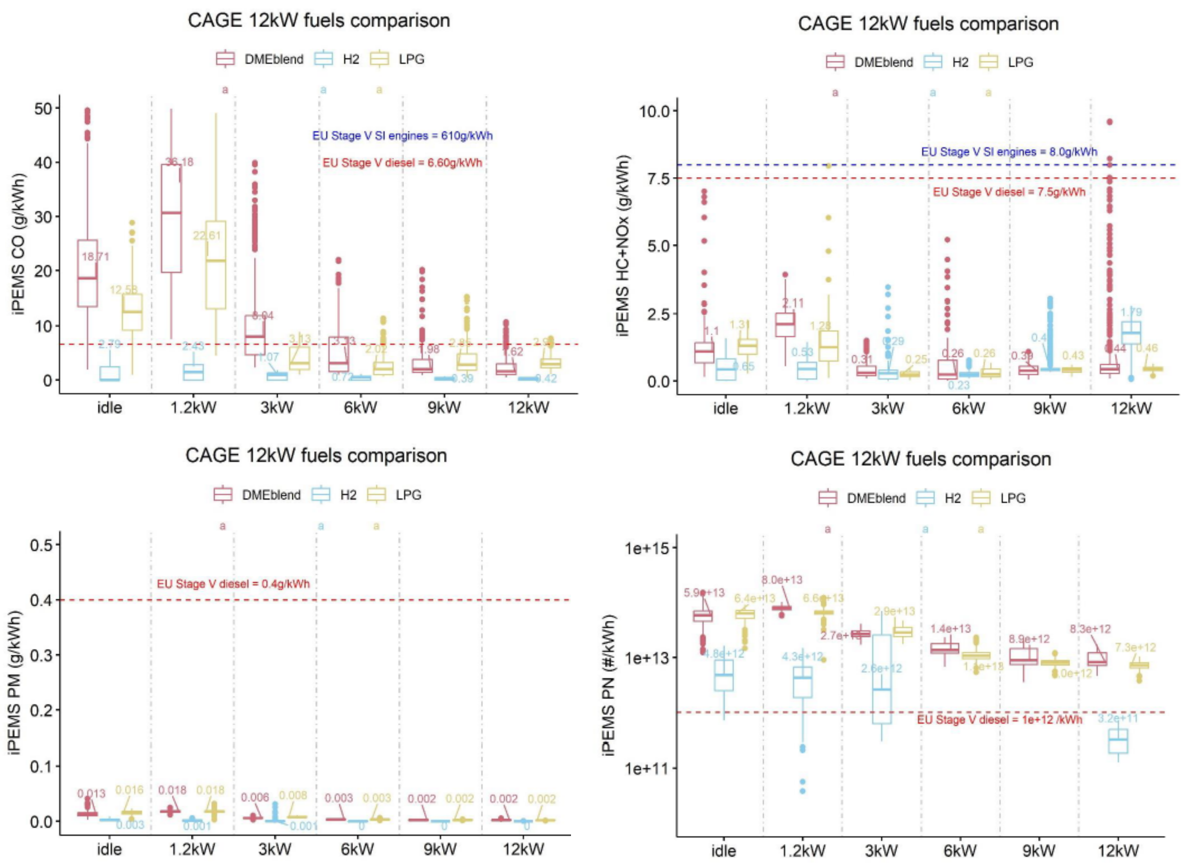
The blend performed similarly to LPG for HC+NOx and PM. CO emissions were higher and exceeded diesel-based limits, although they remained far below spark-ignited engine reference values. PN values were elevated compared with hydrogen but consistent with expectations for small gaseous-fuel engines.

5.3 Comparative Behaviour Across Fuels

The emissions behaviour across fuels shows clear differences:

- Hydrogen achieves the lowest CO, lowest HC+NOx, and lowest PM levels, confirming its suitability where supply permits.
- LPG maintains compliance and delivers stable emissions performance across all loads.
- The LPGrDME blend behaves similarly to LPG for most pollutants but shows higher CO levels.
- PM emissions were very low for all fuels, demonstrating the benefit of gaseous fuels compared with diesel.
- PN values varied but do not impact regulatory compliance, as no PN standard exists for this engine category.

Figure 23. Emissions comparison of the HGE2 generator for three fuels (LPG, LPG+rDME and hydrogen) showing CO, HC+NOx, PM and PN across the full load cycle. Taken from: (Desouza, 2025)

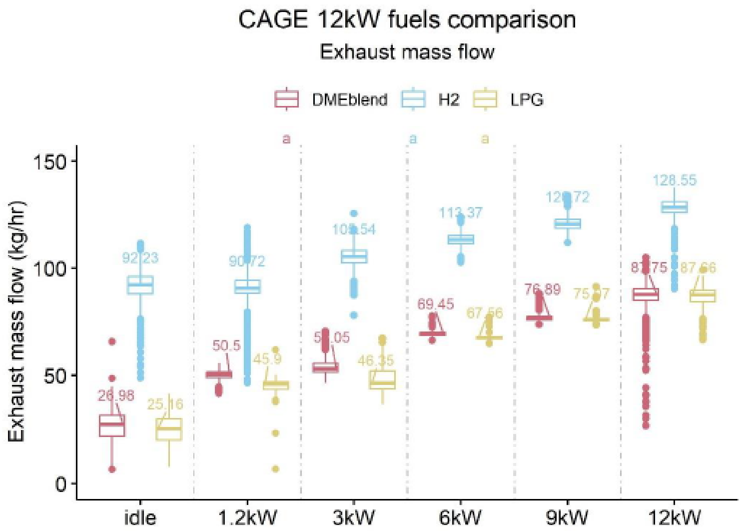


5.4 Operational Insights

The testing also produced several observations relevant to real-world operation:

- Hydrogen combustion results in higher exhaust mass flow due to lean-burn characteristics.
- Emissions expressed in g/kWh appear higher at idle because power output is near zero, reinforcing the importance of avoiding unnecessary idling.
- Integrating the generator with a battery-hybrid unit and start/stop capability could improve efficiency and reduce emissions.
- Appropriate generator sizing based on site demand is important for optimal performance.

Figure 24. Exhaust mass flow (kg/hr) from the CAGE-HGE2 measured for each load point.



5.5 Conclusion

The Imperial College assessment demonstrates that the HGE2 generator delivers very low pollutant emissions when operating on hydrogen, LPG or LPG+rDME. Hydrogen provides the strongest environmental performance, but both LPG-based fuels remain viable and compliant alternatives. These results confirm the technical feasibility and emissions benefits of deploying the HGE2 in construction and industrial environments.

6 Demonstration Study

6.1 Overview

The project set out to validate the HGE technology through an extensive trial with partner EKFB on 6 sites within the HS2 construction phase between London and Birmingham.

At the application phase and the start of the project the exact structure and demonstration planning were not clear as the partners relied on HS2 to reach an agreement with one of the construction supply partners to host the trial. Additionally, with the rail construction being a moving programme, locations of activity change regularly and needs for power vary.

HS2 proposed the trial to EKFB who are constructing 80km of railway in the Oxfordshire region based near Banbury. An agreement was reached with EKFB subject to an acceptable business plan being approved at senior level that showed potential financial viability of the technology and that appropriate use cases could be found for what are relatively small output generators by construction standards.

The sites selected for the trials are shown in the table below.

Table 6. Trials information

Site name	Site operations	Proposed fuel type (After change request)
Twyford	Satellite compound	LPG/H2
Halse Copse Compound	Satellite compound	LPG/Rdme 2 gensets
AX15	Satellite compound	LPG/H2
Aston le Walls East	Water Management Zone	LPG/H2
LBE South	Water Management Zone	LPG/H2
Fir Tree Nursery Site	Water Management Zone	Hydrogen

The ideal use for this size of generator was to charge battery systems on construction sites. With the rapid growth in electrification, many battery products are coming to market, but most are still charged inefficiently by large diesel gensets. The plan developed with EKFB was to use HGE generators to charge hybrid batteries and power water management pumps and site welfare units.

Initially the trials were scheduled for the post-Christmas period, but some delays caused by the change request process caused by the unforeseen rDME supply problems and technical irregularities with H2 combustion in the engine pushed the trials back.

All of the sites chosen by EKFB had resident large diesel generators provided by Power Electrics with battery systems on 4 of the 6 sites and the HGE machines supplanted these for site operation. Where there were no battery packs on site, Speedy supplied them, as their system had been integrated and tested extensively at CAGE during the project.

6.2 Benefits and challenges.

The trial phase experienced unusually warm and dry weather, and this brought challenges to the project. The water reservoirs that are managed by the pumping systems were low on water and resulted in low power demand for the batteries and generators. To compensate for this some of the generators were used to power a total loss pumping regime meaning that the water was pumped out and back into the reservoir to make the generator work harder. Warm weather also meant that there was less demand for energy in the welfare units as they did not use their drying facilities. Extreme heat also caused a malfunction to the emission control thermal sensor in the ECU leading to an erroneous emission test on one generator.

The rationale behind a multi-generator trial enabled machines to be worked using both fuel types with performance demonstrated and assessed. It allowed the site operators, EKFB, to experience several working units close to a production specification rather than a single ‘prototype’ machine.

During the trial 3 machines experienced reliability problems resulting in 2 of them being recalled to CAGE. These issues were unrelated to the core HGE technology. One machine reported low oil-pressure and this was found to be a poor connection in the Deep Sea wiring. A second machine was reported to be smoking on startup, this was traced to a failed starter motor. Both problems were quickly remedied and the machines returned to site.

Other issues occurred with oil leaking from an incorrectly fitted dipstick and a dislodged seal around the oil filler again easily remedied but requiring a modified filler cap going forward.

Challenges arose with hydrogen supply through incompetence from the supplier and responsibility for re-fuelling. Extensive health and safety assessments were needed by the EKFB H&S (Health & Safety) team before approval could be given. Initially no party wanted to take responsibility for swapping over hydrogen fuel MCP’s. To resolve this a detailed instruction manual was written and, when approved by H&S, the site teams took responsibility for the task.

The most serious hydrogen related problem was the delivery of the fuel to site. This was a result of strict site access rules not being followed due to incompatibility between the supplier’s procedures and those of EKFB as site owner. This caused delays, made hydrogen delivery difficult, and resulted in fuel being delivered to the wrong locations on site and, in one case, to completely the wrong address.

Despite these problems there has been a very positive reception to the HGE technology from partners and stakeholders.

The core technology has always performed as designed and with no differentiation between fuel types in operation. The machines have proved to be very simple to switch between fuels. The LPG fuel costs have been very low for EKFB, and the emission performance has been as predicted at the start of the project. This success is reflected by the stated desire of EKFB to continue the trial with one HGE generator using a commercial hire model. Speedy are in dialogue with CAGE on a direction forward and new relationships are being formed from great interest from outside of the project.

At the application phase multiple generator trials were proposed but exact details could not be determined until the project had been planned with the site operators, who had not been selected at the project start. When the project was underway it was planned to run half of the generators with ‘rDME’ and later following R&D, 2 of 7 generators on blended rDME and LPG on the same site, Halse Copse. As rDME became unavailable during the project the proposed use was changed Halse Copse to one H2 and one LPG side by side to enable a direct comparison to be made by the site team.

A further proposal was made by CAGE following the unexpected combustion issue with hydrogen that the project focus all the hydrogen testing on one site to get as many hours on a single generator as possible, to see if the issue manifested further in terms of becoming progressively more prominent. We anticipated being able to use all of the £20k hydrogen test budget on the one machine. However, DESNZ requested that all generators be demonstrated with hydrogen to show their true multi-fuel capability and it was agreed that over the last few weeks of the project the LPG tanks were to be removed, and hydrogen supplied to all sites for this demonstration.

The demonstration showed the practicality of gas fuels as a substitute for diesel and proved without question that in the HGE technology, they can perform as well as the diesel machines they replace but with very strong emissions benefits. Using hydrogen, the engine can have performance parity with LPG and diesel. There can be significant fuel cost savings compared to the diesel norm of running a large generator at low load.

Figure 25. HGE system and Speedy battery on the HS2 Aston Le Walls site

The project proved that bulk gas tanks offer a good solution for long running times and infrequent need for refuelling. The project brought sharp focus on the difficulties and challenges of conducting activities on these heavily regulated sites that deflects from business as usual. In particular, processes and protocols of getting people and equipment on site was difficult but overcome as the project progressed, and to resolve this the advantage of using Speedy as a delivery partner cannot be underestimated.

Hydrogen deliveries to site were a big problem and failures in the delivery process caused major disruption to the final phase of the project trial.

Other than the minor issues described, the core flexible fuel engine technology worked without a single issue which has provided great reassurance to the commercial value of the technology. In addition, it proved its suitability to work with the many types of battery systems and electrified product currently being introduced into the sector.

7 Project Metrics

7.1 Technology Readiness Level (TRL)

In RDR Phase1 the HGE technology was developed to TRL 4 with lab scale prototypes developed and tested. The HGE2 project has progressed that through to TRL7 where pre-commercial HGE generators have been trialled in a working environment.

To achieve TRL7 an intensive process of development and testing of the technology combined with generators manufactured by an established OEM and CE certification ensured that this pre-production level was met.

At the same time Commercial Readiness Level 5-6 has been reached with partnership building, certification and business modelling all in progress.

7.2 Comparison to Diesel

It is well accepted within the construction industry that diesel generators are usually considerably over specified for particular applications, and it is most often the case that they operate considerably outside of their efficient working zone. By doing so they waste large amounts of fuel, create carbon emissions and damage air quality with soot and particulates.

Whilst some applications have occasional large or unpredictable power demands this is not the case for charging battery systems where the rate of charge acceptance is known. As an example of this, and a worst-case scenario, when the trial was being set up the diesel generator that was being replaced by HGE was delivering 300W of power from a generator with 65kW rated output. It’s exhaust and surrounding metalwork was black with exhaust soot.

CAGE generators are designed to use intelligent control and operation functions to provide a much more optimised solution with an initial focus on providing charge for site battery storage and electrical machines. The generators are sized so that they can provide charge at, or near to, the ideal charge rate for the battery whilst working close to the gas engine’s most efficient regime, in so doing not wasting fuel and energy. They can be set to switch on and off as a battery reaches a desired state of charge. When running with hydrogen they emit no CO2 and only very minimal levels of NOx emissions.

7.3 CO2 Emissions Compared to Diesel

Within the project extensive testing was conducted to understand the fuel use on both fuel types in a controlled test and an on-site operating environment. The generators were configured to deliver exactly the same power characteristics on hydrogen and LPG fuels. Prior to the tests EKFB was asked to supply data of diesel fuel used and costs of diesel fuel used on the sites from telemetry provided by Power Electrics through consultancy Hydrocks. It was found that the telemetry provided very random and undefined data. When requested to provide some more accurate data PE revised their telemetry to offer some more useful information. Because of the nature of using a large diesel generator for a lower than ideal power demand the fuel use, carbon emissions and costs were very high.

Data from the trial phase was affected by the unusually warm dry period during which the trial took place. The primary power applications were ‘Siltbuster’ water pumping systems. These manage water provision for dust suppression during the construction process using water stored in specially created reservoirs. In wet weather they store and manage local water and when the reservoir reaches a certain level pumps and filters it into the main drainage system. Throughout the trial the water levels were very low so, on some sites, EKFB artificially set up a closed loop system to pump out and back into the reservoir to enable the generators to work hard. Again, the generator powering the welfare facility had low power demand because of warm dry weather.

During the site selection process CAGE requested data from EKFB and Power Electrics around the generator and diesel use profiles for the sites being consider. Streams of data was provided, and it was not formatted in a way that made sense. Latterly for EKFB’s business plan Hydrocks got some site data that correlated diesel use with average power generated and this information is being used for the comparisons. The diesel generators on site were 65kVA output.

7.4 Diesel Consumption and CO2

On the application provided as a sample by Hydrock the diesel generator was averaging 1.43 kW output over a 3-day period. Its fuel consumption over this period was 36.85 kg of diesel per day equating to a rounded figure of 1050g/kWhr of diesel consumption. At the cost price of £1.67/kg used in the EKFB business case the diesel cost is £1.75/ kWhr using the generator/battery systems currently on site.

In a diesel engine 1kg of diesel produces 3.15kg of CO2 so the diesel generator used for this data produced 3.3kg of CO2 per kWhr. This represents a typical use case of the set up currently in use by EKFB on the HS2 sites. The fuel consumption and CO2 will be lower if the generator is working on a higher load but, in this case, it will always be significantly underloaded as the batteries have relatively low charging capacity.

Figure 26. Hydrogen storage

To gather data for hydrogen performance tests were carried out at CAGE running a full Multi Cylinder Pack (MCP) with a known weight of hydrogen from full to zero at constant load. Additional tests used a full MCP to understand the pressure drop of gas and therefore fuel used at loads between 2kW and 12kw in 2 kW steps. This proved inconclusive as the resolution on the pressure gauge was not accurate enough to give the required level of confidence in the results.

Fig27 & Fig28 graps the Brake Specific Fuel Consumption (BSFC) data for LPG and hydrogen at set load points. These plots show the clear benefit of running generators at high load. Fuel used in terms of g/kWhr is almost 4 times higher at low loads for both fuels. Accurate set point data for diesel was not available, but the consumption figures set out earlier in this paragraph, although far less granular, point to a very similar effect when using diesel equipment. Increased fuel consumption is, of course, inextricably linked with increased carbon emissions. Particulate emissions from diesel equipment also rise massively when running at low load.

Figure 27. Brake Specific Fuel Consumption (g/kWh) vs Load (%) for LPG (5-Minute Tests)

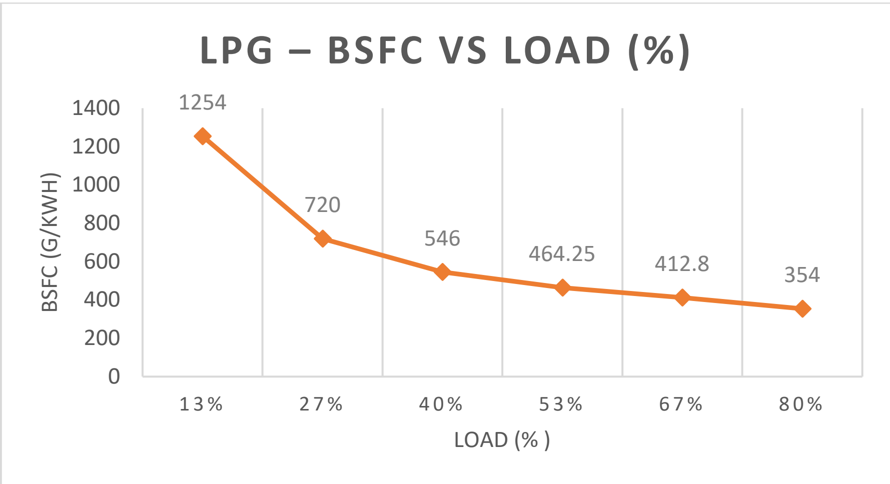
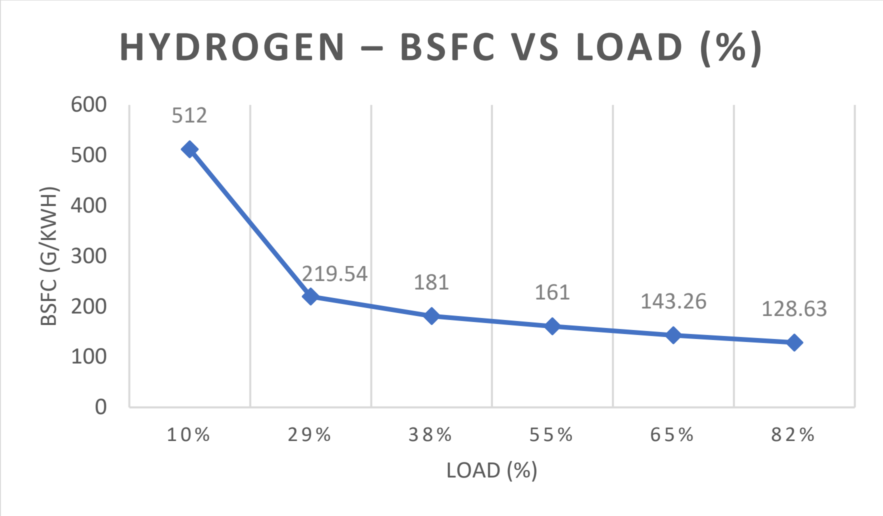
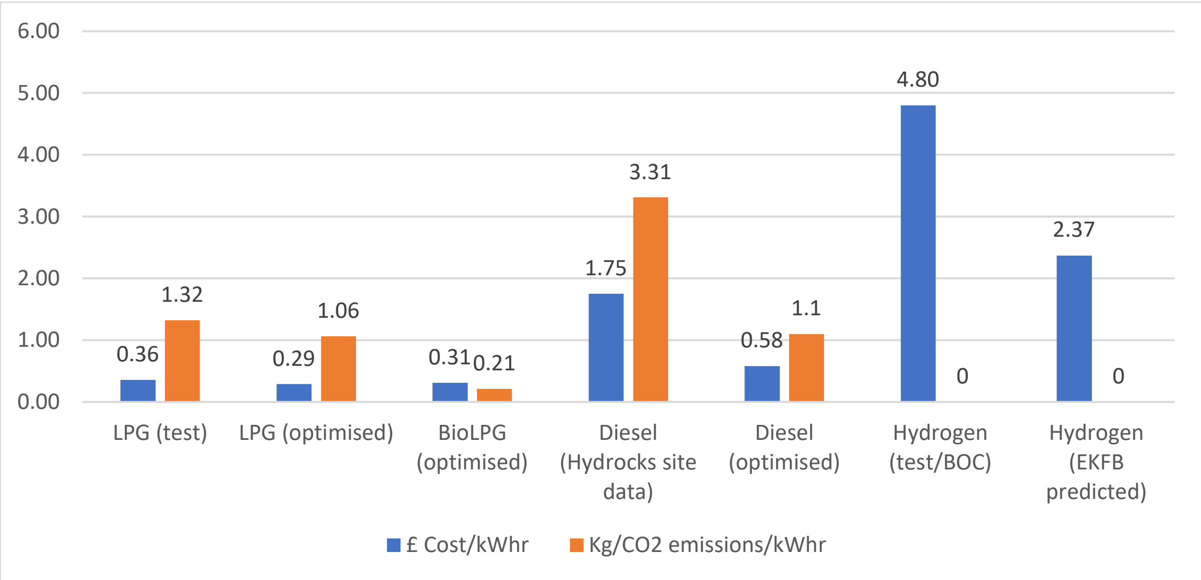


Figure 28. Brake Specific Fuel Consumption (g/kWh) vs Load (%) for Hydrogen (5-Minute Tests)



Further tests were carried out using a BOC small Genie bottle containing 420g of H2 and scientific weighing scales to understand the mass of fuel used at the higher load points where the generators operate.

Figure 29. Comparison of Energy Cost (£/kWh) and Carbon Emissions (kg CO_2/kWh) for Various Fuel Types



Tests carried out by CAGE using the HGE generator running on hydrogen at 9kW continuous output used 9.4 kg of hydrogen to produce 73kWhrs of electrical power. This equates to 128g/kwhr electrical output. However the cost of hydrogen through the current supply chains is very high and using the metric of £37.39/kg equates to £4.80/kWhr. This does not account for the very high costs of bottle rental and delivery incurred in the project, but assumptions can be made that these costs can be negotiated down with regular high volume supply.

The cost approximation used by EKFB in their business case was £18.48/kg which would represent a more reasonable £2.37/kWhr but still significantly more costly that the non- optimised diesel solution. Hydrogen costs will reduce considerably over time as the hydrogen supply-chain matures and this will be the key to unlocking the considerable potential of the fuel in this type of application.

Of course the great advantage of hydrogen in this application is its emission and carbon saving. As a carbon free fuel it has no carbon emissions and, as optimised in the HGE engine, very low levels of NOx emissions.

7.5 LPG Consumption and CO2

LPG was used as the baseline gas fuel for development and testing and in this case becomes the stepping stone to a full net zero hydrogen solution. LPG has good energy density and, in liquid form, is easier to store and transport than most other gases. It is a carbon fuel although bioLPG is now commercially available and synthetic LPG fuel types are in development that may ultimately carry net zero status.

Within this project fossil LPG supplied in bulk form by Calor was used for some of the trial period as a cleaner substitute for diesel. This enabled the emissions test team from Imperial to quantify the emissions levels and compare against baseline data for diesel generators they have previously tested. It also allowed an assessment of the economics and practicality of using bulk LPG against incumbent diesel. EKFB used their diesel budget to purchase the LPG from Calor at £0.414 per litre equating to £0.81/kg.

Figure 30. CALOR bulk fossil LPG

Measured with CAGE telemetry, in the trial at the LBE South site, the HGE generator produced 2.32MWhrs of power over the month of May and used 2002 litres of fuel according to Calor's telemetry that gave daily readouts. This equates to 1021kg of fuel and 440g/kWhr (electrical) over a mixed duty cycle. The fuel cost at £0.81/kg means that the energy cost of HGE using LPG is £0.355/kW hr.

When testing LPG at CAGE using a measured weight of gas over at set time frame at peak 12kW load LPG was used at 354g/kWhr so in this optimised operating regime fuel cost is £0.287/kWhr.

7.5.1 Carbon Emissions from LPG

In an engine, 1kg of LPG produces 3.0kg of CO2 as against 3.15kg of CO2 for the same amount of diesel. However, the replacement of the large inefficient diesel generator with the more optimised HGE system can deliver a 55-70% reduction in CO2 using LPG because of the efficiency improvements of the system.

8 Secondary Project Benefits

8.1 Dissemination

The project held a dissemination event in July 2025 where all partners and stakeholders met on site for a project presentation and demonstration. Present at the event were key personnel from CAGE, Calor, DESNZ, EKFB, Frazer Nash, HS2, Imperial College, and Speedy.

The EKFB media team was present. The event involved an explanation of the project and a live onsite demonstration of the generator using LPG and then hydrogen. All participants were invited to ask questions. From this demonstration media releases are being prepared to be shared with the communication teams from all partners. A combined release has been posted on LinkedIn and has generated good feedback. Further media will be disseminated such as the project within the HS2 annual Learning Legacy report.

Figure 31. Project team at the dissemination event

8.2 Intellectual Property

Significant and valuable IP has been gained from the project. This IP is centred around combustion control in engines using fuels with widely different combustion characteristics and the development of engine controller technology to enable this. This IP puts CAGE in a strong position to be able to commercialise products that offer a unique value proposition with net-zero hydrogen fuel capability yet full functionality with other gas fuels when hydrogen is not available.

8.3 Jobs

The project helped secure the jobs of the CAGE team and enabled new roles to be created in project management, design engineering for the data systems, and manufacturing technicians. The whole team benefited from working ‘hands-on’ with a large construction company and with delivery partner Speedy Hire who provided valuable insights into the supply mechanisms to the construction sector.

8.4 Partnerships

The CAGE team has pushed hard to develop relationships that can grow to commercial opportunities for HGE in the post project period. These include the major LPG supplier in Canada and a UK founded specialist company operating in several global territories supplying off grid power to installations such as mobile telephone towers. An HGE generator with a hydrogen focus is likely to go on trial with Ryse in Q4 2025. CAGE is now discussing further collaboration with existing partners Speedy and Calor which are the obvious routes to market for the product.

8.5 Supply Chain

CAGE had well developed supply chains at the start of the project and these are being strengthened with the push to follow the project quickly with commercial products, in particular the relationship with UK ECU manufacturer to manufacture CAGE branded products. Sutton power has agreed to manufacture CAGE gensets products based on the design developed within the HGE project, thus cementing a long-standing relationship between the two companies.

9 Project Management

9.1 Structuring and Scheduling

The project was broken down into a number of phases: a planning and procurement phase, a development phase, a build phase, and a trial phase. A Gantt chart was created to visualise the project targets and timelines and daily stand-up meetings had with the engineering team to review technical progress. Reporting to DESNZ with monthly meetings, extended meeting each quarter.

9.2 Recruitment

The project enabled the recruitment of a new technician, project manager, engineering manager temporary and permanent staff to help with project management and engineering assembly and prototyping. A CFO was hired part time to advise on financial structure of the business and efficiency of processing financial systems

9.3 Risk and issues

The project was governed using a detailed risk register with regular reviews and actions to mitigate risks. Financial management and cash flow were always the biggest risk and continue to be an issue for the business whilst external investment or follow on funding is raised. Timing offered many challenges particularly around processing project change requests. Other challenges were technical relating to hydrogen combustion control and the combustion and supply of rDME which required a PCR. These issues have been covered in previous reports. Key staff had health problems during the project which caused some delays.

Commercial risks in terms of market demand are low, but investment is vital to fully exploit the potential of the technology.

9.4 Project Management Lessons Learned

The project was under resourced in terms of project management due to the more demanding nature of reporting. CAGE is more familiar with the Innovate UK reporting structure, which is more formatted and, in some ways, less demanding. For example, an Innovate UK PCR can often be processed over a few days with very simple and logical processes. In retrospect CAGE would have created a larger team to deliver the project and requested a higher budget. Working within the confines of large construction projects continued to be an education for the technology and fuel supply partners but we must credit EKFB, HS2 and Speedy Hire for making every effort to ensure that the trial phase was delivered as smoothly as possible.

10 Commercialisation Plans

HGE was always planned with a commercial end game and within the business we are confident that we are on the cusp of achieving this. The business needs to be able to capitalise on its innovation advantage by getting net zero products into the market before the competition and to build on existing strong partnerships and opportunities. Additionally, investment is critical to this growth and in the current market it is very hard to raise money without showing a strong commercial roadmap.

10.1 Scalability

With contract manufacturing in place and mature supply chains the HGE product is in a position to scale quickly to supply construction and other sectors.

An opportunity exists to supply HGE technology into the Lower Thames Crossing (LTC) project and CAGE is meetings are ongoing with contractors to discuss CAGE onboarding. LTC has a diesel free policy so is looking for alternative solutions to provide clean power. Several construction companies and battery system suppliers have been in contact with CAGE and are visiting in to discuss HGE.

Initially it is planned that the current HGE product is used on site for charging of batteries and electrical equipment as its 10-15kW output suits this application. However, Speedy and other contractors have expressed the need for larger, higher output machines and it is imperative that the technology can be transferred quickly to a larger engine platform to meet this need.

CAGE will be seeking funding through grant or private equity to enable this.

10.2 Other Sectors

Whilst construction is the focus to build quickly on the success of the project, there is interest from other sectors in the technology. These include micro-grid power to integrate a genset with solar/wind and batteries and CAGE has had interest in this solution to power Vodafone mobile telecoms towers throughout the EU. The customer specification for this solution demands hydrogen/LPG capability and the power output is suited to the current HGE.

CAGE also had an enquiry from Tata Power for an HGE solution using biomethane as the NZ fuel option for Micro Grids in India, but these needed a minimum of 40kW output.

10.3 Challenges of scaling

Finance is the absolute challenge to scaling. It appears that there is enough interest from early adopters to gain market traction and sales ramp up in sufficient volumes to create a strong business case but finance to fund this early-stage growth is very difficult in the current market. Capital intense industrial hardware products are more difficult to finance than software only commodities and working capital to cover manufacture is very expensive and high risk with potentially quite long lead times for expensive component sourcing.

Otherwise manufacturing partners and supply chains are in place to allow the initial phase of scaling although to achieve later high-volume sales into global markets new contract manufacturing partners are needed to bring costs of product down.

In terms of regulation compliance an initial piece of work was concluded within the project on CE marking to enable sales into domestic markets. Formal emission compliance remains a challenge in terms of cost and appropriate regulations around alternative fuels although the project has proven conclusively that the engines fall easily within the EU and global standards on all fuels tested.

11 Conclusions and Next Steps

The HGE project enjoyed many successes and has delivered on its principal objectives of developing and trialling a multi-gas engine and generator technology that enables a pathway to move from diesel to net zero fuel types including hydrogen. Development of internal combustion engine control technology to optimise the combustion of gas fuels enabled the HGE engines and generators to be trialled in a harsh working environment on a live HS2 construction site and to prove their capability as a direct clean substitute for incumbent diesel-powered machines.

The objective of trialling rDME fuel on site could not be fulfilled due to the fuel ultimately not being available in renewable form although the project successfully developed and tested an engine that ran to specification using a blend of DME and LPG.

Whilst hydrogen was shown to work very well in a generator as a diesel substitute the project confirmed the generally accepted current challenges of cost, supply difficulties and energy density.

The next step for HGE is to supply units to the market so that a broader mix of industrial and construction users can experience the advantages of the technology and support a commercial launch. A growing interest in using biomethane from waste as a diesel alternative within the CAGE partner network has generated a strong interest in introducing this second renewable fuel to the HGE capability. It is believed that a generator that can switch between hydrogen, biomethane and LPG will further strengthen the proposition.

Success of HGE2 has generated interest from Bennamann who are owned by Case New Holland (CNH). They have developed a small scale biomethane production facility that can process biogas and bottle biomethane at an anaerobic digestion (AD) or landfill facility. CAGE is receiving biomethane from them for the R&D needed to develop the engine and Speedy is interested in supporting further development of a 'tri-fuel' HE product. A biomethane MCP will contain seven times more energy than the hydrogen units supplied by BOC to the trial and is much lower cost than hydrogen. Potentially this third fuel can be trialled with EKFB in the proposed extension of the current trial.

11.1 Legislation

Meeting CE standards and the process involved has been a great success of the project. The project had hoped to be able to work with a UK partner to overcome some of the challenges of emission certification of alternative fuels in small engines based on the EU Stage V standard and in fact establish a mechanism whereby engines that comfortably bettered the emissions standard could be formally recognised. A lot of effort was invested by CAGE and Imperial early in the project to achieve this and it became apparent that there was a general disinterest from established UK service providers in offering certification services with non-conventional fuels.

The project would have needed to carry out these activities overseas and at higher cost than the project could stand. To engender a market environment where small companies can launch innovative products into the market this issue needs to be addressed. Some perspective on this challenge is given by the effort and investment JCB has given to certify its £100M hydrogen engine (JCB, 2025), where a Netherlands agency gave initial approval before other agencies followed. The multi-fuel capability of HE makes for an even more complex certification process.

11.2 Lessons Learned

HGE2 has been a huge learning process for CAGE and all the partners involved. It has highlighted the serious challenges of introducing technology to disrupt the business-as-usual mindset where diesel is the go-to for easy power. Forward thinking partners including Speedy, Calor and EKFB have worked patiently and tirelessly to overcome the many barriers of getting novel gas fuels onto construction sites and in use as diesel replacement in as a ‘non-disruptive’ way as possible.

The key challenge of using clean hydrogen as power has been shown as entirely feasible providing the cost and supply issues can be overcome.

11.3 Management

The management benefitted from a weekly reporting meeting run by HS2 where all issues could be monitored. The project had complex processes for the many changes needed to execute delivery of the technology and the delays these caused were sometimes disruptive. Whilst accepting that scrutiny is needed when public money is used to support innovation, compared to several Innovate UK projects previously delivered successfully, the volume of work involved in management and reporting was burdensome and sometimes was felt to be holding the project back.

The project also helped us realise the importance of full engagement with stakeholders on even the smallest details. For example, although the generators were built to UK industry standards, Speedy has their own protocols around generator output specifications meaning that we had to change all the machines before they were deployed. If Speedy engineers had been involved in the original specification of the machines we could have built this in and saved delay.

12 References

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