NRMM Red Diesel Replacement Phase 1

HYDRATE

Hydrogen Recuperated Advanced Thermal Engine

Final Report

Project RDR/P1/L2/8861

Executive Summary

The HYDRATE project developed a Hydrogen combustion system for the Recuperated Split Cycle Engine and studied its implementation in construction equipment.

The Recuperated Split Cycle Engine is an innovative thermal engine that offers potential for high efficiency (up to 55% brake thermal efficiency, matching or bettering the installed efficiency of a fuel cell), and low emissions (to below the lowest proposed legislation anywhere in the world), while retaining the ease of manufacture, uptake and servicing of any internal combustion engine. Originally conceived as a better Diesel engine, it targets a range of heavy duty applications in the 100kW to 10MW range. Following from some earlier research at very limited loads, HYDRATE successfully demonstrated stable, efficient combustion of Hydrogen as a fuel, using a “dual fuel” system whereby a tiny injection of Diesel is used to ignite the Hydrogen. Good combustion was observed on a single-cylinder laboratory engine over a range of conditions.

A multi-cylinder engine was built and commissioned, but was unable to run on Hydrogen due to lack of time. However, a simulation was matched to the combustion performance of the single cylinder and the overall thermo-fluidic performance of a similar Diesel multi-cylinder; this model predicts that the multi-cylinder engine, with expected initial development and rectification of some faults detected on the single, would perform at an efficiency level of over 50%. If this were achieved in reality, it would be the most efficient Hydrogen engine ever built. That work will take place in 2024; there is potential for further improvement beyond that.

The project found that the construction sector represents a good early-adopter for the technology, with suitable access to a captive machinery fleet, trained staff and options for hydrogen supply; in the long term, the economics of Hydrogen as a fuel are competitive, while in the shorter term the high value of whatever is being constructed permits a more costly fuel to be tolerated if this is mandated. It is likely that larger, hydrogen-fuelled machines will coexist alongside smaller, electric plant.

More detailed studies were performed on a wheeled loader and a generator set, as examples of suitable machinery. These showed that installing the RSCE in place of an existing Diesel ICE was feasible, but highlighted the critical importance of onboard fuel storage space.

As this high-risk, high-gain technology did not advance enough during HYDRATE, it was not able to join the RDR2 process for a field trial; however, a route to market is proposed whereby it can follow in the footsteps of more conventional Hydrogen ICEs, which can establish the fuel supply infrastructure. The first recuperated split cycle engine to market may however be fuelled by natural gas / biomethane, as this has similar combustion benefits and is more readily available today. Development of the engine is continuing, including exploration of an alternative combustion system that replaces the pilot Diesel fuel with spark ignition. Using future “green” hydrogen, this is therefore a true “net zero” solution for multiple heavy duty sectors, with potential to create up to 2000 high value UK jobs and reduce global CO2 emissions by over half a billion tonnes per year by the mid 2030s.

1. Introduction & Project Structure

1.1 Introduction – Construction Sector Needs

Machinery used in the construction sector is challenging to de-carbonise. Its duty cycles can be demanding in terms of long hours at high load, while the environment in which it works is often muddy or dusty; permanent refueling or recharging infrastructures are not a usual feature of construction sites. And the machinery is usually leased, putting strong pressure on both capital and operating costs. The traditional solution, across a wide spectrum of machines such as excavators, loaders, tippers and specialized machinery, plus gensets to power the site, is a Diesel engine. In the UK construction sector, un-taxed "red" Diesel was permitted for any machine not operating on the highway. However, this fuel was banned from 1st April 2022, as part of the UK Government's drive to de-carbonise the economy. In the short term, the construction sector must either use taxed Diesel, or alternatives like Hydrogenated Vegetable Oil (HVO); in the longer term, it will transition to net-zero fuels. To support that transition, The Department for Energy Security & Net Zero (DESNZ, formerly a part of BEIS, the Department for Business, Energy, and Industrial Strategy) supported a number of technology development projects, of which HYDRATE was one.

1.2 The Recuperated Split Cycle Engine

While electrification is likely to become globally dominant in "light duty", smaller or intermittently used applications such as cars, vans and some smaller construction equipment, it is recognized that this will not be the case in "heavy duty", larger and more heavily used applications such as trucks, agricultural equipment, marine propulsion, construction and mining / quarrying. Here, the opportunity exists for a cleaner, sustainably fueled engine.

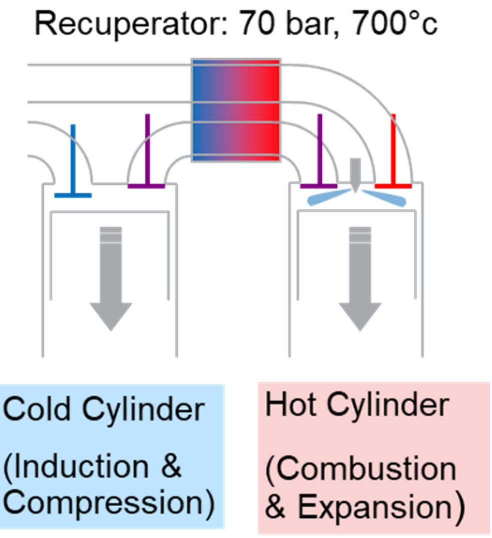
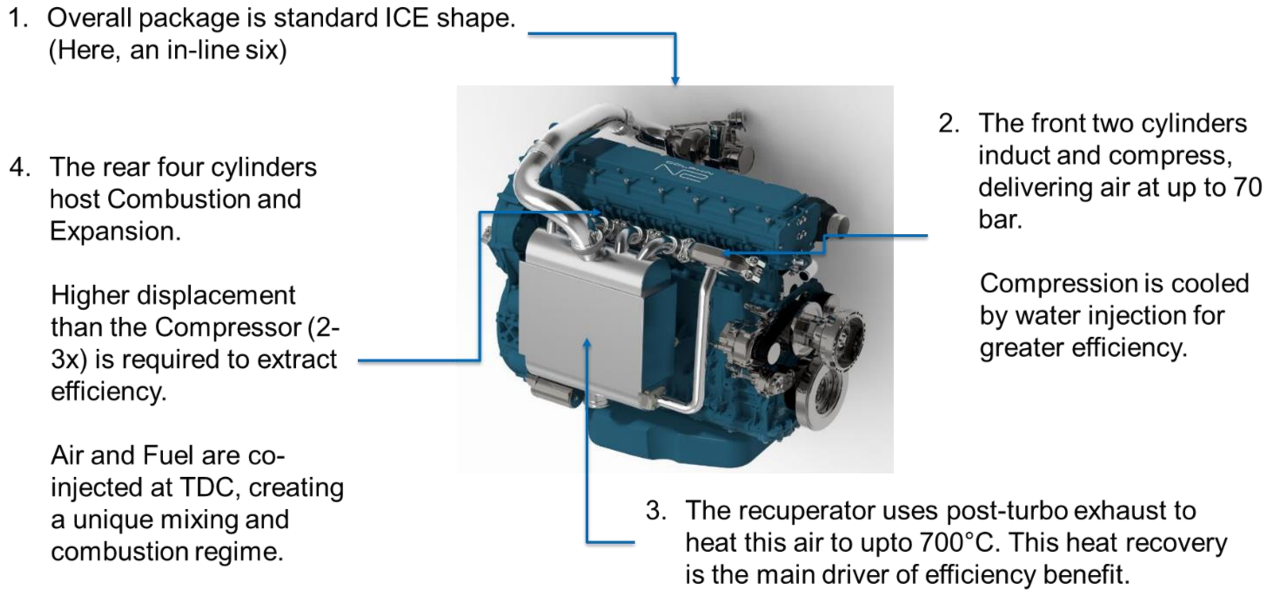


Figure 1: Recuperated Split Cycle Engine

HYDRATE's objective was to develop a Dual Fuel Hydrogen version of the Recuperated Split Cycle Engine (RSCE). This is an advanced type of thermal engine, where the principles of the traditional "four-stroke" are re-organised for better efficiency and lower emissions, by breaking down the cycle into separated cold and hot cylinders, and adding recuperation of wasted exhaust energy between the two (Figure 1). Further efficiency gains are delivered by injecting a fluid into the compression process to keep it cooler – for most applications, this fluid is water, the system known as ThermoPower®. For a larger, peak-shaving power-generation engine, injecting liquid nitrogen made from wrong-time renewables gives even higher system efficiency and is known as CryoPower®, but that variant was not appropriate for construction.

In practice, the RSCE resembles a conventional 4-stroke Diesel engine, and can be based upon its major parts, manufacturing, and supply infrastructure. The ThermoPower® prototype being developed by Dolphin, known internally as "Upgrade 5", is based on an in-line 6-cylinder Iveco Cursor 9 truck engine, with two cylinders acting as compressors and four expanders (Figure 2).



1. Overall package is standard ICE shape. (Here, an in-line six)

2. The front two cylinders induct and compress, delivering air at up to 70 bar.

   Compression is cooled by water injection for greater efficiency.

3. The recuperator uses post-turbo exhaust to heat this air to upto 700°C. This heat recovery is the main driver of efficiency benefit.

4. The rear four cylinders host Combustion and Expansion.

   Higher displacement than the Compressor (2-3x) is required to extract efficiency.

   Air and Fuel are co-injected at TDC, creating a unique mixing and combustion regime.

Figure 2: "Upgrade 5" engine, as developed in HYDRATE (picture shows a simplified display engine)

1.3 RSCE Development History

The principle of recuperating a combustion engine is well known in the world of gas turbines, where adoption in power generation and marine propulsion started in the 1970s and is now universal. However, for piston engines the RSCE principle was first proposed by Innogy, a part of the then-recently privatized National Power energy utility (References 1, 2, 3). Two IsoEngine prototypes were built, targeting a low-speed power-generating engine at megawatt scale. These demonstrated combustion of Natural Gas and successful reduction of compression work; however, the idea was not taken forward.

Further innovative thinking was then developed within the UK engineering company Ricardo, who had supported the original IsoEngine program, in particular around starting, valve timing and combustion control. To commercialise the technology, Ricardo spun out the company Dolphin N2 Limited, which was sold in 2019 to FPT Industrial, now a part of the Iveco Group and supplier of engines for commercial vehicle, construction, agricultural, marine and genset applications. Dolphin has since developed the technology, initially as a Diesel-fueled engine (4), but more recently also as a Hydrogen version. This work was both investor-funded and supported by two prior grant-funded projects:

Project	Funder	Achievements
StepCO2	InnovateUK	Single-cylinder engine mapped Diesel combustion. Single-cylinder compressor and valvetrain rig mapped key component performances. Recuperator designed, built, and tested. First multi-cylinder “Mule” engine designed, built, and run. Simulation identified potential of Hydrogen and Biomethane as fuels.
RE-ARMD	APC	Ceramic thermal insulation developed for durability and performance. Base engine developed for durability and performance. Single-cylinder Hydrogen Dual Fuel engine built and tested over a limited operating envelope.

Table 1: Previous grant-funded projects

The first multi-cylinder prototypes were essentially "mule" engines made by converting two existing engines into a Compressor and Expander, the two being linked by a prop-shaft and gas pipes (Figure 3). This work then led to the development of the integrated engine known as "Upgrade 5", which combines all functions in a product-like, and considerably tidier, single unit (Figure 2). The Diesel version of Upgrade 5, known as 5.2DD, engine underwent development towards targets for power, efficiency and emissions during 2023, and served as a starting point for HYDRATE.

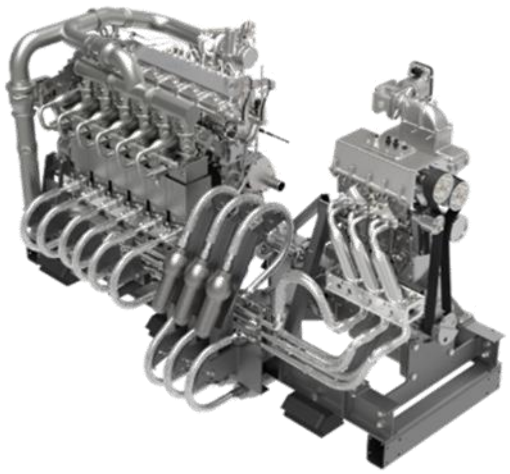


Figure 3: Mule Engine made from two separate units

1.4 Why Hydrogen Dual Fuel?

Heavy duty vehicles and machinery need to carry enough fuel for their duty cycle or mission, and to be able to refuel quickly enough to fit with efficient operation. High energy density and fast refuelling are therefore the requirements that define the fuel from the operator's perspective. The best fuel is therefore a liquid, and Diesel has filled that role well. Sustainable replacements are available, including biofuels and synthetic liquids made from renewables. However, the total quantity of biodiesel available is limited to around 7% of Europe's Diesel needs (5), and synthetic liquids are not yet a mature technology in terms of cost or volume available. Furthermore, considering the holistic picture, there is concern that these valuable energy-dense resources will be needed most by the aviation sector, therefore their use in surface transport and power is discouraged (6).

Next in the energy density pecking-order are Liquid Methane and Ammonia. Ammonia made from renewables is seen as promising for marine propulsion, although it presents significant fuel-handling challenges in the construction context. Methane can be manufactured from a wide range of bio-wastes – indeed, this happens in nature, leading to the release of large quantities of a gas with global warming potential 28 times that of CO_2. This means that operating just one vehicle or machine on fugitive methane that would otherwise enter the atmosphere, has the same impact as taking ten fossil-fuelled units out of service. This is certainly an attractive fuel, and it is already popular in agriculture, where there is a very strong business-case for producing it on the farm (7). However, as with biodiesel, limits on resources (at least, on those that are easily captured) may apply; more significantly, many national policies for the on-highway vehicles that provide their engines to construction are (rather unhelpfully and incorrectly) specifying that Net Zero will be interpreted as "Zero carbon emissions from the exhaust pipe".

Which leads to Hydrogen. Hydrogen does have four strong advantages:

1. It is readily made from renewables by a variety of means
2. It is also the fuel of choice for the Fuel Cell (albeit at a higher purity requirement than ICE)
3. There is already an industrial infrastructure for handling it in bulk, as it is used in the petrochemical industry
4. It emits nothing but water (provided that emissions such as NOx are avoided), so it fits within "zero at the tailpipe" rules on carbon emissions

Diesel fuel in the RSCE works by auto-ignition. The preceding work in the StepCO2 project (Table 1) had shown that Hydrogen might also auto-ignite, although subsequent work has shown that this is probably not desirable (8). Instead, a controlled ignition event allows greater control over the whole combustion process, especially its timing. The conventional way of doing this is with a sparking plug; however, under marginal ignition conditions this can prove insufficiently repeatable. For this reason, the concept of "pilot ignition" was developed for gas engines, whereby a small injection of an auto-igniting fuel (Diesel) creates a plume of flames to light the main charge. Given uncertainties around this new fuel, the pilot principle was chosen for HYDRATE, although spark ignition was explored in a follow-on project, CMDC2 HydroMAR-E. The Westport dual-fuel injector system, already used in LNG trucks, was adopted for this purpose as described in more detail in Sections 2 and 3.

1.5 HYDRATE objectives & structure

The over-arching objective of HYDRATE was to develop a multi-application, advanced Hydrogen-fueled thermal engine in readiness for field trials; supported by concept work on installation into applications, and preparation of plans for field trials. The output of this would be an easy to adopt, universal, enduring NRMM solution for the many applications whose duty cycles and operations are not suitable for direct electric connection or battery power.

Specifically, objectives were:

1. Develop a TRL5 multi-cylinder Recuperated Split Cycle Engine that operates as a dual-fuel Hydrogen engine, offering installed system efficiencies equivalent to or better than those of a fuel cell (meaning, a Brake Thermal Efficiency over 50%), and very low emissions equivalent to SULEV; To the point of readiness for installation and trial in one or more NRMM applications.
2. Develop planning for application installations including identifying hardware and suppliers for donor machinery and supporting installation hardware (e.g., Hydrogen storage & handling)
3. Develop a Phase 2 and Deployment plan, including identification of User Requirements (vehicle / machine types, duty cycle, servicing, maintenance, refueling) , Business Model (technology comparisons vs 4-stroke Diesel, 4-stroke Hydrogen and Fuel Cell; CapEx & OpEx, value of "intangibles" such as clean & quiet operation) and Field Trial definition (site, aims, types of machine, potential partnering up and down the value chain (Fuel, Refueller, Vehicles, Servicing) in readiness for a potential bid for "NRMM Phase 2" funds to support such a trial.

The project was structured into five Work Packages, as shown in Figure 4:

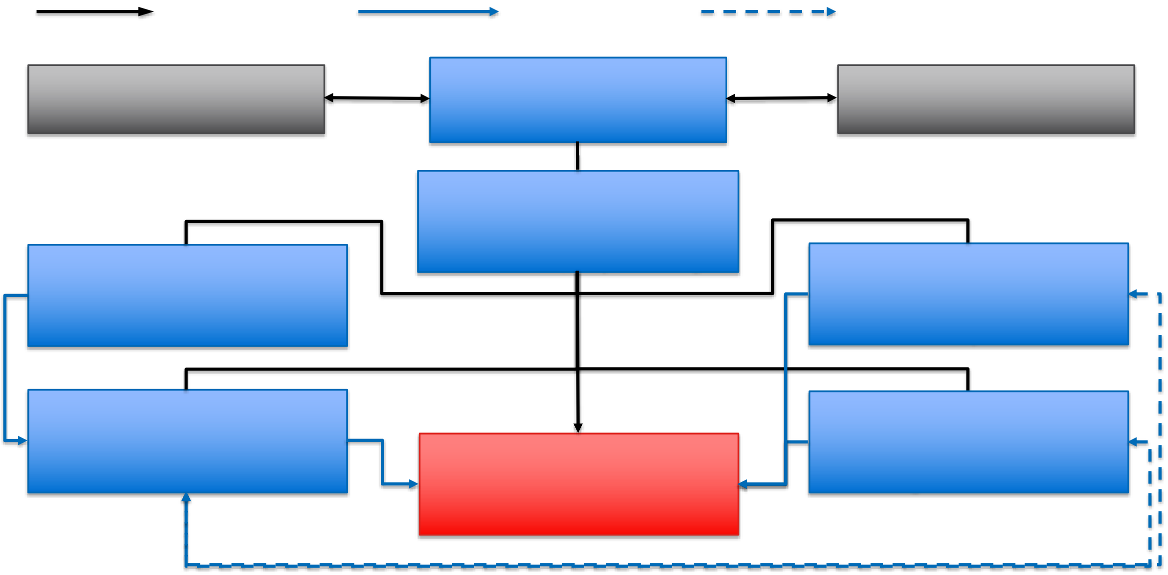


Figure 4: Project Structure & Organogram

WP1: Project Management (Lead: Dolphin; Input: All partners): This WP managed the governance, delivery, and administration of the project. Tools used included: Maintenance of a master Project Plan identifying critical paths and interactions; Use of RASIC (Responsible, Approver, Support, Informed, Consulted) matrices to define responsibilities; Maintenance and regular review of a Risk Register; tracking of Deliverables and Milestones, Percent Complete etc. Weekly progress reviews were backed up by more detailed 1:1 discussions and workshops on specific issues. The consortium held a quarterly Steering Group, usually immediately before the Monitoring Officer review, and operated under a Collaboration Agreement.

WP2: Single Cylinder development (Lead: Brighton; Support: Dolphin): The existing Titan single cylinder engine, which ran with a low-pressure Hydrogen injection system during 2021, was upgraded with a new cylinder head to receive a High-Pressure Direct Injector. This “Upgrade 5” head is common with the multi-cylinder engine, and was an existing design adapted for the single-cylinder and the use of the Westport injector, as described in Section 2. The principle of Single Cylinder testing is to screen the basic combustion process over a range of speeds, loads, valve, and injection timings, with the aim of developing a reproducible cylinder for the multi-cylinder engine of WP3.

WP3: Multi Cylinder Engine (Lead: Dolphin; Support: Brighton; Input: Costain): A multi-cylinder Hydrogen engine was built, based on the existing “Upgrade 5” Diesel unit, and Dolphin’s bespoke controller was upgraded to drive dual-fuel injectors. Multi-cylinder development was intended to use a dedicated test cell at Brighton, but with extensive involvement of the Dolphin team; this laboratory was up fitted for Hydrogen as part of the project. Development sought to replicate the single cylinder outcomes in the integrated package, matching the functions of turbocharger, piston compressor, recuperator, and expander. However, a number of delays to the project meant that this engine was commissioned and briefly fired but not tested; an alternative approach using a simulation was adopted to predict how it might have performed.

WP4: Vehicle Application Planning (Lead: Dolphin; Input: Costain): The HYDRATE engine is suitable for a number of machinery applications at around 180kW, including dumper trucks, tracked excavators, wheeled loaders and generator sets. Input from the field trial planning in WP5 was used as a basis for considering candidate trial vehicles / machines; studies were then performed around the selected Wheeled Loader and Generator Set (including Hydrogen tank location), as these were available using the base Cursor 9 engine for easier conversion. 3-d design concepts for both were produced. Added components such as after-treatment, cooling packs, generators, hydrogen tanks and pumps were identified from the supply chain, with several new partnerships being developed.

WP5: Field Trial Planning (Lead: Costain; Input: All): WP5 developed a vision for Phase 2 field trials and deployment, from the perspective of a real construction user. Use requirements such as vehicle types, duty cycles, servicing & maintenance schedules, and logistics (how often; on or off site), refueling and other “daily use considerations” were mapped to develop a picture of both what the HYDRATE engine must do, and how it might compare to alternative solutions. A review of technology comparisons was conducted, using both published and confidential information; to develop comparisons on the basis of CapEx (machine, infrastructure), OpEx (Fuel, Servicing), and “intangibles” (value of clean & quiet). This information was used, in discussion with partners and other stakeholders (including the Phase 2 matchmaking event) to create a Field Trial definition: Objectives, scope, types of machine and infrastructure, potential partners, and logistics of operating the trial (including how to cope with immature technology in a pressured operating environment, backup machinery etc.). This created the basis of a potential Phase 2 bid; however, the partners chose not to proceed as the technology had not achieved sufficient readiness yet.

2. WP2 Single Cylinder Engine Testing

2.1 Introduction & Aims

Single-cylinder research engines are commonly employed to develop combustion systems, by replicating one cylinder of the intended multi-cylinder product. For the Recuperated Split Cycle Engine there are of course two-cylinder types – compressor and combustor/expander – both having unique thermodynamic processes worthy of this single-cylinder approach. In the prior StepCO_2 project, two such single cylinders were built and tested, one for each function, but the focus of that project was Diesel combustion.

During 2020-21, a follow-on project, RE-ARMD, built and tested a very basic single cylinder engine to validate Hydrogen Dual Fuel combustion (12). This engine was very much compromised by its low-pressure fuel injector (limited to 30 bar, whereas air will enter the expander at 70 bar at full load), but demonstrated stable combustion of a mix of Diesel and Hydrogen at light load, with lower NOx and similar efficiency to the base Diesel system. Because of the low injection pressure available, there was limited choice of strategy for when the Hydrogen and air could be injected. However, the work gave sufficient confidence to initiate the HYDRATE project with a much more capable, 350 bar Dual Fuel injector.

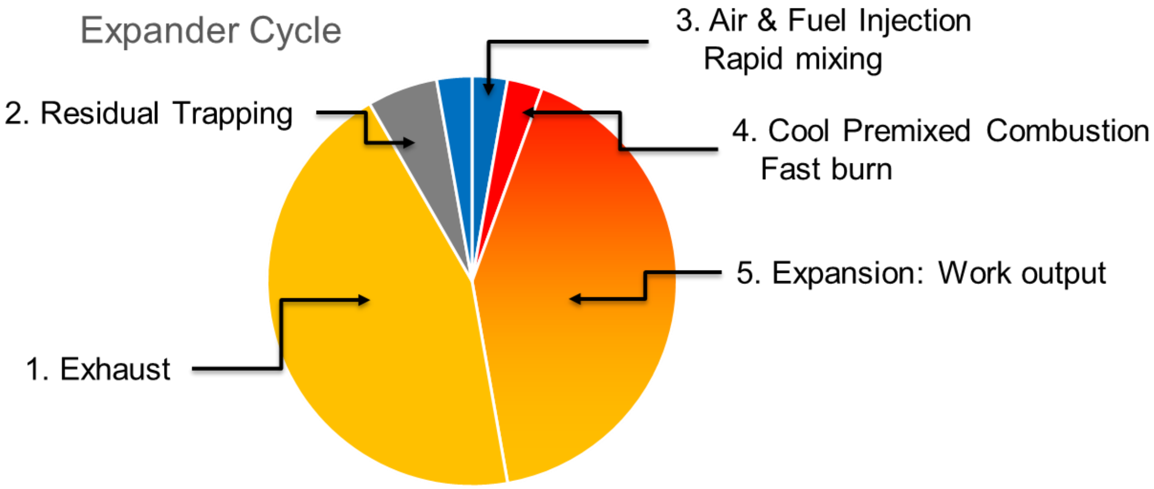


Figure 5: Expander cycle

Figure 5 shows the principles of the expander cycle, which is essentially a 2-stroke cycle. The upward motion of the piston drives an exhaust stroke, with the timing of exhaust valve closure determining what, if any, hot residual exhaust remains in the engine. This serves three purposes:

1. As with a conventional engine, this inert gas can be used to reduce the combustion temperature and NOx formation (known as "Internal EGR".)
2. As with a steam engine, the presence of a small amount of trapped gas prevents unchecked expansion of the incoming high-pressure gas, which leads to cooling by expansion.
3. This trapped gas, already hot, is compressed by the incoming pressurized air, and becomes even hotter, providing a source of auto-ignition.

This third factor was found to be important in the combustion of Diesel as the sole fuel (8). However, excessive temperature here was found to ignite the Diesel too early, while the air inlet event was still in progress, leading to loss of efficiency and engine damage. Hydrogen has very different properties to Diesel, (Table 2) and is usually ignited externally – by a sparking plug, or a small Diesel pilot spray, which self-ignites and then lights the hydrogen.

	Diesel	**Hydrogen**
Autoignition Temperature	~315°C	565-582°C
Octane Number (RON)	-25	130
Adiabatic flame speed	0.5-1.0m/sec	3-5 m/sec
Ignition Energy	n/a	0.011mJ (low)

Table 2: Key properties of Hydrogen vs Diesel

The key properties that make Hydrogen potentially attractive are:

- It has a much higher auto-ignition temperature than Diesel, so it will resist igniting too early, while the inlet valve is open; its high-Octane Number is a practical measure of its resistance to igniting when not wanted.
- It requires relatively low energy to ignite it (lower than Gasoline, for example), and is ignitable over a wider range of air:fuel ratios (meaning that it does not need to be perfectly mixed)
- Once ignited, it burns fast, which is thermodynamically efficient.

These properties are important because timing of combustion is critical (Figure 5). The window for admitting air and fuel, then igniting and burning it, is small, so it is vital to controllably initiate a fast burn. Diesel combustion in this type of engine has been modelled using 3-d computational fluid dynamics (12), with results that match observed engine tests. However, the detailed combustion model used was not available for Hydrogen, so a simplified, zero-dimensional approach was used to model combustion. The key question is "can uncontrolled auto-ignition be avoided?"

The model used an open-source chemical-kinetics code called Cantera. Diesel combustion was modelled and tuned to match real measurements (12). The same model was then applied to Hydrogen, with a range of high air inlet temperatures that might trigger unwanted auto-ignition.

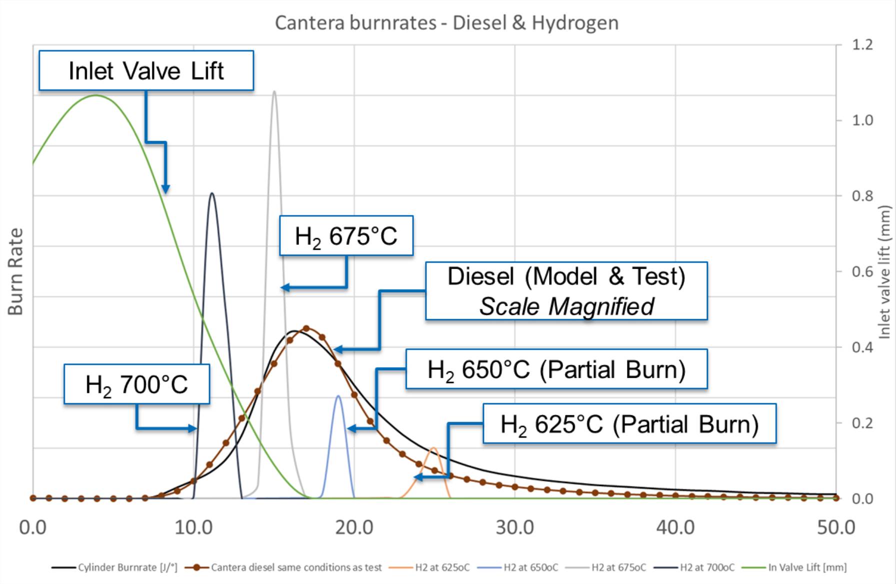


Figure 6: Modelled burn rates of Diesel and Hydrogen

The model (Figure 6) outputs a burn-rate for each scenario. The Diesel combustion is seen to start while the inlet valve is in the final stages of closing, which is undesirable. The same occurs with Hydrogen (with no deliberate ignition source) at higher temperatures, with a very fast burn. However, at 650°C and below, the Hydrogen does not auto-ignite fast enough to burn completely, and below 600°C no auto-ignition occurs. This suggests that an air temperature of 600-650°C – which is well suited to the overall thermodynamics of the engine – would allow ignition to be initiated deliberately at the point of valve closure. The aim of WP2 was, essentially, to demonstrate that this could be achieved.

2.2 Engine Hardware

2.2.1 Titan Single Cylinder

The ‘Titan’ engine represents the single cylinder engine, used for the development of combustion strategies, primarily. For the HYDRATE project this was that base engine used to upfit a full dual fuel system (with high pressure hydrogen capability) to allow further development of the RSCE combustion approach with hydrogen being the primary fuel used.

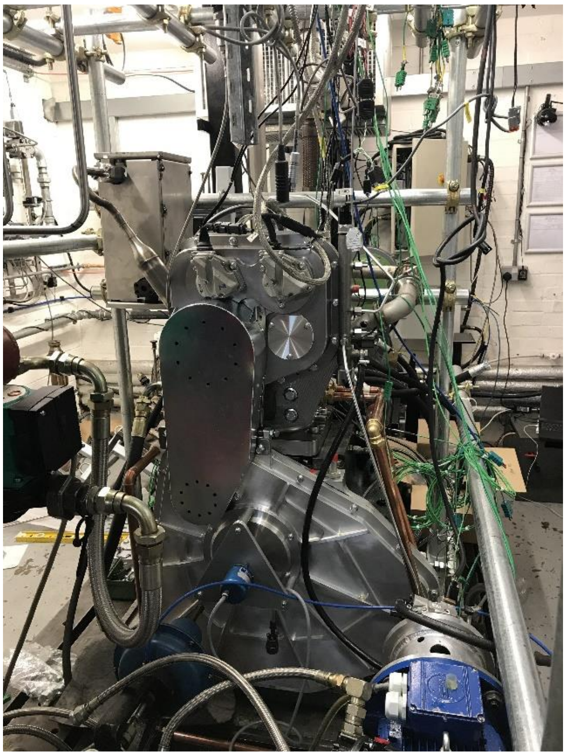


Figure 7 - Titan Single Cylinder Engine

Figure 7 shows the base Titan engine after the upgrade to a new specification. This allowed the inclusion of the new, and larger, dual fuel injector along with updating key components of the combustion geometry such as the air paths in to and out of the cylinder head as well as the combustion chamber itself. Learnings were carried forwards from the previous Titan engine to inform the positioning of the injector to ensure we could closely match the positioning of the diesel injectors in similar systems.

As this engine is only an expander cylinder, its high pressure working air is supplied from a bank of air cylinders, these are charged overnight by an oil-free compressor of the type used by Scuba divers. The air is delivered to the engine via a regulator and two recuperators, the first being heated by a gas burner (to compensate for the very cold air arising from expansion in the regulator) and the second heated by exhaust as in a multi-cylinder engine (Figure 8).

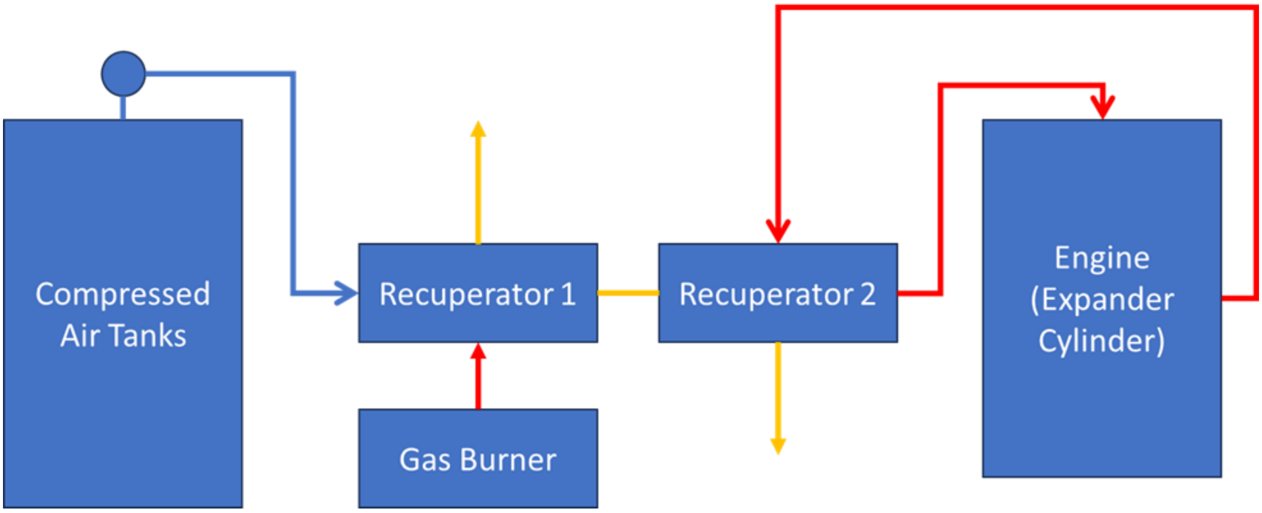


Figure 8: Air supply system for Titan

2.2.2 Split Cycle Dual Fuel Cylinder Head

As part of the upgrade to the base Titan engine the cylinder head was swapped with one designed to accommodate the dual fuel injector. This design needed to account for the increased size of the injector, while allowing the currently existing hardware to remain intact. This meant avoiding assemblies such as the valve springs and retainers that are located on the cylinder head assembly.

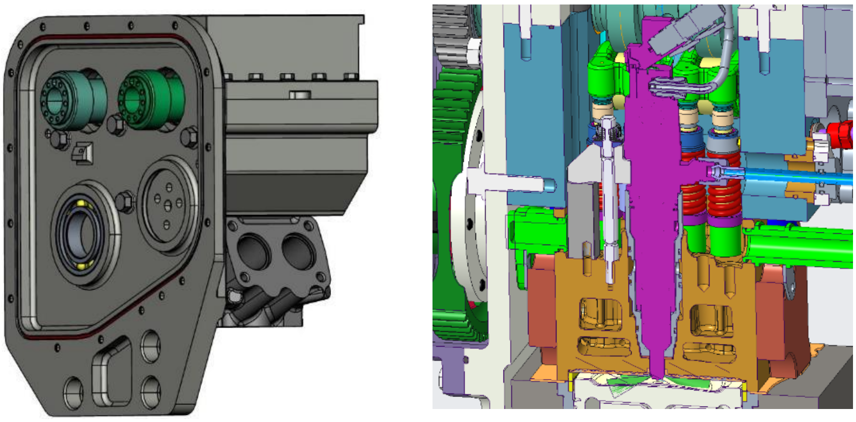


Figure 9 - Titan overhead assembly (left) and Cylinder head cross section

The images in Figure 9 show the general assembly of the upper timing cover, overhead and cylinder head components of the Titan engine. These are also pictured in cross-section to show the fitment of the injector. Due to the interface requirements of the injector and the existing head geometry the injectors have been fitted with a sleeve and the overhead sections have been modified to accommodate the pipework for both the diesel and hydrogen fuel systems.

In order to make changes to the cylinder head to accommodate an injector much larger than originally intended, analysis needed to be carried out on key components to ensure the tight packaging constraints could be met.

Analysis completed on the upgrade hardware included, but is not limited to:

- Cylinder Head Finite Element Analysis (FEA) – Analysis used to provide confidence that modifications to the cylinder head had not compromised its structural integrity under expected use conditions.
- Computational Fluid Dynamics - Analysis of the coolant flow in the new barrel and subsequent flow to the cylinder head to ensure adequate cooling flow given the constraints of the package.
- Exhaust System FEA – Analysis used to inform the design of the full exhaust system and bellows to allow for thermal expansion of the overall assembly.
- Intake Plenum FEA – Analysis to confirm changes to the high-pressure plenum do not compromise the integrity of the part.

An example of the FEA analysis performed on the cylinder head can be seen in Figure 10 below.

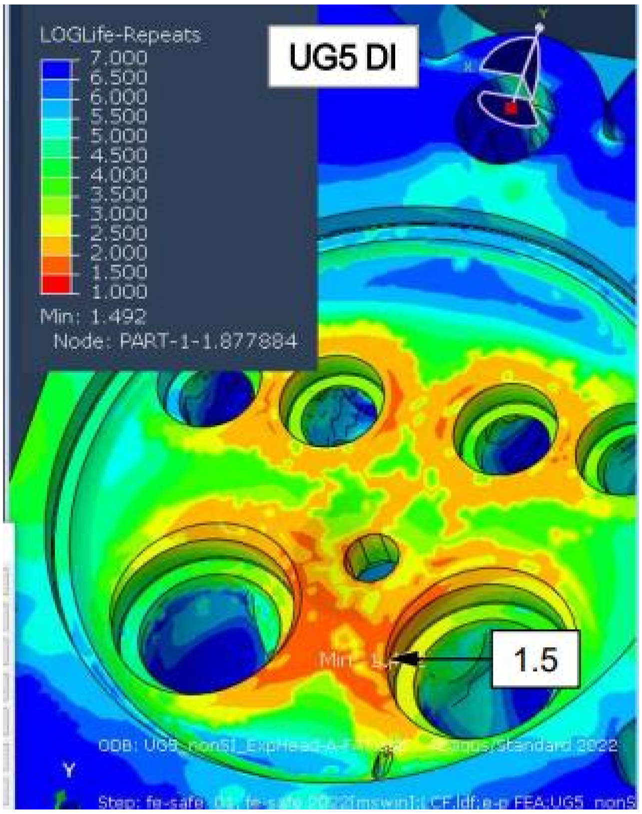


Figure 10 - Cylinder Head FEA

The work on the cylinder head followed similar analysis steps to that of most FEA undertaken on the project. Once boundary conditions were defined, based on theoretical figures or test data, the analysis could be completed and an iterative process of design improvements could be made, when needed. For the cylinder head, no further changes were deemed necessary, but other analyses highlighted above did require further iterations.

2.2.3 Hydrogen Dual Fuel System

As well as the changes made to the cylinder head and overhead (cam carrier), the main significant change to the installation was the hydrogen supply infrastructure. To supply the injector with the two fuels required, some changes were needed to the test cell infrastructure to accommodate the gaseous supply, while the diesel system was able to accommodate the new diesel supply requirements with minimal changes. The main change that formed part of the infrastructure upgrade was the addition of a high pressure hydrogen boost pump, to allow the control of the hydrogen supply pressure supplied to the injector. This pump is supplied with low pressure hydrogen from a gas bottle, which the pneumatic pump then boosts to the desired injection pressure for use in the injector. A general overview of the gas supply circuit can be seen in Figure 11.

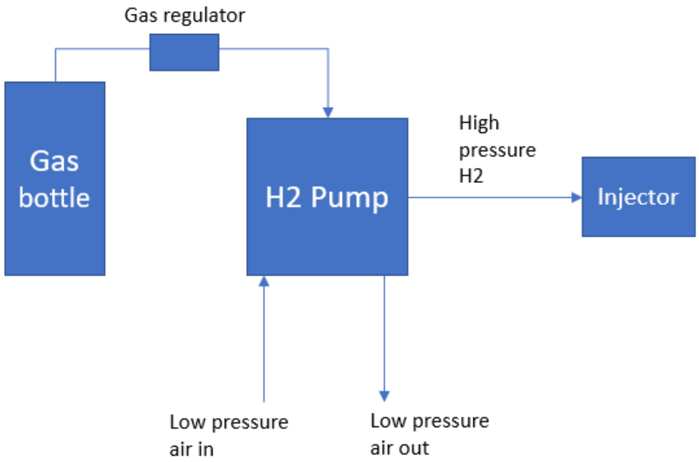


Figure 11 - General H2 Boost Pump Diagram

A simple control system allows air to be regulated to the boost pump, meaning the supply pressure can be controlled as needed and during testing.

The diesel system that was carried over from the original test setup can meter fuel pressure to balance the pressures of both diesel and gaseous supplies.

Based on the fuel flow rates and the boost pump capability the installation is able to be used as an 'on demand' high pressure hydrogen supply system, meaning that if hydrogen is available in gas bottles, it can supply hydrogen pressure at the injector as needed by utilising the boost pumps as the supply flow is large enough to avoid starving the injector of fuel when running at maximum flow. This may not be possible with larger engines or higher flow injectors as the pump could be the limiting factor in high pressure hydrogen flow. For a single cylinder engine however, this is suitable, although it was found to limit high power.

2.2.4 Hydrogen Safety

Hydrogen safety is a significant topic of discussion when aiming to utilise hydrogen in a test cell environment. While combustible fuels are standard practice for engine test cells, hydrogen has not been a typical part of that, until recently. In light of this new fuel, many areas of the cell and operating processes needed to be reviewed as well as on engine protections against hydrogen combustion taking place outside of the cylinder, that may remain unburned after passing through the engine.

The main feature on the engine to protect against unexpected hydrogen combustion is the use of a burst disc in the exhaust system to mitigate backfire of unburnt gases. The general function of this is to provide a failure mode to a particular pressurised volume which is predetermined and set at a much lower pressure than any other component in the system, thus protecting those parts in the event of a sharp pressure pulse due to combustion in, for example, the exhaust manifold.

The laboratory itself used an existing system of ventilation and detection, similar in principle to the new system in the multi-cylinder lab described in the next section.

2.2.5 Instrumentation

The engine was equipped with standard instrumentation for a research unit, which includes:

- Pressures and temperatures of air inlet and exhaust
- Dynamic pressure (resolved by crank degree) of the high pressure air inlet, and in-cylinder
- Flowrates of Diesel, Hydrogen and Intake Air
- Metal temperatures in the cylinder head (valve bridges) and liner (top ring reversal point)
- Exhaust emissions including CO_2, CO, Hydrocarbons and NOx (with NO separated)

As a result of previous issues, particular attention was paid to air and hydrogen flow. Both had been measured using a Bronkhorst meter, a device that uses heat transferred from a hot wire as a means of determining flow. This is a well-known approach, but it can be subject to pulsations leading to incorrect readings. In the Titan set-up, pulsations can be produced by the cyclic (once per rev) air intake and fuel injection events, and by the slower (around once per second) action of the hydrogen pressurization pump.

On the air side, a second flowmeter was built using the principal of a venturi and differential pressure measurement, which is less susceptible to pulsation and also acts to suppress pulses, so by positioning it downstream of the Bronkhorst, the latter was isolated from the engine. The two flowmeters were used together, so that readings could always be compared; static and running-engine flow tests were also performed by comparing both measurements to the rate of pressure drop in the air supply tank. The two flowmeters always agreed within 1% of each other, but indicated 18% lower flow than the tank pressure drop; a calibration was applied on this basis. However, this calibration testing also highlighted an air leak in the inlet valves of the engine which permitted intake air to flow through the cylinder during the exhaust stroke; this is discussed in the results section.

On the Hydrogen circuit, just a Bronkhorst type meter is used, but here other means can be used to cross-check readings: again, rate of pressure drop in the hydrogen feed bottle; plus oxygen content of the exhaust in a running engine. The comparison with the feed bottle pressure drop suggested that the meter was under-reading by 7% under steady conditions, but over-reading by 7% once the pressurization pump was turned on. Again, a correction factor was developed, which was checked for consistency with the first law of thermodynamics as seen in energy released to combustion.

2.3 Test Results

2.3.1 Combustion stability

A key question was whether combustion of Hydrogen would be stable, avoiding issues such as misfire due to poor mixing, or burning back up the inlet ports as seen in the Diesel variant. It soon became apparent that neither were a problem. Burning back into the inlet ports happens with Diesel because, being a liquid fuel, it has to be injected as early as possible in the inlet event to break up and mix the fuel droplets; being an auto-igniting fuel, there is then no direct control over when combustion starts, and it would often start too early. As shown in Figure 12, Hydrogen's higher auto ignition temperature avoids this efficiency-killing behaviour; it was also found that the fuel could be injected later in the air event, or after it altogether.

The first Titan single cylinder tests, conducted in 2022 using a low pressure injector (30 bar), had highlighted a tendency to unstable combustion due to uneven ignition delay, requiring a very early inlet valve timing to regain control (at the expense of efficiency); a comparison with the new high pressure injector (350 bar) in Figure 13 shows this behaviour completely banished.

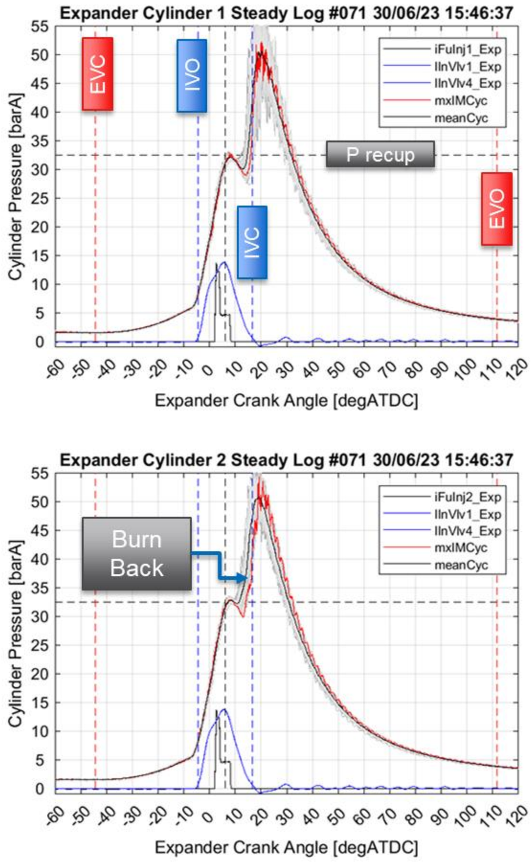


Figure 12: Combustion comparison of Hydrogen (top) and Diesel (bottom)

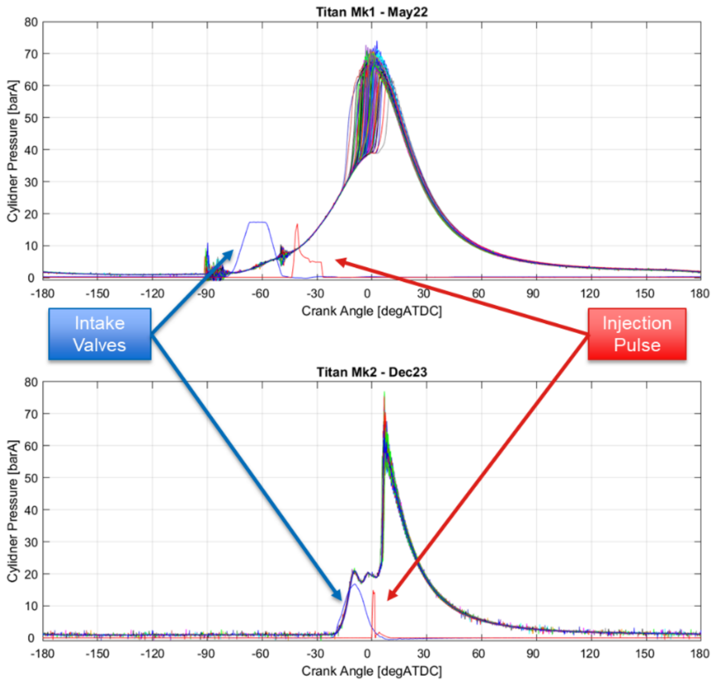


Figure 13: High pressure injection (lower graph) stabilises combustion

2.3.2 Combustion Modes and Ideal Combustion

Referring back to Figure 5, the ideal combustion process is defined by three characteristics:

1. The intake event should be as short and late as possible, because incoming air is pressurizing the piston as it finishes rising, thereby trying to turn the engine backwards, which is harmful to efficiency; however, if this event takes place entirely after Top Dead Centre (TDC), the piston is now moving down the bore, leading to a cooling charge and a risk of triggering misfire. So

timing this inlet event is both a delicate balancing act and a powerful control parameter for the engine.

2. Burn should happen fast, but not before the inlet valve has closed. The closer this happens to TDC (but after, never before), the more expansion can be realized.
3. Good stability, as discussed above; it is of little use if 1 & 2 above are only achieved on some cycles, or some cylinders of a multi-cylinder engine.

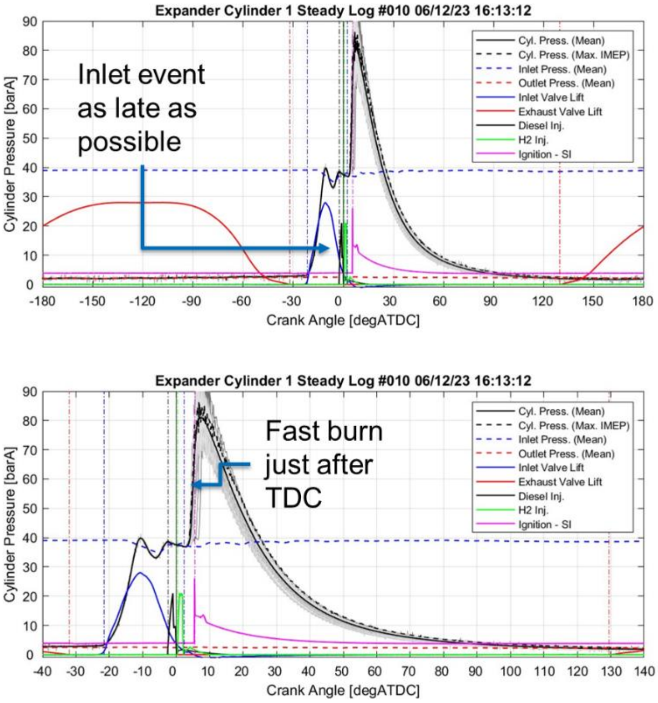


Figure 14: Characteristics of good combustion

Figure 14 illustrates these characteristics, with some real data, noting that:

1. The air inlet event is timed to finish just after TDC, but the pressure trace shows that the cylinder has filled less than halfway through the event. Therefore a shorter valve opening would be more efficient; this was later confirmed in simulation described in section 3.
2. Combustion is reasonably fast (though not as fast as seen in Figure 13), however, it could happen 5 degrees earlier at TDC; further optimization might achieve this.
3. Stability is good enough, as shown by the grey band of cyclic variation; but this condition was approaching the limit of what is acceptable.

It was soon found that four stable combustion modes existed (Figure 15):

- Dual-fuel ignition with the Diesel pilot before the Hydrogen, creating a flame into which the hydrogen is injected (like a pilot light on a gas burner); this is a stable mechanism (and is used on the Natural Gas engines for which the Westport injector is designed), but Hydrogen burn is likely to be diffusional, leading to higher NOx
- Dual-fuel ignition with the Diesel pilot after the Hydrogen; this allows time for the Hydrogen to mix better, and here the pilot spray works like a sparking plug
- Spark ignition, where no pilot fuel was used, was found to work stably in the parallel HydroMAR-E project

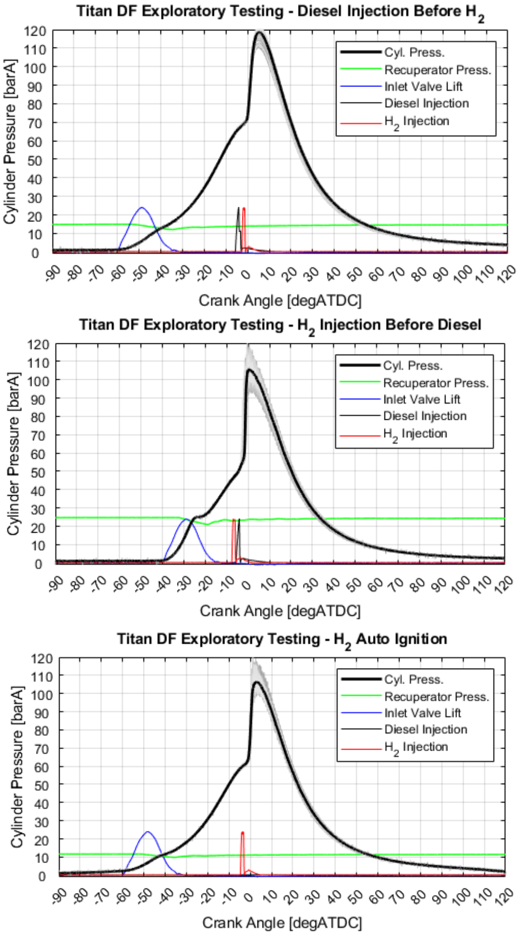


Figure 15: Combustion Modes

- Auto-ignition, was found to exist under certain conditions with no spark or pilot; however this tended to require early inlet closure to create extra heat by compression

2.3.4 Parameter Swings

Having established how to achieve stable combustion safely, key parameters (essentially, things that can be adjusted while running, such as operating speed or load, valve and fuel injection timings, and system pressures) were then swung to identify the best combination of parameter settings (and to validate the 1-d model described in section 3, across the swing). These tests identified a significant air leak through the engine from the inlet valves, which is not thought to impact combustion (during combustion, the pressure rises in the cylinder, so gases leak outwards), but does impact data, in that:

- Any estimation of overall system efficiency, which relies on airflow to estimate compressor drive power, will be pessimistic, as air continues to flow straight through the engine during the exhaust stroke
- The loss of combusting gases back into the inlet port, leads to lower power and efficiency than should be delivered

The 1-d modelling approach described in section 3 removes these factors by making adjustments to respect the First Law of Thermodynamics; data presented here does not, so it represents trends rather than true efficiency potential.

Figure 16 shows the effect of swinging the offset between exhaust valve closure and intake opening. This shows a preference for a larger offset, in terms of both higher system efficiency and lower NOx (rising hydrocarbons are less of an issue in any lean-burning engine). Interestingly, the simulation described in Section 3 predicts the opposite trend, favouring no offset. There is a balance of factors at play: trapped exhaust gases can be used to reduce the sudden early inflow of fresh air when the inlet opens (a technique that was used to improve steam engine efficiency), but the trapped gas then has to be compressed (which consumes power). More clear, is that these trapped inert gases reduce NOx formation, as on any engine, by lowering the temperature of combustion.

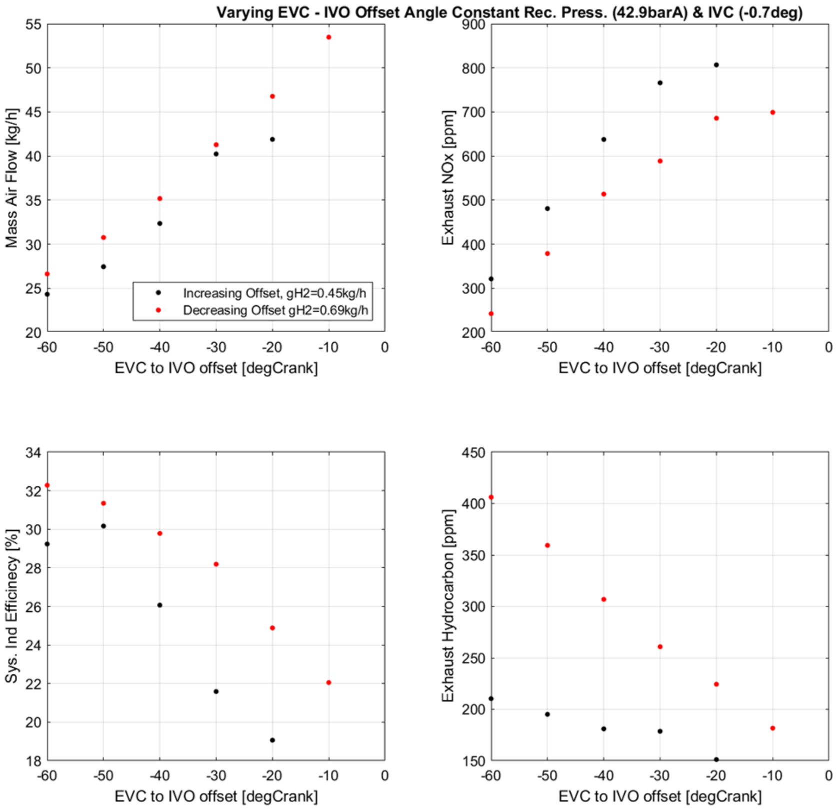


Figure 16: Sensitivity to EVO-IVC offset

Figure 17 shows the effect of exhaust backpressure. This is not a controllable parameter per se, because it is simply the result of pressure drops through the turbocharger turbine and (to a much smaller extent) the recuperator LP side and after-treatment.

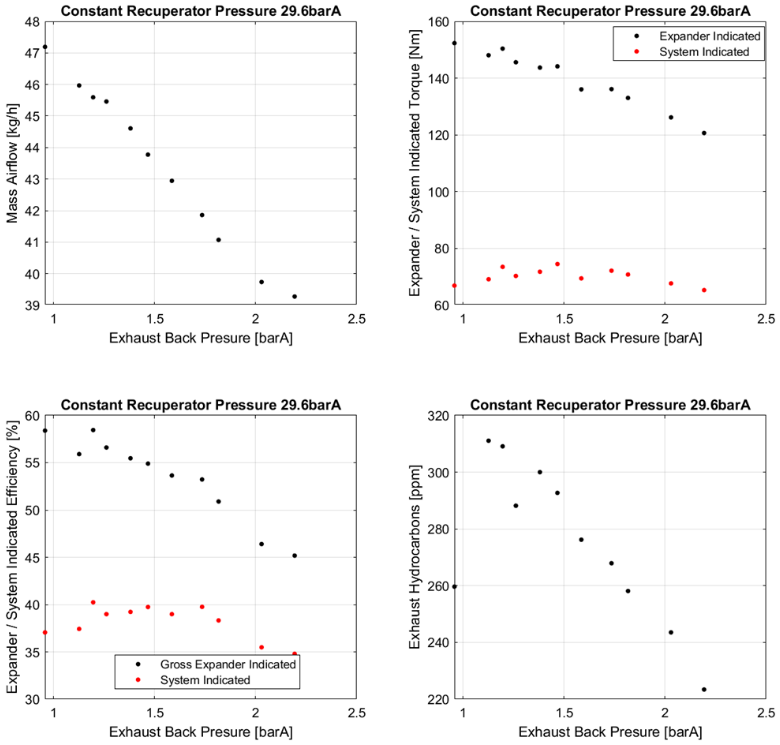


Figure 17: Exhaust backpressure swing

Here, the effect on efficiency is shown as Gross (black, expander without compressor work deducted) and Net (a simple estimate of compressor work, assuming isentropic compression). As expected, Gross efficiency falls with rising back-pressure, as the piston has to push harder to remove spent gases on the exhaust stroke. But the Net value holds a plateau, because the back-pressure leads to more trapped residual gases in the cylinder, and lower fresh air flow, which requires less compressor work. The engine is effectively running a little richer, but with internal EGR which helps to reduce emissions. This effect stops after about 1.8 bar (absolute) backpressure, but at this light load, the turbocharger requires less than that in order to work – typically 1.3 bar or less.

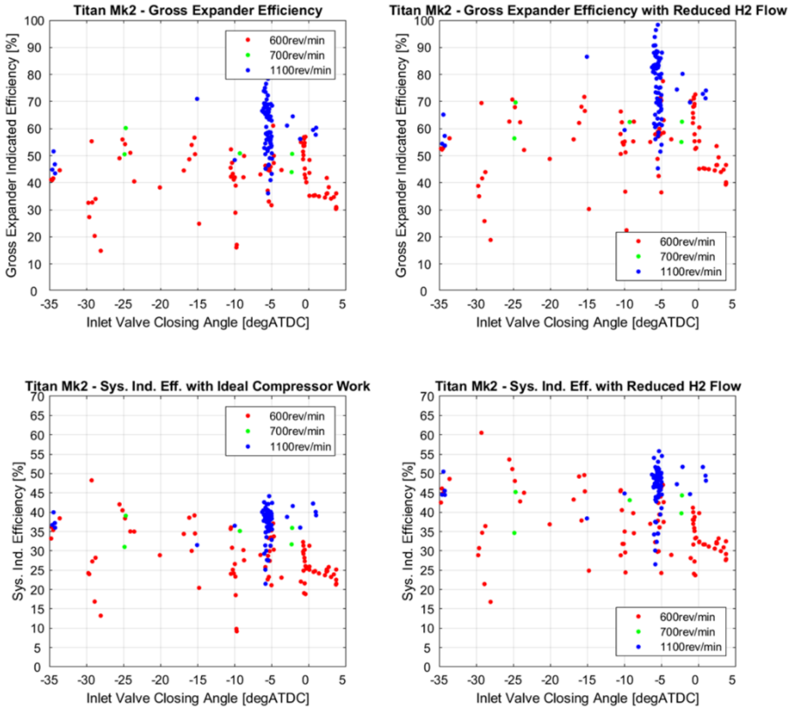


Figure 18: Inlet Valve Closing swing

Figure 18 shows the effect of inlet valve timing on efficiency, with three speeds denoted by different colours. 1100rpm (blue) is expected to be the peak efficiency speed, and so it proved, although some restrictions in hydrogen supply prevented testing at higher speeds. Again both Gross (no compressor work subtracted) and Net (isentropic work subtracted) are shown; however, as described a discrepancy was observed between measured Hydrogen consumption and a reasonable first-law analysis of what should have been consumed. Pulsating flows account for part of this, as described at the start of this section; it is also likely that the valve leakage caused some burnt gas to escape and therefore reduce efficiency. The corrected values on the right were adjusted using the 1-d model of Section 3, which performs a "first law" energy balance; they are also more consistent with other indications such as exhaust oxygen. There is a wide scatter of indicated efficiencies, but the best are up to 55%ITE, which is absolutely consistent with the simulation conclusions of Section 3.

2.4 Conclusions

Although there were challenges leading to delays in WP2, it was ultimately successful in its aim of informing a future multi-cylinder optimization program; in getting to this point, many things were achieved:

- An adaptation of the original, Diesel-fuelled cylinder head to accept a larger dual-fuel injector, was successfully implemented, and proved durable in service
- Safe designs and working practices were implemented around Hydrogen operation, with no incidents of concern arising
- The stable combustion of Hydrogen has been thoroughly validated over a range of speeds and loads, with no occurrences of the “burn-back” phenomenon seen with Diesel fuel; Hydrogen has established itself as the fuel with which the Recuperated Split Cycle concept is most likely to succeed
- An extensive set of parameter swings has highlighted the combustion system’s responses, informing both simulation and a future multi-cylinder engine test program of the type intended for WP3
- A valve leakage issue, which has not impacted previous prototypes but could do so in future, has been identified, allowing a post-project investigation to identify and eliminate root causes; by disaggregating the thermodynamics of the cycle, impacts of this upon data have been removed
- Combustion performance has been shown to be sufficiently efficient to permit a multi-cylinder engine to be optimized towards target efficiency, as described in the next section; indicated efficiencies of up to 55%ITE are consistent with meeting targets and with the findings of that work.

3 WP3 Multi Cylinder Engine Testing

3.1 Introduction & Aims

Having developed a successful combustion system in Workpackage 2 using the Single Cylinder engine, the aim of WP3 was to apply it to a multi-cylinder engine, which could then be evaluated for whole-system performance, efficiency and emissions, and developed towards readiness in a Phase 2 trial.

For a standard 2- or 4-stroke engine, this would essentially involve replicating the cylinder; in the case of the RSCE, the single-cylinder Titan engine represented only the expander cylinder. The approach adopted was to utilize multi-cylinder RSCE knowledge developed on a parallel Diesel project (not part of Hydrate), applying the Hydrogen combustion system to an already proven integrated engine with unmodified compressor cylinders.

The project experienced a number of delays meaning that this engine was designed, built, commissioned (including firing on pilot Diesel fuel) but never run on Hydrogen. Instead, data from the Titan single and Diesel multi was used to validate a high-fidelity simulation tool to predict how it would have performed, and identify further changes required to achieve targets.

3.2 Engine Hardware

3.2.1 The “Upgrade 5” family

The “Upgrade 5” family of engines were conceived to operate on Diesel or Hydrogen with only changes to the expander cylinder head. While earlier Diesel RSCEs had been “mule” prototypes with separate Compressor and Expander “engines” (section 1.3), Upgrade 5 created an integrated, application-installable engine with two compressor and four expander cylinders in a common cylinder block (Figure 2, at the start of the report). As with the earlier Mule units, individual cylinder heads were used, so the conversion effectively required four copies of the Titan head to be used alongside two carryover compressors. In reality, the Upgrade 5 heads are a mirror-image of Titan, because the base Iveco Cursor 9 has its valve-timing drive at the opposite end of the engine, driving a mirroring of the head architecture.

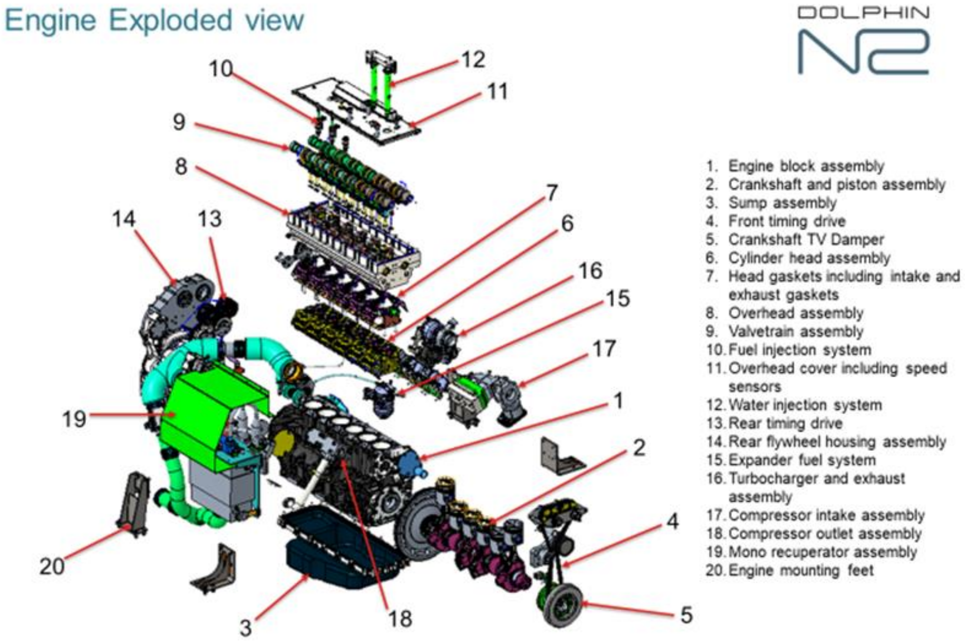


Figure 19: Exploded view of Upgrade 5.2 multi-cylinder

In all, three Upgrade 5.2 engines (Figure 19) were built:

- U5.2DD (Diesel Demonstrator) was the lead engine, tested outside the HYDRATE project.
- U5.2DF (Dual Fuel) was the HYDRATE engine, commissioned but not tested.

- U5.2SI (Spark Ignited) is a DF copy with added sparking plugs to explore monofuel operation; built but not tested under the InnovateUK CMDC2 project “HydroMAR-E”

Table 3: 5.2DF specification vs previous builds

Feature	4.1	5.2DD	**5.2DF**
Design	Mule, C9 + S8000 (6+3cylinders)	Integrated, C9 (6 cylinders, 4+2)	Integrated, C9 (6 cylinders, 4+2)
Expander CR	22.55	21.69	21.55
Compressor CR	61	60	60
Expander inlet cam	IK33	IK33	IK33
Crank	Standard C9	Bespoke 90° 2+4 crank	Bespoke 90° 2+4 crank
Recuperator	6 off HiFlux + RecuBalance	4 off HiFlux (ex 4.1)	HiFlux Monolith
Lube Oil, Scavenging & Cooling	Lab Umbilical		
Fuel Injection	Delphi 19.45mm	Delphi 19.45mm	Westport Dual Fuel
Ignition	CI/Auto Ignition		
Internal Insulation & thermal management	PSZ Cuff & Yttria Thin (see table)		
Turbo	Pankl WG	Van der Lee WG (Version 1A)	Van der Lee WG (Version 1C)
LP Manifold	Standard	Revised	Monolith manifold
Recubalance	Yes	No	N/A
Water System	Same lab pressure system and in water injector rail water pressure sensor		
EMS	A100	B107	B107

3.3 Hydrogen Safety

As a multi-cylinder engine contains and consumes more hydrogen than a single, and the laboratory hydrogen system was new, particular emphasis was placed on creating a well-documented safety analysis. There were three elements to this work:

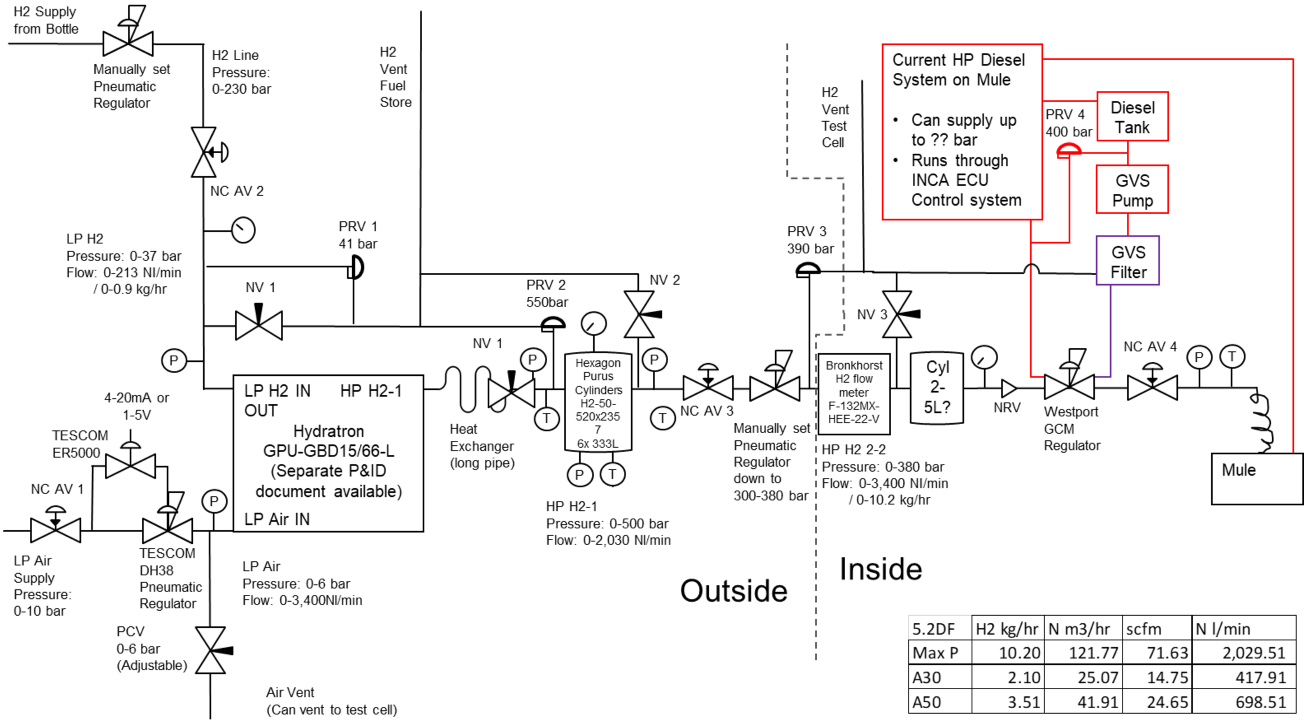
1. Safety review of the laboratory and fuel system.
2. Measures to mitigate hydrogen explosions inside the engine.
3. Measures to mitigate a hydrogen backfire in the high-pressure recuperator / plenum system.

Figure 20: Completed 5.2DF with build team

3.3.1 Laboratory Safety

The primary risk to safety in the laboratory as a whole, is a leak of hydrogen within the building leading either to a jet of flame, or a build-up followed by an explosion. There is an established set of regulations called DSEAR (Dangerous Substances and Explosive Atmospheres Regulations, 2002) which specify the approach that must be taken. The underlying principle of DSEAR is to categorise a “zone” according to the risk of an explosion. An engine running on Hydrogen in a laboratory is typically classified as “Zone 2”, meaning that an explosive atmosphere should not exist under normal circumstances, but could do in the event of a failure. The mitigation used was to:

- Ensure that the bulk of hydrogen was stored outside in a fenced compound with ATEX-rated electrical fittings, with a minimum of pressurized gas in the building.
- Provide ventilation at a sufficient flowrate that a typical expected leak would not accumulate to above 25% of the Lower Explosive Limit
- Place a gas detector high in the laboratory, such that a leak would be detected in the extraction flow, triggering a shutdown.



5.2DF	H2 kg/hr	N m3/hr	scfm	N l/min
Max P	10.20	121.77	71.63	2,029.51
A30	2.10	25.07	14.75	417.91
A50	3.51	41.91	24.65	698.51

Figure 21: Lab Hydrogen system

The system was similar in principle to the single cylinder set-up described in the previous section, except that in this case the Hydratron pump could not meet the full flow needs of the engine. Therefore, a bank of six 500bar cylinders were used to store Hydrogen via overnight pressurization, providing sufficient fuel for a few hours of running – adequate for research, if not durability testing. These cylinders resided outside the building, with regulated 350bar Hydrogen passing into the lab. An independent consultant was commissioned to review the system, and a number of recommendations were implemented, such as combining vent lines so that a hydrogen release would occur only in one designated place. Unfortunately, these changes on top of previous delays in the up-fit of the laboratory meant that the engine could not be run on Hydrogen within the lifetime of the project, and the system, though completed, was never commissioned.

3.3.2 Hydrogen inside the engine

Hydrogen can accumulate inside the crankcase or cam box of the engine. The usual mechanism for this on 4-stroke engines is blow-by of unburnt mixture during the compression stroke; however, on the Hydrogen RSCE, fuel is injected at or near top dead centre, so this is unlikely to occur. But a second mechanism was identified, in the event of a leak in the fuel connections to the injector, which sit inside the engine. The same DSEAR principles showed that, with the designed level of crank-case ventilation, the mixture could become explosive. While the volume of the explosion would be much smaller than the whole lab (and contained by a robust cast-iron cylinder block), the material risk is pressurization of the sump and oil breather system, causing hot oil to be ejected and starting an oil fire.

Two measures were recommended: "Burst discs" were fitted to the cylinder block and cam cover, providing controlled relief in the event of an explosion; and it was suggested that a hydrogen detector be placed in the vent line from the external oil separator (which was not implemented, but the separator ventilated in such a way that the master lab sensor would detect a leak).

3.3.3 Hydrogen explosions in intake plenum

The final scenario considered was that of an explosion in the hot, high-pressure system that links compressor to expander via the recuperator. This system contains only air, not fuel, but Hydrogen could enter it in the case of a malfunction to injection and valve timing. The HP system (Figure 22) contains a pressure relief valve (although IC engines are excluded from the Pressure Equipment Directive and similar codes, that exemption is intended to apply to standard combustion cylinders; the external HP system is PED compliant); however, this PRV was only sized to handle a malfunction such as an obstruction restraining compressor discharge, not an explosion; also, it is on the cold side of the recuperator matrix, whereas an explosion is more likely on the hot side.

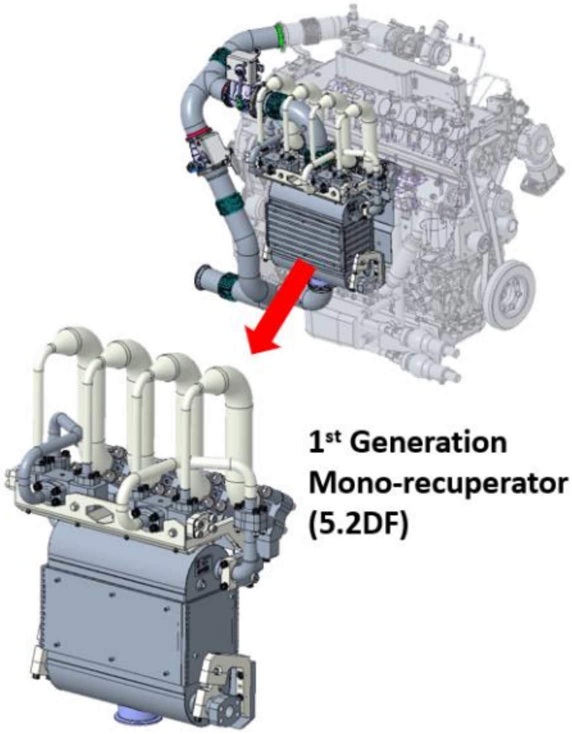


Figure 22: Recuperator and HP plenum system

Hot compressed air (up to 70 bar, 700°C) exiting the recuperator enters four individual pressure accumulators (named "plenums" following ICE practice, although technically a plenum would imply joining the cylinders together), which are necessary to provide a reserve of air for the very short air-inlet event. As the recuperator itself is a pin-matrix heat exchanger, it is likely to act as a flame arrestor, so the plenums themselves are the most likely location for an explosion.

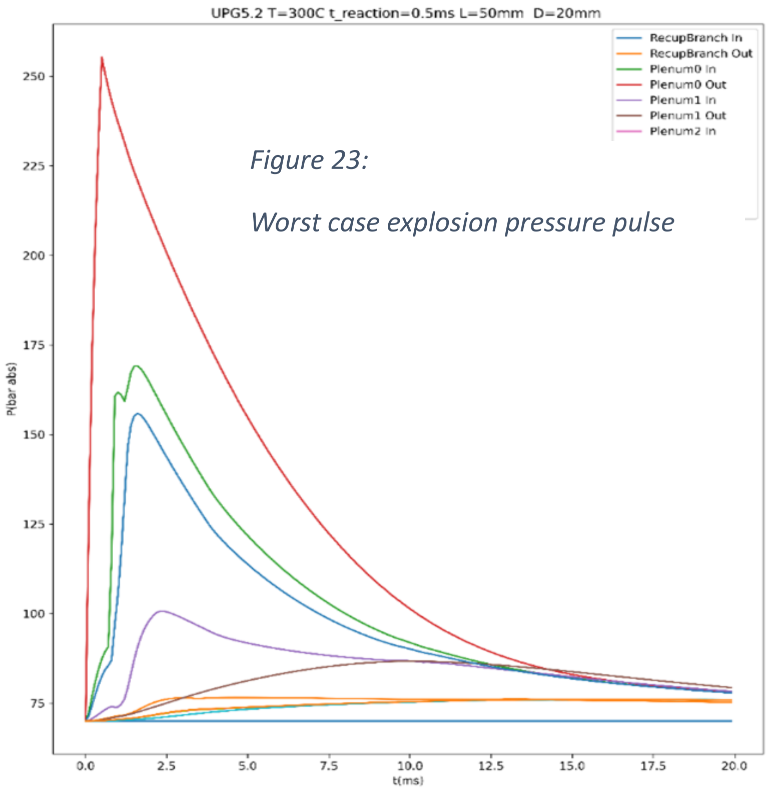


Figure 23:

Worst case explosion pressure pulse

Two pieces of analysis were conducted. In the first, a one-dimensional gas dynamics model was used to estimate the size of the pressure spike based on a range of burn-rates and the rate at which pressure waves could disperse it down the connecting tubes to the other plenums

(Figure 23). The second was a Finite Element Analysis of the plenum to determine how many such events it could tolerate before failure.

The worst-case pulse predicted was 255 bar, based on a 0.5ms burn time in a cold (300°C), dense gas scenario with a stoichiometric mixture. Other scenarios indicated a lower peak, between 130 and 200 bar, and a range were applied to the FEA model. This was used to estimate peak stress, then material fatigue properties were used to estimate cycles to failure.

None of the cases created stress in excess of the hot tensile strength, meaning that the risk of sudden rupture is low. And all but the worst case led to a prediction of infinite fatigue life. The worst scenario (Figure 24) gave a predicted life of 2891 cycles, meaning that a safe strategy would be to detect a backfire event using the pressure sensor already fitted, and inspect the components after, say, 300 events.

In practice, no such issue was experienced while running the single cylinder engine, which has a single plenum of the same design; the multi, as described, never ran on Hydrogen.

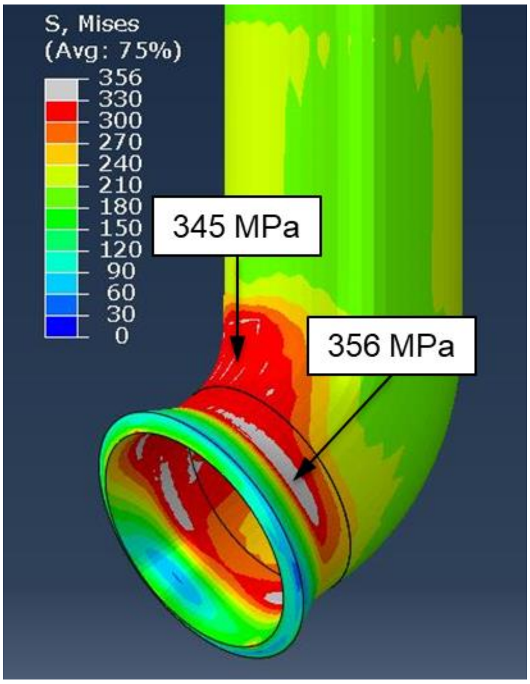


Figure 24: Von Mises stress, worst case pulse

3.4 Engine Installation & Commissioning

The engine was installed in the Advanced Engineering Building (AEB), University of Brighton, whose dynamometer and lab instrumentation (including Horiba emissions measurement equipment) had already been validated running a Diesel mule engine (Upgrade 3.5) prior to HYDRATE. Although integrated, the Upgrade 5.2 series relies on external oil and water pumps (there is provision for these within the engine, but as uprated components were required, a laboratory system was chosen for expediency), therefore new rigs were created to pump and heat or cool these fluids. Finally, a control panel was constructed, containing the master engine control unit (ECU), separate cam phaser controller, fuses, and current-clamp monitoring for injectors.

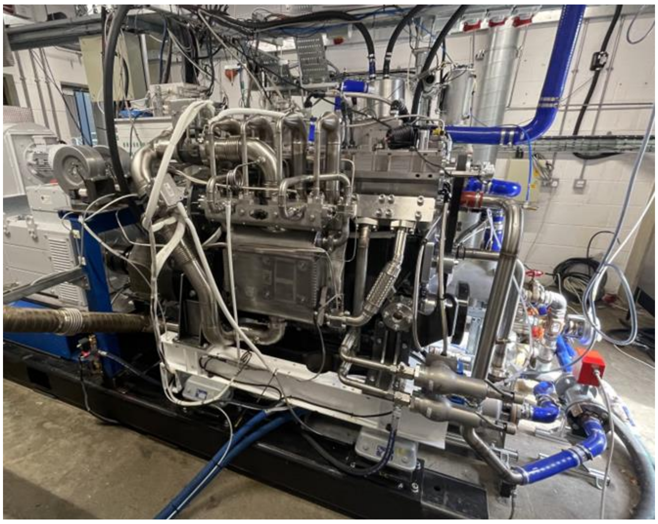


Figure 25: 5.2DF engine installed in laboratory

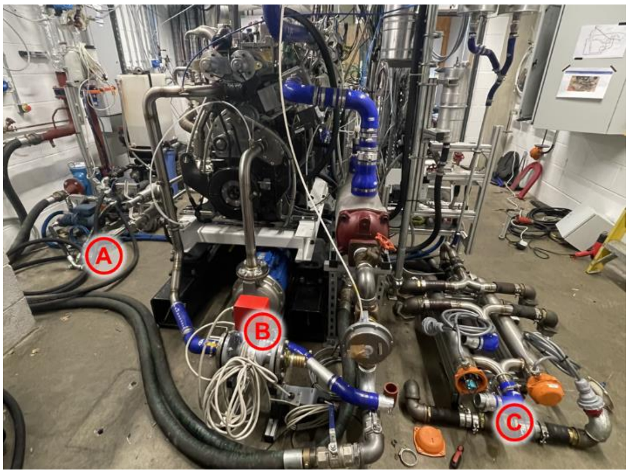


Figure 26: Engine showing rigs for oil scavenge & pressure (A), and coolant pumping and control (B, C)

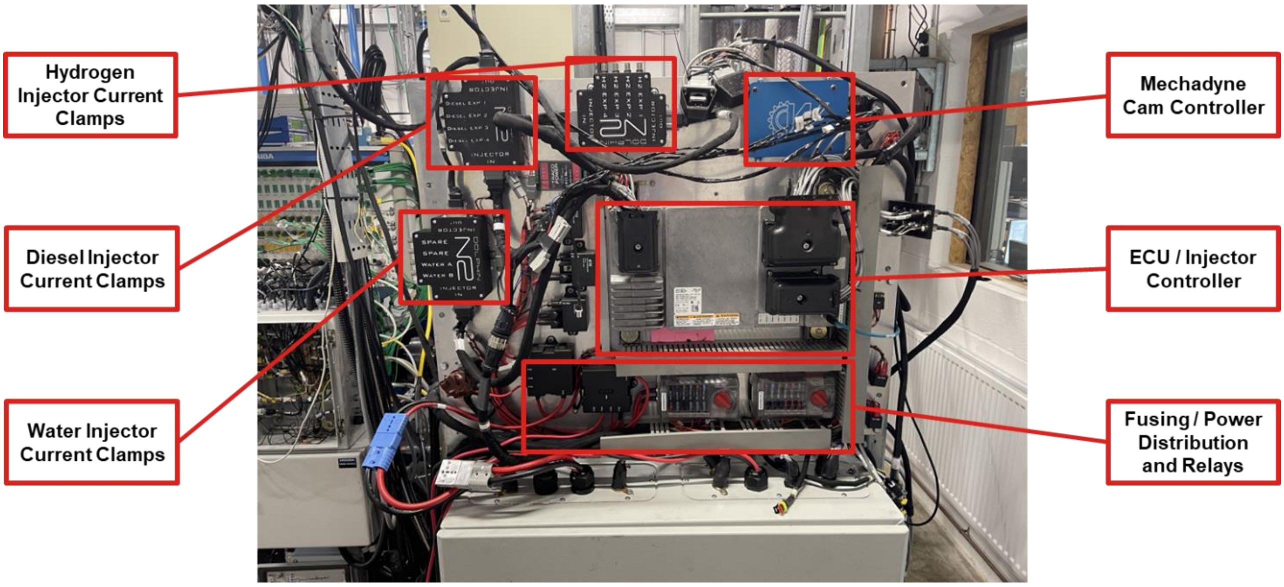


Figure 27: Controls board

Although Hydrogen fuel was not available, the engine was commissioned to the point of firing on just its Diesel pilot fuel. In this mode the engine has limited power, and was unable to warm up sufficiently to transition into Split Cycle mode; however, stable combustion was observed in starting mode, with early inlet valve closure providing heat by compression (Figure 28).

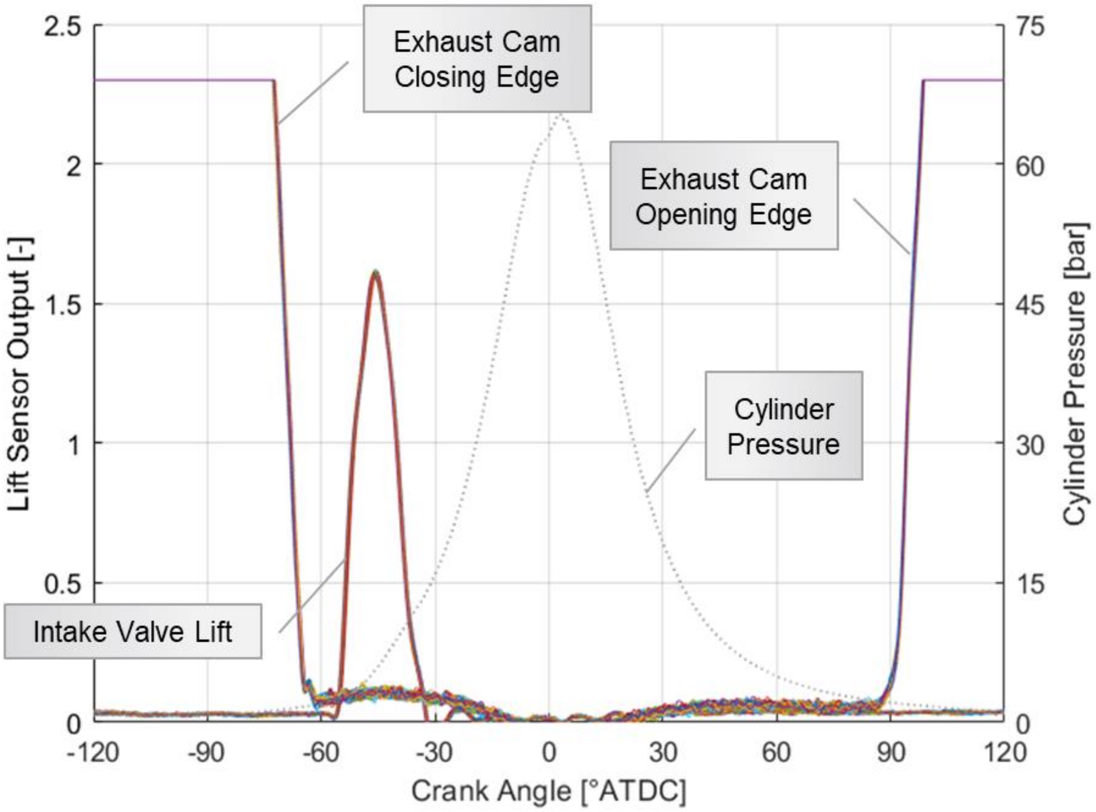


Figure 28: Cylinder pressure and valve lift traces from fired commissioning.

3.5 1-d Simulation

3.5.1 About 1-d modelling

As the project was unable to run the multi-cylinder engine, an alternative approach was sought. In the case of a conventional engine, all cylinders are identical, so multi-cylinder performance is easy to infer from a single (essentially, by applying a correct level of friction, because the single has more per cylinder; its crank is "all ends and no middle"). However, for the RSCE, the Titan single just represents one expander cylinder of four; there is no compressor work in its power output, and this depends quite critically on air-fuel ratio and valve timings as well as the basics of speed and pressure. These factors can be estimated using basic thermodynamic assumptions (as described in Section 2), but this assumes ideal behavior.

A better approach is to use a 1-d simulation model. This is an industry-standard computer modelling tool used to predict power and efficiency of engines. Described as "1-d", they use established physics to predict how air and fuel pass through the engine in one dimension, meaning that they do not resolve 3-dimensional detail; however, this makes computation much faster and if "tuned" to match data from a real engine, reasonably accurate (power, torque and fuel consumption to within ~2% is feasible). In the case of HYDRATE, the model is matched to the combustion (fuel burning rates) of the single cylinder at different speeds and loads; and to other aspects of operation of the "5.2DD" Diesel multi-cylinder engine that is geometrically identical to the HYDRATE engine, and was run in the first half of 2023. This approach allows both extrapolation of performance from real Single to modelled Multi Cylinder engine, and further extrapolation to how performance can be improved through simulated changes (which is of great value in planning future work).

3.5.2 Model Matching

The model-matching process consisted of two elements:

- Matching of a multi-cylinder model to the general thermo-fluidics of a multi-cylinder Diesel engine, which had already been done outside the HYDRATE project, but was re-used here
- Matching the specifics of the Hydrogen power-cylinder to the WP2 Titan single cylinder engine, which was done within WP3; this power-cylinder model could then be substituted for the Diesel one in the multi-cylinder model

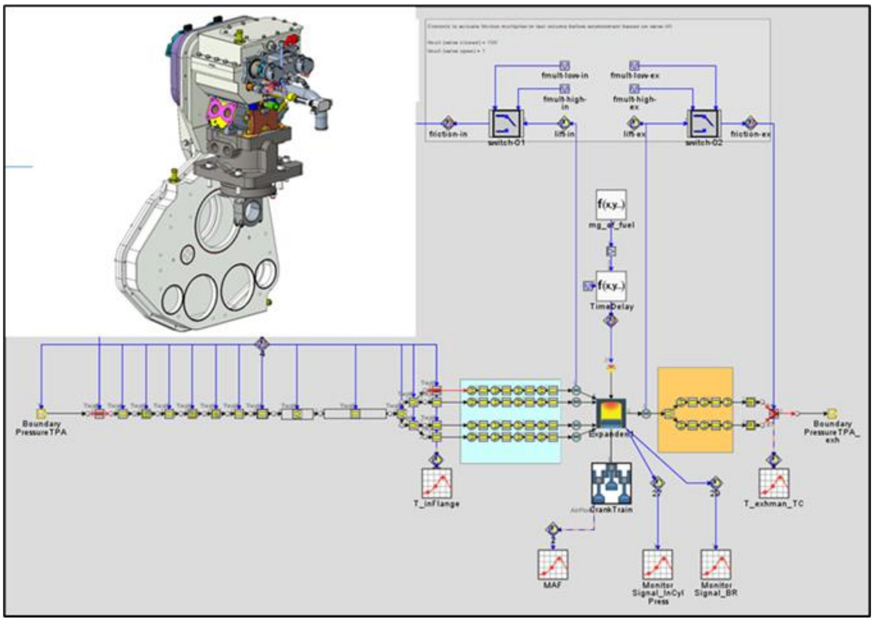


Figure 29: Model of the Titan single-cylinder engine

A new model was built, representing the geometry of the Titan engine as installed in the laboratory. The process known as “matching” then consists of adjusting coefficients in the model until its outputs match the real engine over a range of conditions (Figure 30).

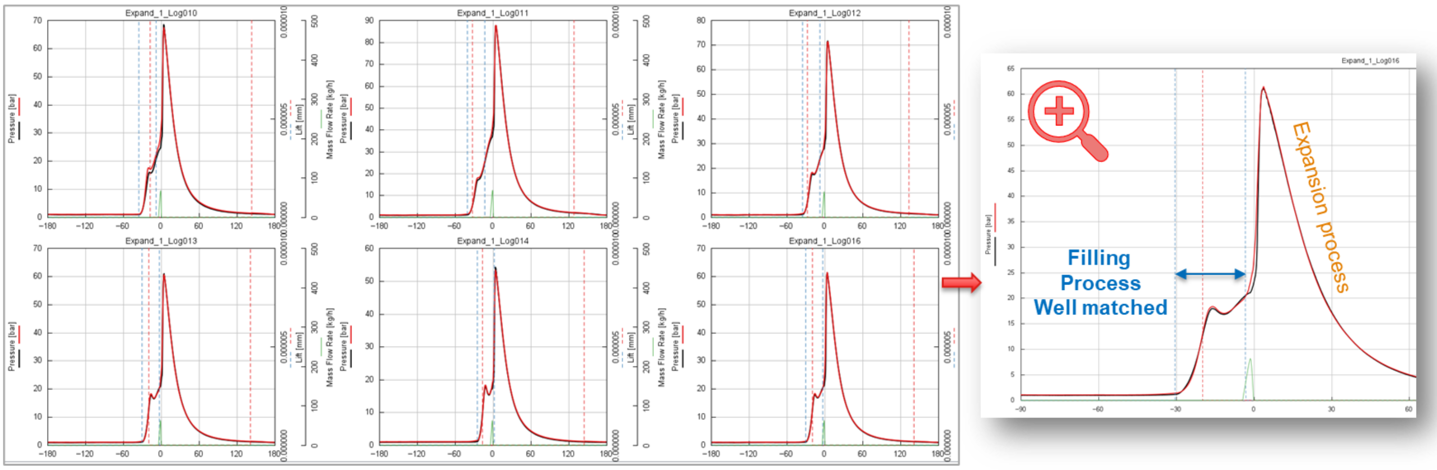


Figure 30: Matching of cylinder pressure traces

This process is centred on the trace of pressure versus crank-angle in the cylinder. First, the filling process is matched by adjusting the flow coefficients of the intake system. Then the later part of the process representing combustion and expansion is matched by adjusting the burn-rate and heat transfer to the cylinder walls. In this case, a good match was obtained without deviating from the normal adjustment range of these coefficients; however, this did highlight the excessive airflow attributed to inlet valve leakage in the prior section. The model essentially removed that leakage, and assumed that it did not impact the part of the cycle where cylinder pressure is high, which is a cautious / pessimistic assumption.

This process can then be checked by making sure that other values predicted by the model, match those measured in the engine across a number of running conditions (Figure 31).

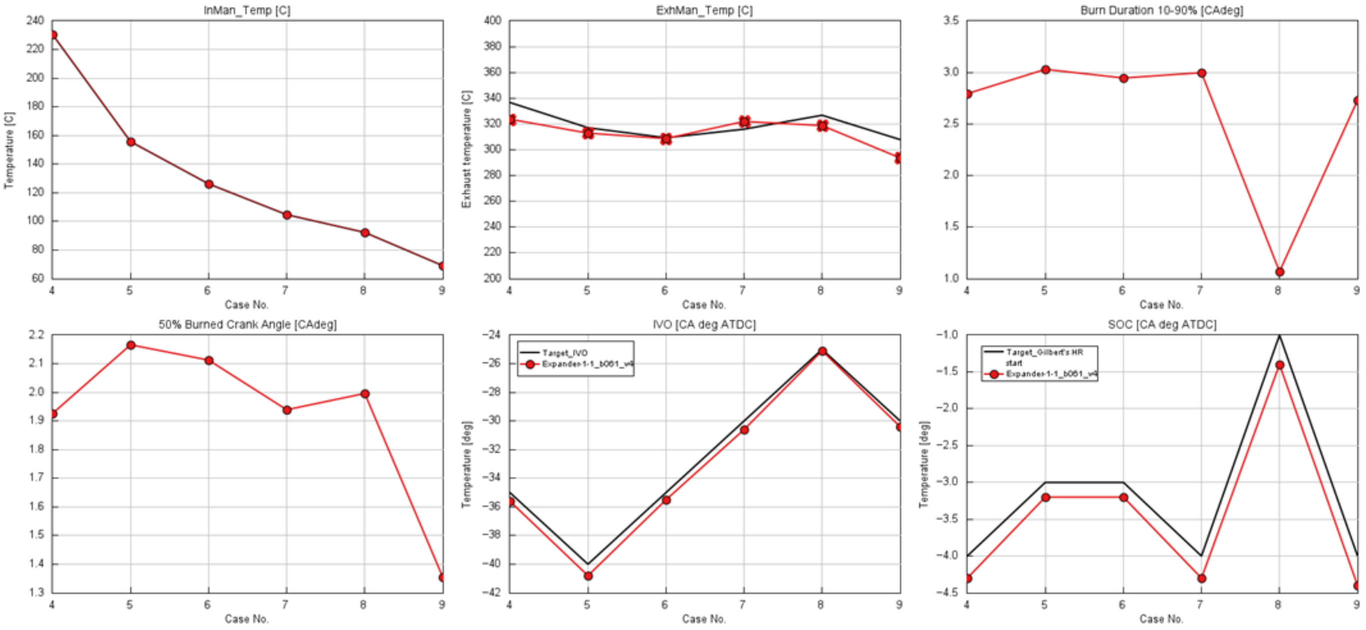


Figure 31: Matching of engine running parameters.

Exhaust temperature is a good indicator of a match; this correlated to within 20°C of the real value, which is within the accuracy of the actual measurement.

3.5.3 Multi Cylinder Simulation & Results

A multi-cylinder model was created by inserting the “matched” power cylinder of the Single Cylinder model, into an existing multi-cylinder Diesel model of the same basic geometry. Water injection into the compressor was omitted, as this type of model can struggle to predict its effect correctly. The other basic parameters of the engine, such as compression and expansion ratios and cam profiles, represented the multi-cylinder engine as built.

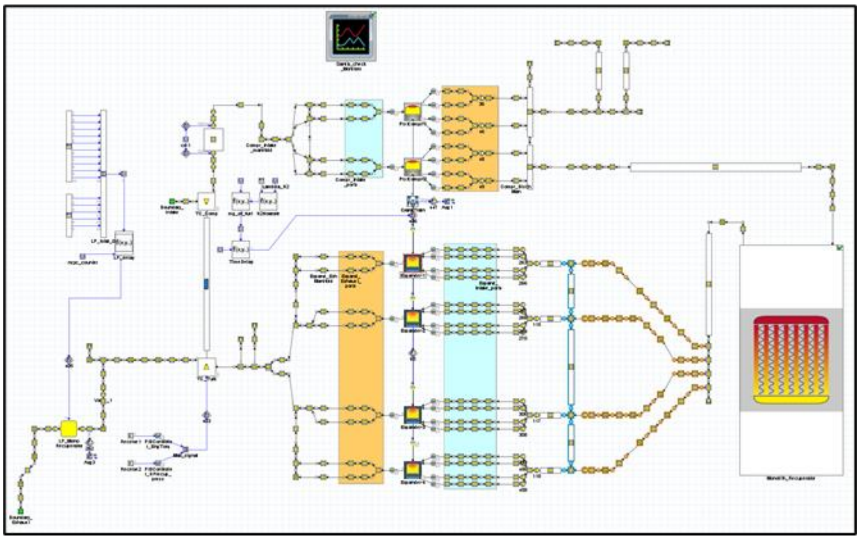


Figure 32: Multi-cylinder 1-d GT-Power model

The model was then set up to run a large array of cases, representing adjustment of parameters that could either be adjusted while running the engine (such as valve and injection timings, and air-fuel ratio) or simply changed on the testbed (such as a camshaft swap), thereby representing an initial test plan that might have been executed; in all, the full-factorial matrix represented 625 keypoints just at 1100rpm and full load (which is expected to be close to the most efficient condition). It is usual that such testing would lead to an interim performance, with a more major hardware upgrade (such as a revised expansion ratio or re-matched turbo) following on in order to meet targets.

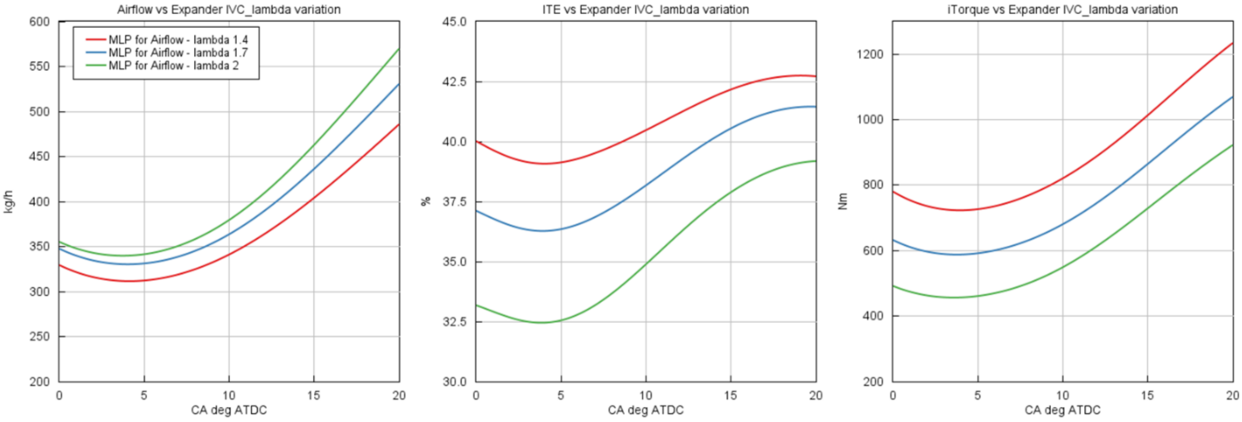


Figure 33: Impact of Air-Fuel ratio (lambda) on airflow, efficiency and torque

Air-fuel ratio is a key parameter. For a 4-stroke engine, lean burn offers low NOx and, because compression happens in the same size of space as expansion, it also promotes high efficiency. Figure 33 shows sweeps of the key inlet valve closure parameter at three AFRs, and highlights a very significant impact, with the richest being up to 8% (percentage points – 40% vs 32%) more efficient. The lean-burn efficiency advantage of the 4-stroke is reversed once the compression process is right-sized and recuperated, because shifting excess air through the engine now carries a loss penalty. It is noted that the best power and efficiency is seen to the right of the graphs, with late inlet valve closure – in the Titan tests, the engine was not stable here, preferring IVC below 5 degrees after top dead centre.

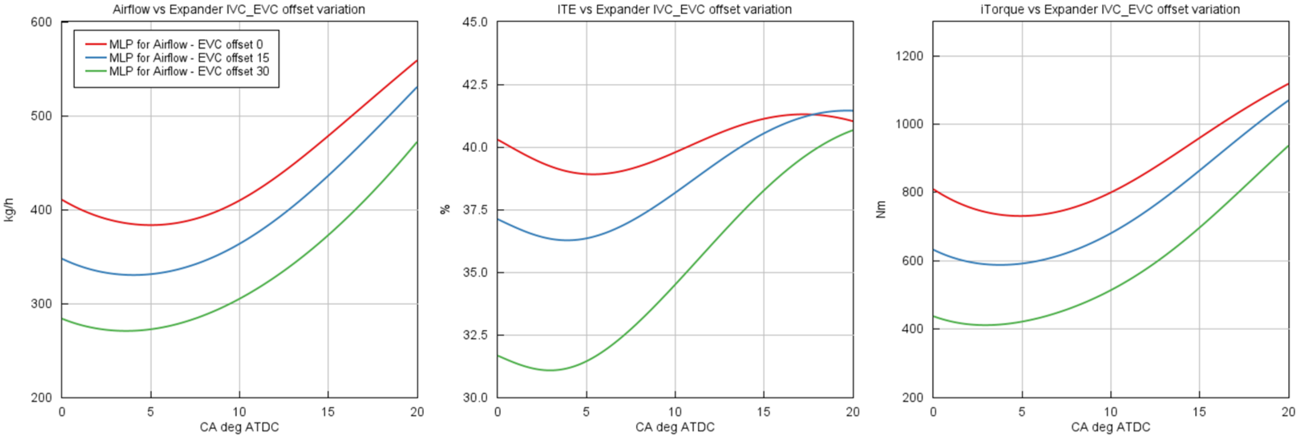


Figure 35: Impact of offset between exhaust closure and inlet opening

Figure 35 shows the impact of another common split-cycle engine optimization parameter, the separation or offset between the exhaust valve closing and the inlet opening (refer to Figure 5, "Residual Trapping"). This is used to trap hot exhaust for re-compression, which is helpful in igniting the pilot fuel. This shows a strong benefit from eliminating this Offset, especially at early inlet valve closures (left of the plots) where the engine was most stable; in reality, most testing tended to use the mid value, although elimination of the valve leakage may allow less.

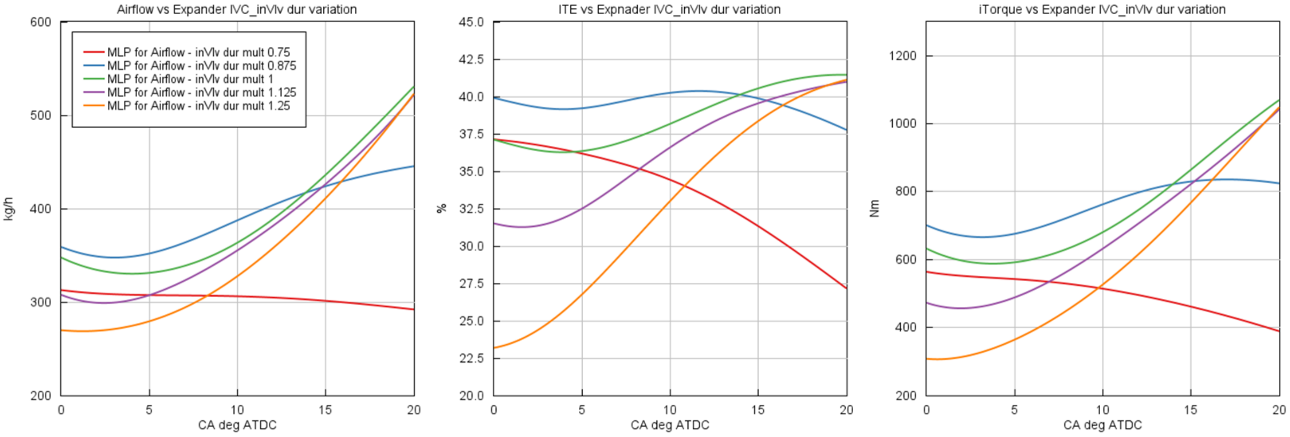


Figure 34: Impact of altered inlet cam profile

Figure 34 shows the effect of re-optimising the opening lift and duration of the inlet cam. In general, it is useful for this cam to open the valves for the shortest possible duration, otherwise the cylinder will fill early and create a "negative work" (trying to turn the engine backwards) on the piston as it rises. However, mechanical constraints mean that a shorter cam also has a lower valve lift, and therefore may become restrictive at higher loads and speeds. A scaling factor was applied to the baseline cam, for both duration and lift; it can be seen that the optimum factor is 0.875 at early valve timings (to the left of the sweeps), and the standard 1.0 to the right. A similar conclusion had already been reached in modelling of the Diesel engine, and a spare cam of similar scaling to 0.875 has been prepared.

The best indicated efficiency from these parameter sweeps was 44%, which is similar to a standard 4-stroke Hydrogen engine, but no better. At this point the Titan single-cylinder engine was showing that even richer air-fuel ratios were possible without inducing excessive NOx, so further sweeps were added at Lambda 1.3. This improved the efficiency slightly, to 44.5% indicated efficiency. The final step was to consider how this would be further improved to the target value of 55%.

3.6 Efficiency Roadmap

The simulation exercise showed that, within a first stage of optimization, the multi-cylinder engine would not have reached its efficiency target. With such a new technology, not benefitting from over 100 years of learning (as a 4-stroke does) this is not surprising. The conclusion of 44.5% ITE is probably a cautious one, as the full impact of the valve leakage issue may be underestimated; it is also a figure for a “Dry ThermoPower” engine without water injection into the compressor, which would shift the outcome to around 47.5%.

Through the development of the RSCE in all its forms, a large database of potential improvements has been developed, validated either experimentally or by similar modelling. A roadmap was constructed of feasible improvements, all of which could be implemented on the existing Upgrade 5.2 hardware within the next phase of testing (which is hoped to start in 2024).

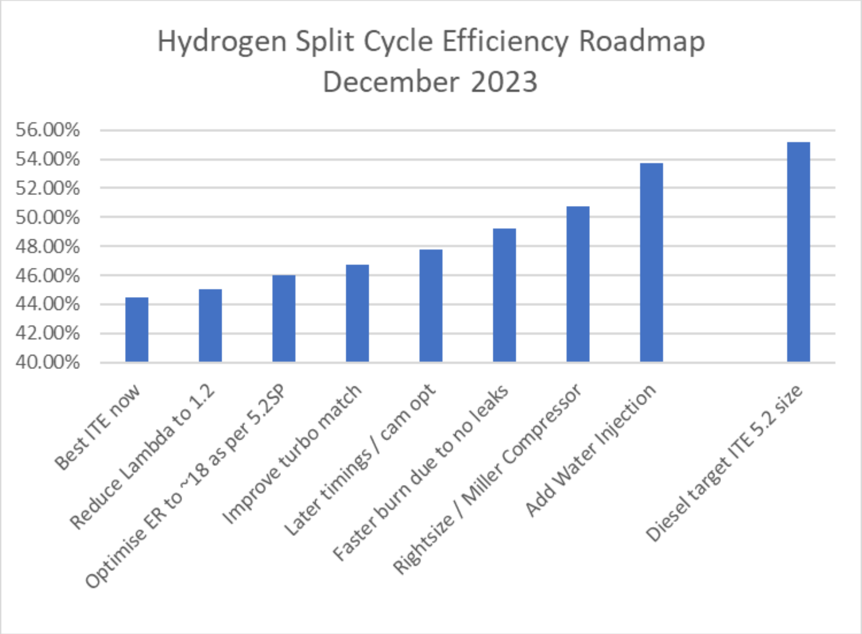


Figure 36: Efficiency Roadmap

Figure 36 shows the Roadmap, with identified improvements including:

- Reduction of air-fuel ratio to Lambda 1.2, already demonstrated on the Titan
- Further reduction of expansion ratio, identified in other simulations as a positive step (and a second Hydrogen multi has already been built at this level)
- An improved matching of the turbocharger, which is currently designed around Diesel requirements
- Optimising combustion to allow later inlet valve closure (which may occur naturally once the air leak issue is addressed) and faster burn (ditto)
- Optimising effective compressor displacement, which can be done via valve timings, then adding water injection to reduce compressor work and improve recuperation

The result is an indicated efficiency of 53.75%, which would equate to a brake efficiency (with friction removed) of exactly 50%BTE. A comparator lean-burn 4-stroke Hydrogen engine in this size would have an efficiency of around 42%BTE. This is therefore a 16% saving in fuel costs; past analyses have typically shown a payback in around a year if the fuel has price parity with taxed Diesel. For early adopters using more costly Hydrogen, such a saving is very attractive indeed.

The long term target for the engine remains 51.4% BTE / 55.2% ITE, carried over from the Diesel variant. This is likely to require more costly perfection of heat insulation, a powerful influencer that was not considered in the Roadmap.

3.7 Conclusions

Despite the apparent "failure" of WP3 to deliver a running engine, many positive things can be concluded supporting the future successful development of a multi-cylinder engine:

- The basics of the multi-cylinder engine have been validated by the process of building and commissioning the engine, albeit only firing on its Diesel pilot; further running of a dedicated Diesel version outside the project adds validation, and the basics of the dual-fuel injector and combustion have been validated on the Titan single cylinder; if these elements are brought together, there is little doubt that they would work.
- Safe systems of operating on Hydrogen have been developed, including an external fuel system (which could be replicated on a vehicle or machine), laboratory systems (which are relevant to any indoor operation), and systems for the engine itself. The most potentially vulnerable and novel recuperator / pressure plenum system has been shown likely to survive indefinitely in the event of backfires using trusted analysis principles.
- A 1-d model has shown a clear and relatively low-risk route by which the engine could be developed to an attractive efficiency level. The engine as built cannot achieve this, but added steps have been identified which would deliver a brake thermal efficiency of 50%, giving a 16% fuel saving over a standard Hydrogen engine, and operator payback within a year.

4. WP4 Machinery Applications

4.1 Introduction & Aims

The Recuperated Split Cycle Engine has only ever been used in a laboratory environment. For development, this is appropriate because the highly controlled conditions of a laboratory dynamometer allow a consistent and scientific approach to development, while avoiding real-world conditions that may trigger premature failures. However, once a new technology has reached TRL5, it can only advance by experiencing uncontrolled real-world conditions.

The overall aim of the RDR Phase 1 program was to incubate technologies so that they could be applied to a controlled real-world trial (TRL6-7) before proceeding to wider trials (TRL8) and first product (TRL9).

The laboratory RSCE, known as “Upgrade 5.2”, is designed for laboratory use. It has no starter-motor, nor provision for ancillaries such as an alternator, power-steering or other pumps; no supporting systems such as fuel tanks, cooling pack or aftertreatment had been identified. The aim of WP4 was therefore:

- To identify some candidate machines for early applications, in a trial or first product.
- To develop a specification for an evolved, vehicle-compatible engine.
- To develop outline packaging CAD for the engine and its systems in two chosen applications
- To identify key supporting components for the installation and develop relationships with suppliers.

4.2 Machine Selection

As discussed in Section 5, a wide variety of machines are used in the construction sector. Ultimately, it is likely that the smaller and/or intermittently used machines will adopt battery-electric power, while larger and more heavily used machines will require Hydrogen (working with a fuel cell or ICE). Particular criteria for an attractive RSCE application are therefore:

- A larger machine, with a power requirement of 180kW (current size) or over
- High utilization and fuel burn, justifying the cost of an RSCE over a conventional H2-ICE
- Ideally, a machine which already uses the base Iveco Cursor 9 engine

Based on a wider review of machinery used by Costain that is described in Section 5, four machine types were shortlisted:

Machine Type	Rating	Typical Power	Available w Cursor9?	Costain Hours/Yr	Costain CO2/Yr	Narrative
Tracked Excavator	30 ton	100-250kW	No	400-7000	10-200 t/unit	Attractive application but not available with base Cursor 9
Wheeled Loader	25 ton	160-200kW	**Yes** (CASE 1021G)	40-500	1-8 t/unit	Fewer in use and lower utilization, but easier to adapt with base C9
Dumper	20-25 ton	170-200kW	No	80-2300	2-70 t/unit	Not available in UK with base Cursor 9 engine
Genset	160kW electrical	180kW	**Yes** (Various inc FPT)	Up to fulltime	Up to 500 t/unit	High CO2 due to utilization; easy first application; use may grow for charging BEVs onsite

Table 4: Machinery shortlist for 180kW H2-RSCE

For a first trial or product, availability of a base machine with the Cursor 9 engine was a major consideration. Access to CAD design data was simplified, and both mechanical and electronic integration would be simpler. In the case of the generator set, access to the parent company FPT’s “parts bin” for wider genset parts would enable a prototype to be built much more easily than if working with a third party. The machines chosen were therefore:

1. A generator set, probably working in tandem with solar panels and limited local grid connection as a means of providing for a range of site power needs.
2. A wheeled loader, used episodically for large earth-moving operations on construction sites, but also used extensively in quarrying, and bulk material handling at ports and depots.

The use of a generator set to charge battery-electric machines is worth discussion here. This may seem like an illogical option, as it is an inefficient energy chain compared to either charging from the grid or using Hydrogen directly to fuel those machines. However, machines are usually leased by the construction contractor, and used on many sites over their lifetime. For the majority of those sites, most of the time, the aim would be to charge batteries using a grid connection or “pop up” solar power on the site. For those occasions where neither is possible, an efficient hydrogen-fueled genset allows these machines to continue operating.

4.3 Specifications

Using expected engine performance and typical daily utilization, a specification was developed for each machine application, to serve as a basis for conceptual layouts and identification of parts. It must be emphasized that the CASE wheeled loader is identified as a notional recipient machine using public domain information and does not represent an actual intended prototype or product.

Item	Genset	Wheeled Loader
High level description	160kW Electrical 50Hz 3-phase 240/415v generator set	25 tonne pivot-steer wheeled loader
Notional Platform	FPT Genset parts bin (actual)	CASE 1021G (illustrative only)
Donor Engine	Iveco Cursor 9 ~200kW	
Hydrogen Engine	Dolphin N2 ThermoPower type U5.3DF, 180kW@1600rpm	
Typical Demo Duty Cycle	24/7 operation, 40% mean load	2h/day at 50% mean load
Demo Environment	Near sea level (<500m) outdoor site trial, UK ambient -5°C to +40°C	
Target Operating Range	1 working day between Hydrogen refills	
Hydrogen Capacity	150kg Tube Trailer + 15kg reserve	15kg @ 700 bar minimum
Diesel / AdBlue / Water l	100 / 100 / 200	50 / 50 / 50
Engine drives to	Generator with battery	Hydraulic transmission
Engine ancillaries	Starter, water pressure pump, hydraulic pump to pressurize H2	As left plus 24v alternator, air-conditioning compressor
Exhaust emissions	“Zero” CO2 (>90% reduction vs base and <50g/kWh from pilot) Eu Stage V NRMM plus “SULEV” NOx <27g/kWh	

Table 5: High level specifications for Genset and Wheeled Loader applications

Beneath this high level, detail specifications (which are confidential) were developed around key systems: Fuel delivery, exhaust after-treatment, cooling system (coolant, oil and intercooler), and the water system for the piston compressor (which is based on the components of an SCR system and Gasoline DI injectors). In all cases, the aim was to identify off-the-shelf components where possible.

4.4 Generator Set

4.4.1 Requirements & Approach

Dolphin's parent company, FPT Industrial, is a supplier of engines for generator sets, and also of complete genset units. This gives access to a range of standard components, including chassis, generators, cooling packs and aftertreatment systems, sized for a range of power outputs.

A Diesel genset will usually store sufficient fuel for between a day and a week's running within its own chassis (often as a large tank between two chassis rails that run longitudinally beneath the engine). However, with Hydrogen this is not possible: 24 hours operation of a 160kW(e) genset at 40% mean load will consume around 125kg of Hydrogen. In context, a traditional tube-trailer (a semi-trailer for an articulated lorry) has a capacity of 150kg; latest, higher-pressure types will hold 300kg or more. So, the aim was to package only buffer tanks for 1-2 hours' running within the genset, to allow the tube trailer to be switched whilst running.

Other key components in the genset are:

- A chassis, on which everything else is mounted, allowing for lifting with a crane or fork-lift.
- The engine, driving the generator via a flywheel coupling.
- Electrical generator (50Hz, synchronous 3-phase, requiring 1500rpm input)
- Tanks for pilot Diesel, compressor water, and AdBlue (for NOx aftertreatment)
- Cooling pack (radiator, intercooler, and fan – the oil cooler is built into the engine)
- After-treatment pack for exhaust (an integrated module, usually including an oxidation catalyst, an SCR system, and a particle filter).
- A hydraulically driven pressurization pump to raise Hydrogen pressure to 350 bar when the main tanks fall below that pressure – plus a small high-pressure receiver for it.
- A controller unit for the whole system.
- Pipes and wires.
- A casing, including soundproofing.

Outline CAD designs were prepared for the major components. For simplicity, casings, pipes, wires, and the controller were omitted, as these are fitted around the major parts. To accommodate the hydrogen tanks, a chassis from a larger genset with a Cursor 13 engine was chosen; likewise, as the power density of the RSCE is slightly lower than a 4-stroke, a generator from a smaller "NEF67" genset was identified as providing the correct power. Two options were developed, the key difference being positioning of the Hydrogen tanks. Those tanks were modelled based on published data for a 4.6kg automotive unit used by a production passenger car; the tank itself is 445mm diameter, 1230mm long and weighs 79kg.

4.4.2 Option 1 – End mounted tanks

The package is based on a standard genset layout, with a radiator in front of the engine, generator behind it, and after-treatment / silencer above. Three fuel tanks (green) are supplemented by a small tank (blue) that maintains a reserve of high-pressure hydrogen, fed by a hydraulic compressor (grey). Diesel and AdBlue tanks are in the normal position in the chassis beneath (Figure 37, 38).

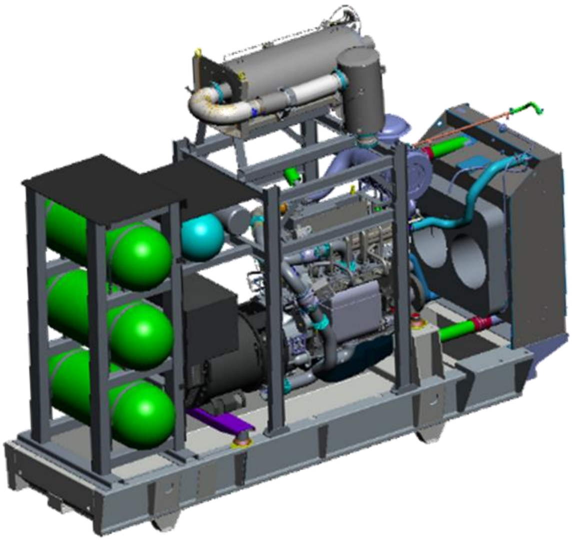


Figure 37: Genset with end-mounted tanks

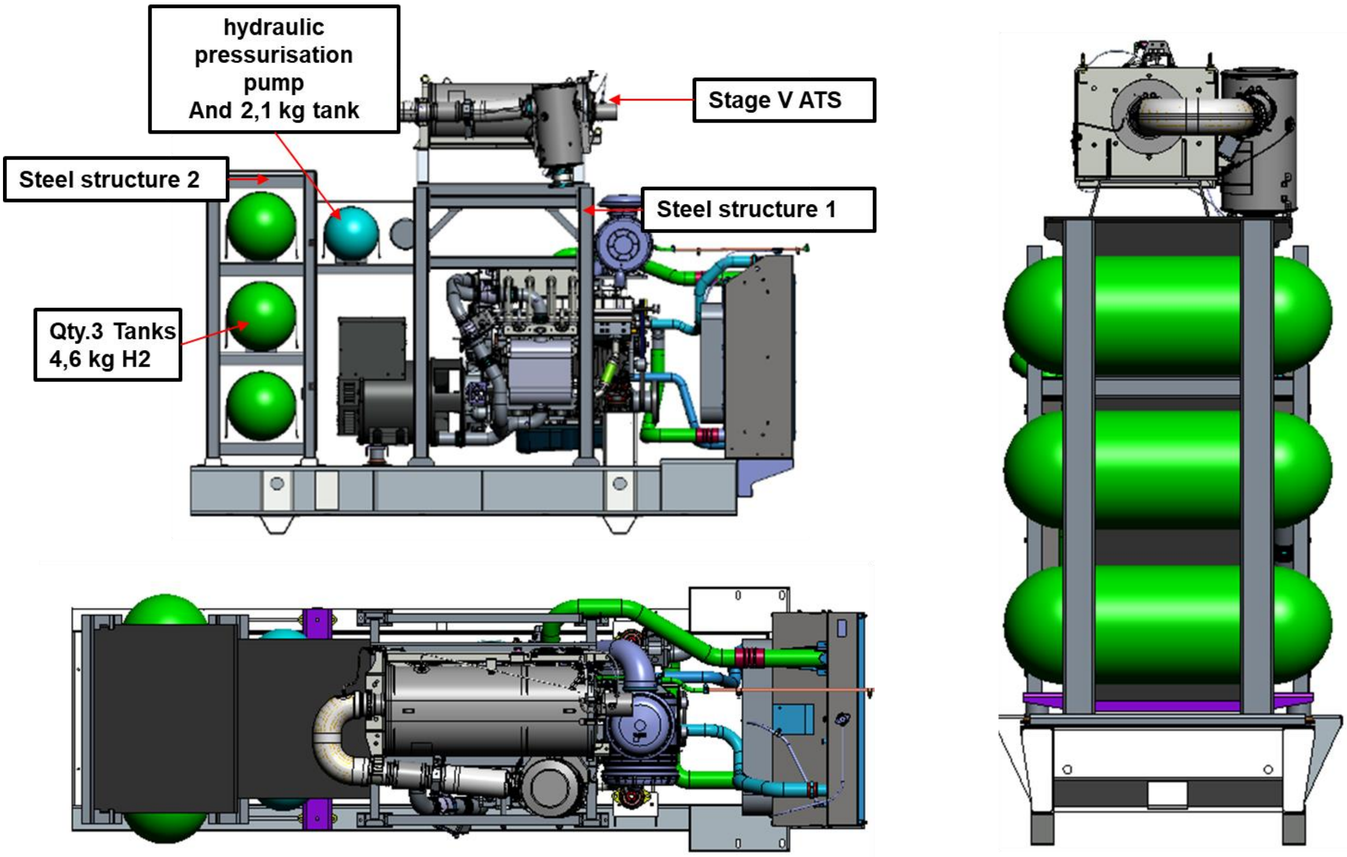


Figure 38: Generator set with end-mounted tanks

4.4.3 Option 2 – Overhead mounted tanks

A second option was examined to understand potential for increased hydrogen storage. An arrangement was devised with four tanks above the engine (Figure 39), in addition to a tank rack at the end (which can hold more than the single tank shown). While this allows increased storage (extending run-time to maybe 4 hours at rated output), there are potential concerns with mounting tanks above the engine. While a hydrogen leak from the tanks would vent upward, an engine oil fire would expose the tanks. The end-mount arrangement of Option 1 allows a fire bulkhead between tanks and engine, which is safer.

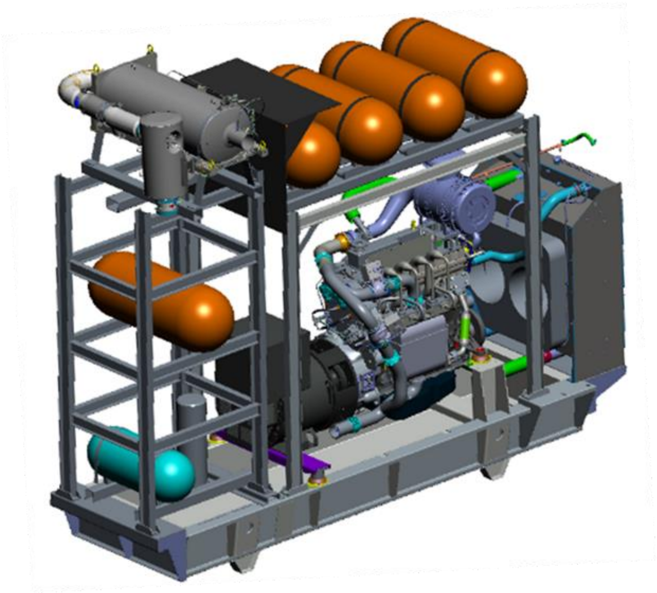


Figure 39: Overhead tank package

4.5 Wheeled Loader

4.5.1 Requirements & Approach

To study this application, the CASE 1121G was used as an illustrative base vehicle, with informal support by CASE who are a customer for the base Iveco Cursor 9 engine in this machine. It must be made very clear that this study does not imply any intent by CASE to adopt this technology or any Hydrogen ICE.

In this type of machine, the engine sits behind the rear axle, driving forward to a multi-function transmission, that sends power to the axles and to hydraulics for operating the centre-pivot steering and the front-mounted loading shovel. Many other types of machines have similar layouts. The first critical requirement is that the engine should match the existing transmission (which it does, although the Split Cycle has a lower maximum RPM) and fit within the existing engine bay (which is more of a risk with the bulky added recuperator and higher cam-carrier). The second, arguably more critical requirement is that of where to package at least 15kg of fuel, and ideally much more.

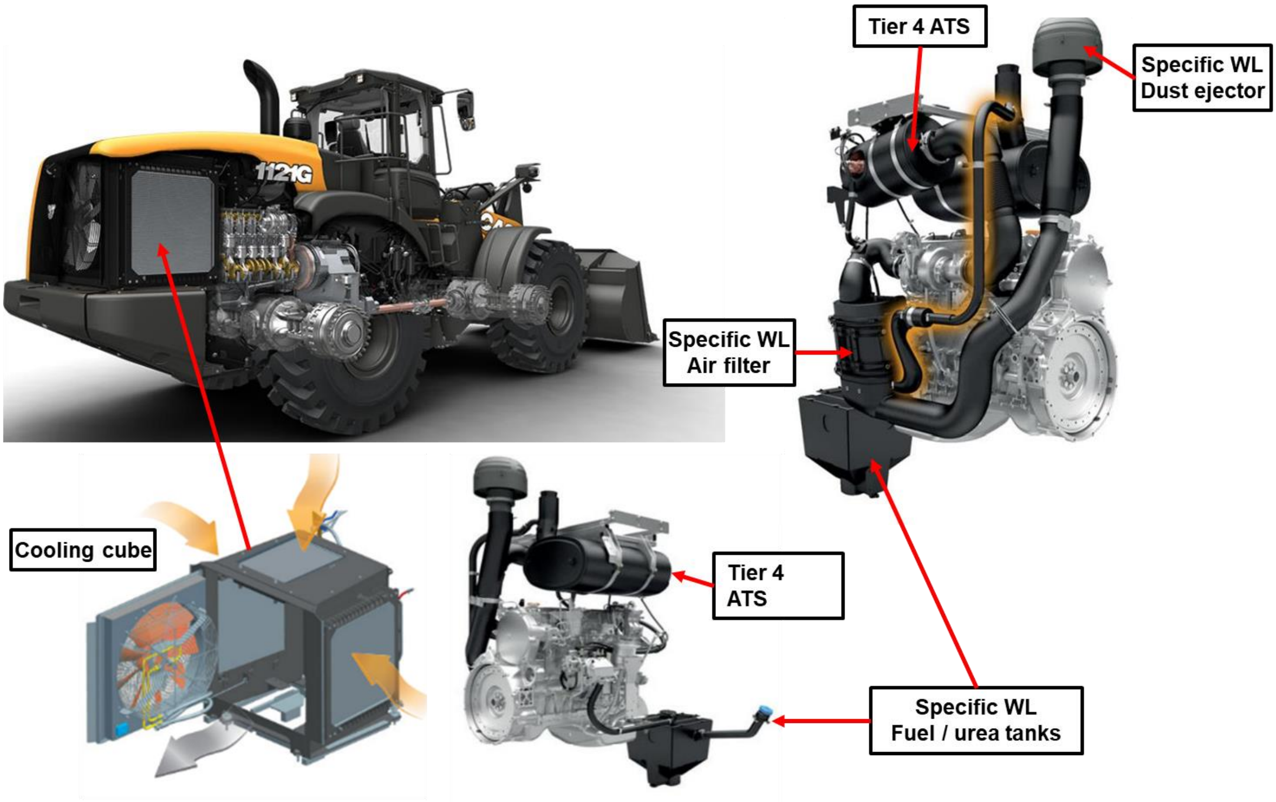


Figure 41: Layout of the standard powertrain on a Wheeled Loader

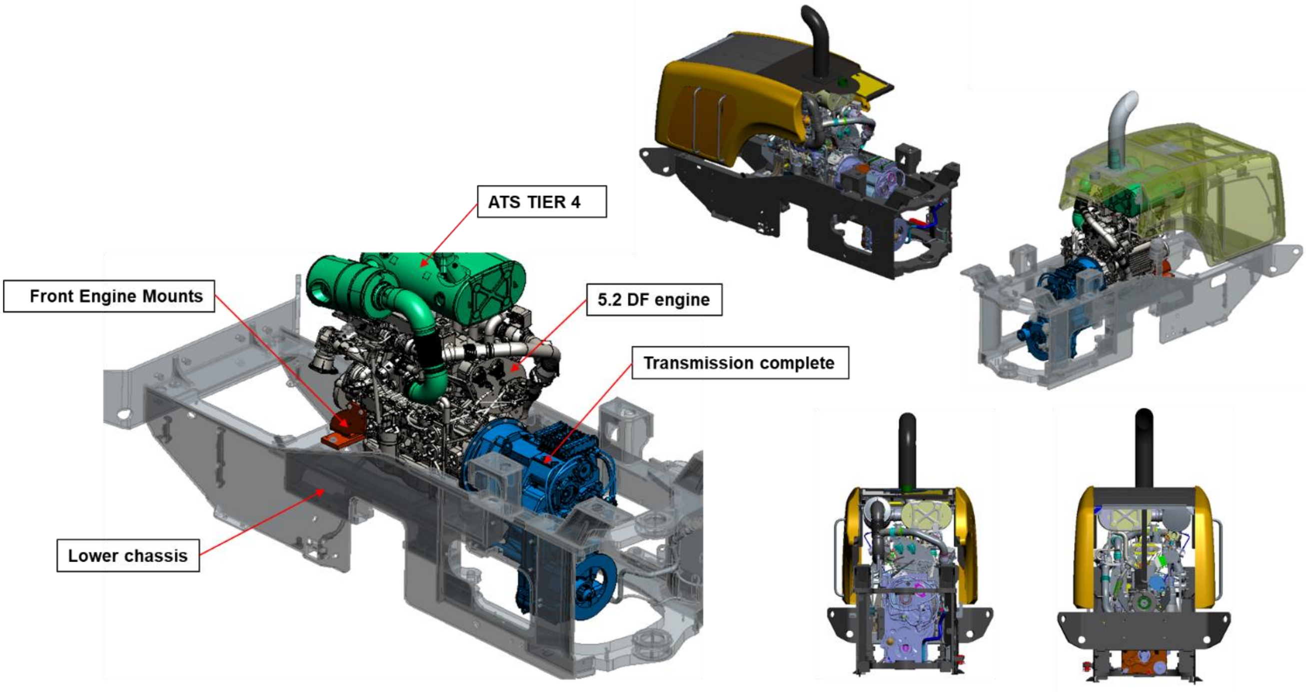


Figure 40: Split Cycle engine installation

4.5.2 Engine installation

Packaging studies (Figure 40) showed that, in the case of this vehicle, the Split Cycle engine would fit within the existing chassis and engine bay. This may not be the case in every installation, although it is worthy of note that the follow-on HydroMAR-E project successfully developed a more compact recuperator and plenum arrangement.

4.5.3 Tank mounting options

Three tank options were studied. In Option 1 (Figure 42), the space between the wheels was considered, as this is similar to the biomethane tank arrangement adopted by New Holland on their T6 Methane tractor. On one side of the vehicle, a cab access ladder occupies this space, so it cannot be used unless the ladder is re-designed to pass outside the tanks (this is the case on the methane tractor). On the other side, two 51l tanks can be fitted within wheel steering limits; some degree of shielding will be needed to prevent a wheel carrying debris and wedging it against the tank (the tanks are very strong; this would be unlikely to rupture the tank, but it could be torn from its mountings or displaced, causing pipe leaks). These constraints limit storage to 8.4kg on one side.

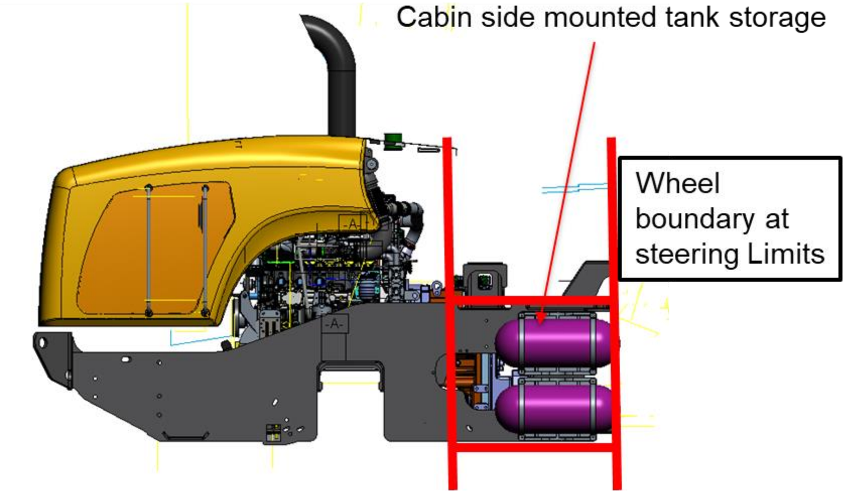


Figure 42: Tank Option 1, 8.4kg

The second option (Figure 43) is roof mounting. This arrangement is popular in Hydrogen buses and has been employed in Hydrogen tractors. It has the advantage of placing the tanks out of the way, in a location where a small leak will rise clear of the vehicle. Four proprietary 4.6kg tanks were packaged (18.4kg), and an arrangement of up to 6 might be feasible with an extended rack. However, there are two major considerations in construction and quarrying: falling object protection is a legal requirement, and roll-over accidents are known to happen. Informal advice received was that this arrangement was very much not preferred.

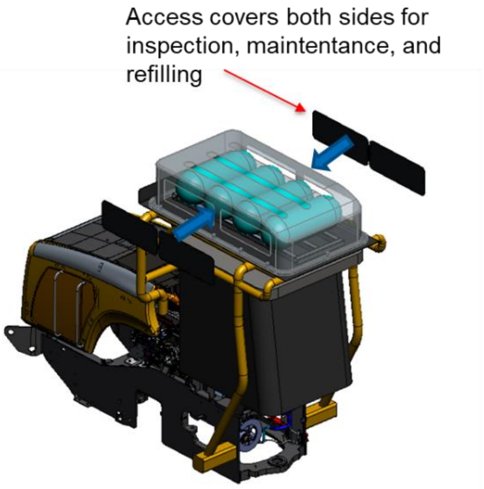


Figure 43: Tank Option 2, 18.4kg

The third option is most likely to succeed. Here (Figure 44), a saddle arrangement hangs the tanks around the engine bay, permitting two long and two short tanks around the wheel arch, giving 24kg of storage. This arrangement would need to hinge open for engine servicing, ideally using a safe hydraulic support; however, it offers the greatest storage and better protection from roll-over.

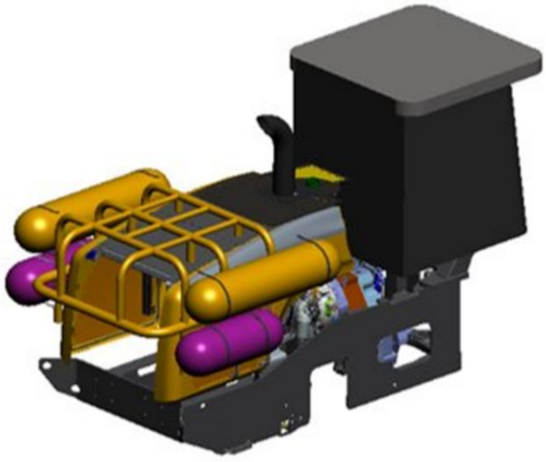


Figure 44: Tank Option 3, 24kg

4.6 Key Technology Suppliers

Throughout the course of the project, a number of discussions were advanced with suppliers of key components or subsystems, with a view either to supplying components to HYDRATE itself, or to a Phase 2 demonstration or future product. These discussions took place under Non-Disclosure Agreement and are commercially sensitive and confidential, therefore they can only be summarized anonymously here.

Supplier	System	Status	Next Steps
Gaseous Fuel Injection Specialist	Dual Fuel Injectors & system	In use on project with ongoing support	Further collaboration
Automotive Tier One (UK)	Mono Fuel Injectors; pressurization pump Water injectors	Discussions ongoing Component in use	Further collaboration
Automotive Tier One (USA)	Spark Ignition	Supplying follow-on HydroMAR-E project	Evaluate SI option
Automotive Tier One (Germany)	SCR system (for water injection)	Existing FPT supplier	Use parts in Phase 2
Automotive Tier One (UK)	Aftertreatment	Discussions held but collaboration did not proceed	Switch to second supplier
Automotive Tier One (UK)	Aftertreatment	Discussions held & strong interest	Further collaboration
Automotive Tier One (UK)	Hydrogen Tanks	Supplied to project	Further collaboration
Industrial Tier One (Germany)	Hydrogen Tanks	Supplied to project	Further collaboration

Table 6: Key technology suppliers engaged

In addition, suppliers in the wider ecosystem in which the engine would be used, were engaged. As with the system suppliers, discussions are confidential, but an anonymous summary is provided.

Supplier	Role	Status	Next Steps
Parent company	Base engine manufacture	Parts-bin engine parts (Cursor 9) in use. Genset parts identified for Phase 2.	Wider discussion around Hydrogen ICE routes to market
Construction & Agricultural Machinery manufacturer 1	Machine manufacturer (customer for engine)	Support given and multiple discussions ongoing	Future collaboration
Construction & Agricultural Machinery manufacturer 2	Machine manufacturer (customer for engine)	Support given and multiple discussions ongoing	Future collaboration

4.7 Conclusions

The conclusions of WP4 are:

- Studies have been made of the application of the Hydrogen Recuperated Split Cycle Engine to two machine types.
- Both have been found to be basically feasible, with only minor modification to the laboratory prototype engine.
- In both cases, a supply chain exists for low to mid volume.
- In both cases, the on-machine storage density of Hydrogen is challenging, but workable solutions have been found.
- Both machine types are potentially suitable for a Phase 2 trial.

Recommended next steps are:

Genset

- Work completed is suitable as a basis for a prototype design in Phase 2 or a future demonstration / trial project.
- As the Genset is a relatively simple application, a degree of hand-fabrication without full detailed design is possible for a one-off prototype, although more formal design processes would be required for more than a single unit.
- The Genset, particularly linked to a solar / battery ecosystem, is an attractive option for high-risk technology as its operation is less transient, and no challenging integration work is needed.
- Phase 2 or future field trial is recommended to favour the Genset initially, for these reasons.

Wheeled Loader

- Work completed requires further work to be performed post-project, using detailed CAD and requirements specifications from an OEM partner.
- Discussion with one such partner has led to direct engagement to the Chief Engineer for Wheeled Loaders, and a CTO visit to Dolphin.
- External hydrogen tanks and refueling arrangements need review by construction stakeholders for acceptability.
- It is also possible that an off-highway machine with a 4-stroke Hydrogen engine will be the direction taken for a future trial or demonstration, until the RSCE is mature enough.

Other applications

Since the completion of WP4, further stakeholder discussions have established interest in the technology for a Tracked Excavator, a mixed use on/off highway truck used to bring materials to the site, and for marine and bus re-powering. Confidential discussions are ongoing on all, although given the immaturity of the technology, a simpler 4-stroke Hydrogen ICE would be a logical first step.

5. WP5 Field Trial Planning & Deployment

5.1 Introduction & Aims

The infrastructure construction industry in the UK is responsible for significant greenhouse gas emissions. According to a report published by the Committee on Climate Change (CCC) in 2020, the infrastructure sector (which includes energy, transport, and buildings) accounted for around 25% of the UK's total greenhouse gas emissions in 2018.

Within the infrastructure sector, the transport industry is the largest emitter, accounting for around 28% of the total emissions from the sector. The energy sector is the second-largest emitter, accounting for around 26% of emissions, followed by the buildings sector, which accounts for around 21%.

It is worth noting that these figures are from 2018 and may have changed in the years since. The UK government has set a target of achieving net-zero greenhouse gas emissions by 2050.

A significant contributor to these emissions is the use of construction plant, especially excavators and generators as the most used pieces of equipment. The UK has tried to encourage the transition away from Diesel by removing access to Red Diesel, increasing the costs to users.

Reducing emissions from construction plant and equipment will be an important part of achieving the UK's target of net-zero greenhouse gas emissions by 2050. This can be achieved through a variety of measures, including using cleaner fuels, adopting more energy-efficient machinery, and reducing the amount of equipment needed through better planning and design.

There is significant policy drive to advocate low emission non road mobile machinery (NRMM) for example in London from Jan 2040 only zero emissions machinery will be allowed.

Work package 5 is a Field Trial Plan conducted by Costain, one of the largest infrastructure companies operating in the UK. Costain are a significant user of Plant within construction projects primarily working in the Transport Infrastructure sector with key Clients like HS2 and National Highways.

A detailed report was supplied to DESNZ as the WP5 output, studying user requirements, types of machine and their annual hours / emissions, technology options and their costs / benefits, and proposing a plan and structure for a field trial to kick start deployment. Some information in that report is commercially sensitive, but a summary of key points is presented here.

5.2 User Requirements

In common with much of the construction sector, Costain do not own their machinery; they lease it from companies such as L. Lynch, Flannery and TCP who specialize in supplying the whole sector's needs. The user requirements therefore have two primary stakeholders: The owner (leasing company) and user (Costain). Throughout this work package, Costain were strongly engaged with their leasing partners.

As discussed elsewhere, smaller equipment is more likely to adopt battery technology, and larger machines are better suited to the size and power of the prototype RSCE. Therefore, machines over 15 tonnes were catalogued across a number of road and rail construction sites; telematic data from selected machines was used to profile typical operating hours and fuel used. This highlighted some interesting facts:

- While some machines are heavily used, others are very episodic, performing a specific task only when needed.

- In the latter case, very high engine-idling times, sometimes exceeding the at-load hours, were logged.

Machine Type	Number Studied	Rating Range	Costain Hours/Yr	Costain CO2/Yr	Narrative
Tracked Excavator	23	14 - 40 ton	100-7600	5-220 t/unit	Wide range of use profiles depending on project; popular machine; RSCE suits 30-35 tonne
Wheeled Loader	4	20-30 ton	40-500	1-8 t/unit	Fewer in use and lower utilization, but easier to adapt as a model is available with base C9
Dozer	8		50-740	1-11 t/unit	Wide range of use profiles depending on project; all used smaller engines than RSCE
Wheeled Excavator	5	14-17 ton	200-3000	4-50 t/unit	Mostly well utilized, but these use smaller engines than the RSCE
Telehandler	4	10-17 mtr	400-2000	5-20 t/unit	Well utilized, but these use smaller engines than the RSCE
Roller	2	13-15 ton	150-400	3-13 t/unit	Have a specific task, therefore more lightly used & smaller engine than RSCE
Dumper	7	20-30 ton	20-2300	2-70 t/unit	More widely used but not all have telematic data; right size for RSCE
Genset	1	70kW electrical	Up to fulltime	Up to 500 t/unit	High CO2 due to utilization; easy first application; use may grow for charging BEVs onsite

Table 7: Machinery types studied

As described in the preceding section, the Genset and Wheeled Loader were selected for specific application study, for entirely practical reasons (ease of building a demonstrator due to a machine being available with the Cursor 9 base engine); however, the Tracked Excavator and Dumper are also the right size and large consumers of fuel, meriting an efficient engine.

5.3 Technology Options

A number of technologies were reviewed qualitatively, based on Costain's experience and stakeholder feedback. A summary is as follows:

Technology	Strengths	Weaknesses	Opportunities	Threats	Trials
Battery Electric	Zero Emission Great transiency No idling Quiet Low maintenance	Cost Charging Infrastructure Charge Time Range	Rapid pace of tech development & adoption in sectors like passenger car	Demand from other sectors for raw materials Energy supply to site	Yes – largest tested was a 25 ton excavator
Umbilical Electric	Eliminates battery issues; otherwise as above	Operational inconvenience; H&S concern; inadequate power to site	Good large machine solution in some situations	May not be universal enough	No
Hydrogen ICE	Familiar ICE; cheap; zero carbon	Some emissions & noise; H2 cost	Easy to adopt; efficiency tech like RSCE attractive	Hydrogen cost, storage, un-availability & unfamiliar safety req's	No, but JCB have a demo fleet at their site

Hydrogen FC	ZEV; quiet; flexible & modular; electric traction	Unfamiliar, complex, vulnerable to impurity, still expensive	Modular systems for multiple sectors	Supply chain ramp-up; generic H2 issues as above	Small gensets – but a number of machines demonstrated
HVO	Drop-in fuel; no process change on site; net CO2 saving 90%	Not zero at tailpipe; Diesel perception; rising cost of HVO	Easy to adopt now as a stop-gap, and has been	Long term competition from aerospace	In widespread use

Table 8: Technology options

General consensus among the stakeholders consulted by Costain, was that electrification would serve machines below 15-20 tons, Hydrogen above. There is a mix of ICE and Fuel Cell technology demonstration in larger machines, but as long as the infrastructure is common, a mix of technologies presents no issue to the operator. In the meantime, HVO has seen widespread adoption, but this is only a stopgap until the new technologies are mature enough to deploy.

5.4 Techno-Economic Analysis

There can be no doubt that any new technology has to make a case for itself in order to be adopted. While "permit to operate" considerations will ultimately drive uptake, it is also essential to consider the most fiscally efficient way to achieve that permit to operate. WP5 therefore conducted an extensive analysis of costs and monetized benefits; detail is confidential and sensitive, but some conclusions are summarized here.

The study considered:

- **CapEx**; noting that most construction machines are leased, so this is experienced by the user as an amortised cost. However, CapEx includes not just the vehicle, but any infrastructure required to store the fuel, and provide refueling.
- **OpEx**; in this case the majority being fuel use, but servicing was also considered.
- **Intangibles**; these do have a value to the user, either in terms of permit-to-operate, or environmental penalties, or consequences of upsetting neighbours of the site. Factors include CO2 emission, Noise, and NOx

The equation is currently dominated by CapEx (~£0.5m per machine) and Fuel (from £200k per year); the current "cost" of CO2, NOx and noise is less than £10,000 per year.

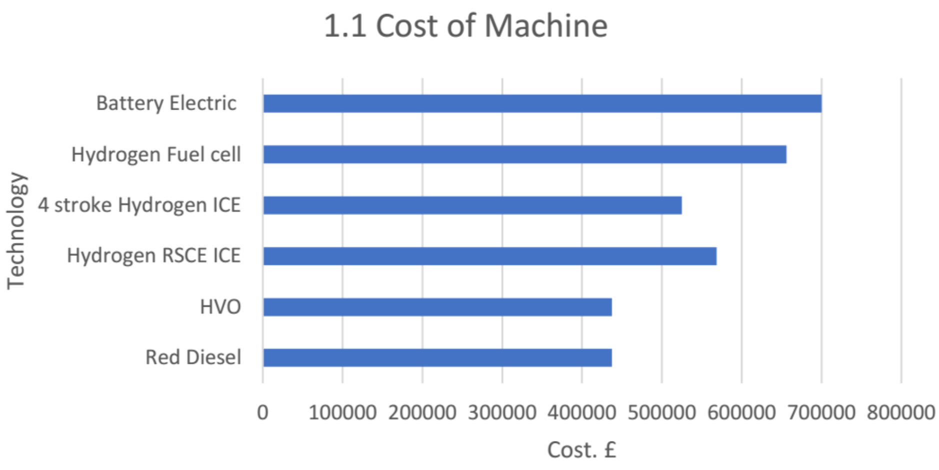


Figure 45: CapEx comparison

The RSCE performs well in these analyses. While costing more than a Diesel machine, estimated purchase cost is below that of fuel cell or battery vehicles, and only slightly higher than a 4-stroke Hydrogen ICE.

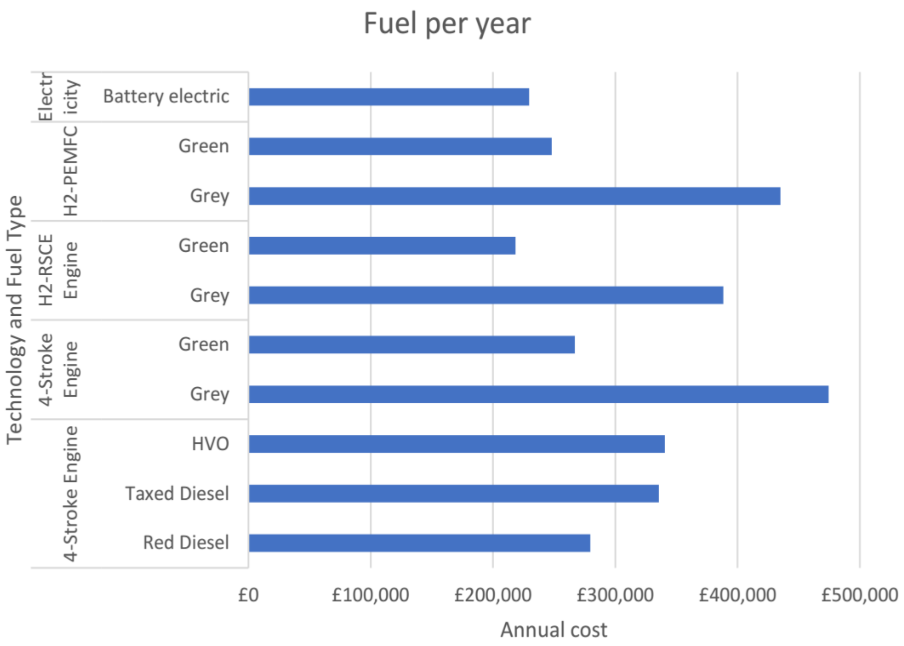


Figure 46: Fuel cost per year

And in terms of fuel costs (using future price scenarios, not those seen today), a RSCE using green hydrogen (which would have to use wrong-time renewables to achieve this cost) is competitive with battery and fuel cell products.

Using this data, it is possible to consider the business case for adoption.

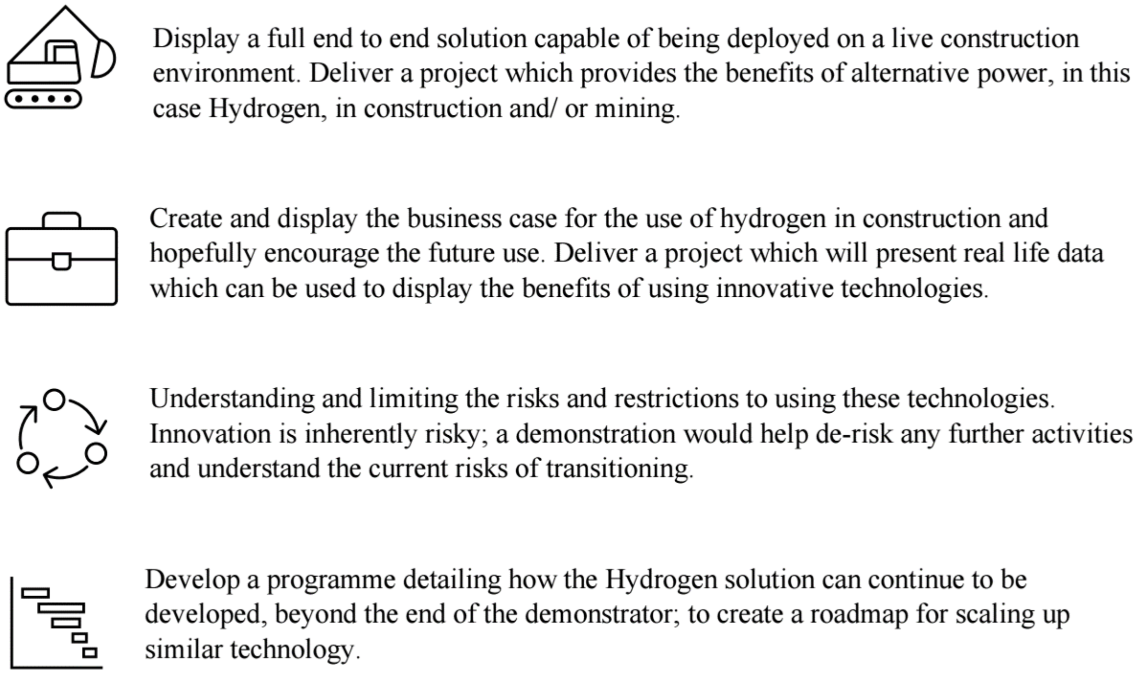
Compared to a current Diesel product, a H2-RSCE vehicle is estimated to add almost £100,000 to the CapEx cost; however, it saves over £100,000 per year in fuel costs if un-taxed cheap green Hydrogen is used in place of taxed Diesel or HVO. Compared to a standard Hydrogen ICE, the RSCE adds around £35,000 to the overall price (and this would be an early, low volume product), but saves £40,000 in fuel per year.

Naturally, such conclusions pivot entirely on the actual Hydrogen cost achieved. As an indication of what is possible, one commercial powertrain laboratory that makes their own hydrogen using solar panels and an electrolyser (both paid for by grants) is offering hydrogen at £16/kg today; another technology developer has told us that the true incremental cost is under £1/kg just as long as the equipment used to make it has a long life.

5.5 Field Trial Planning

5.5.1 Strategic Objectives

Technology development in the lab is often divorced from the realities of field operation. In HYDRATE, every effort was made to correct this, including conversations between the technical team and construction site managers or leasing operators. This highlighted an astonishing level of interest in the technology amongst the type of stakeholder whom one would expect to be change-averse. There is clearly an opportunity for field trials in construction.



Display a full end to end solution capable of being deployed on a live construction environment. Deliver a project which provides the benefits of alternative power, in this case Hydrogen, in construction and/ or mining.

Create and display the business case for the use of hydrogen in construction and hopefully encourage the future use. Deliver a project which will present real life data which can be used to display the benefits of using innovative technologies.

Understanding and limiting the risks and restrictions to using these technologies. Innovation is inherently risky; a demonstration would help de-risk any further activities and understand the current risks of transitioning.

Develop a programme detailing how the Hydrogen solution can continue to be developed, beyond the end of the demonstrator; to create a roadmap for scaling up similar technology.

Figure 47: Objectives of a Field Trial

5.5.2 Consortium

A field trial consortium would consist of:

- **Host / End User:** This would be Costain or similar, at a nominated site
- **Technology Providers:** This would include Dolphin, but potentially other providers of Hydrogen-fueled or otherwise complementary technology (if Dolphin were supplying a Hydrogen genset, then another provider might supply electric vehicles).
- **OEM:** For any technology provider, integration to anything more complex than a genset is impractical without support of an OEM.
- **Leaser:** These are key stakeholders, as the business case must work for them; leasers often have trial grounds for training which can be used for a pre-trial; two major players offered their support for this
- **Fuel Supplier:** As discussed below, local or centralized production are both options; one major household name in the supply of green energy expressed interest.
- **Fuel Storage and Refueling:** While this may be performed by the supplier, further technology providers or OEMs may be engaged (one bowser-maker expressed strong interest), and the plant could be owned by leasing companies.

5.5.3 Fuel Supply

Onsite production has its attractions, principally the absence of transport, which plays a major role in the delivered cost of hydrogen (and its emissions, until fossil-free trucks are used). However, this route either requires a substantial grid connection, or very significant space for a pop-up solar farm. A site using ten machines at a mean daily power of 50kW each would need 500kW of mechanical power, or 2MW of electricity. A solar panel may be rated at over 300 watts, but may only produce 100W on an average day; this would require 20,000 standard domestic solar panels, an area of 40,000 square metres. And the site operator would need access to expertise to keep the set-up running.

Such an arrangement may be better suited to other types of user, such as an arable farm or industrial park (and has been trialed in both), but will only suit certain construction sites; it is not infeasible, however.

Off-site production is simpler, as a larger electrolyser can serve many users, matching sales of gas to output. Once such a supply chain exists, this is a lower risk option, although the flow of tube trailers (potentially 3-5 per day for the 10-vehicle fleet described) would need managing within the site.

In either case, vehicle refueling needs to be by mobile bowser. While these exist, most are not adapted to off-road operation. These may operate either via an on-bowser pump, or a cascade system of cylinders.

5.5.4 Sites

It soon became apparent that use of a pre-trial site would be wise when introducing any new technology. This allows shakedown and final development of the technology, potentially exposing issues that were not evident in the laboratory without disrupting a live site; it also allows training, and practice of emergency procedures such as a simulated leak, fire or breakdown. The project identified several such sites owned by leasers, training establishments and an OEM.

For the actual trial, six sites were compared – five being road works (new bypasses or junctions), and one being a major rail project. These were evaluated for strategic fit, value for money, risk to ongoing works, regulatory alignment, and ability to deliver a trial scope. A favoured site was identified, in which the right size of machinery would be required in the trial timescale.

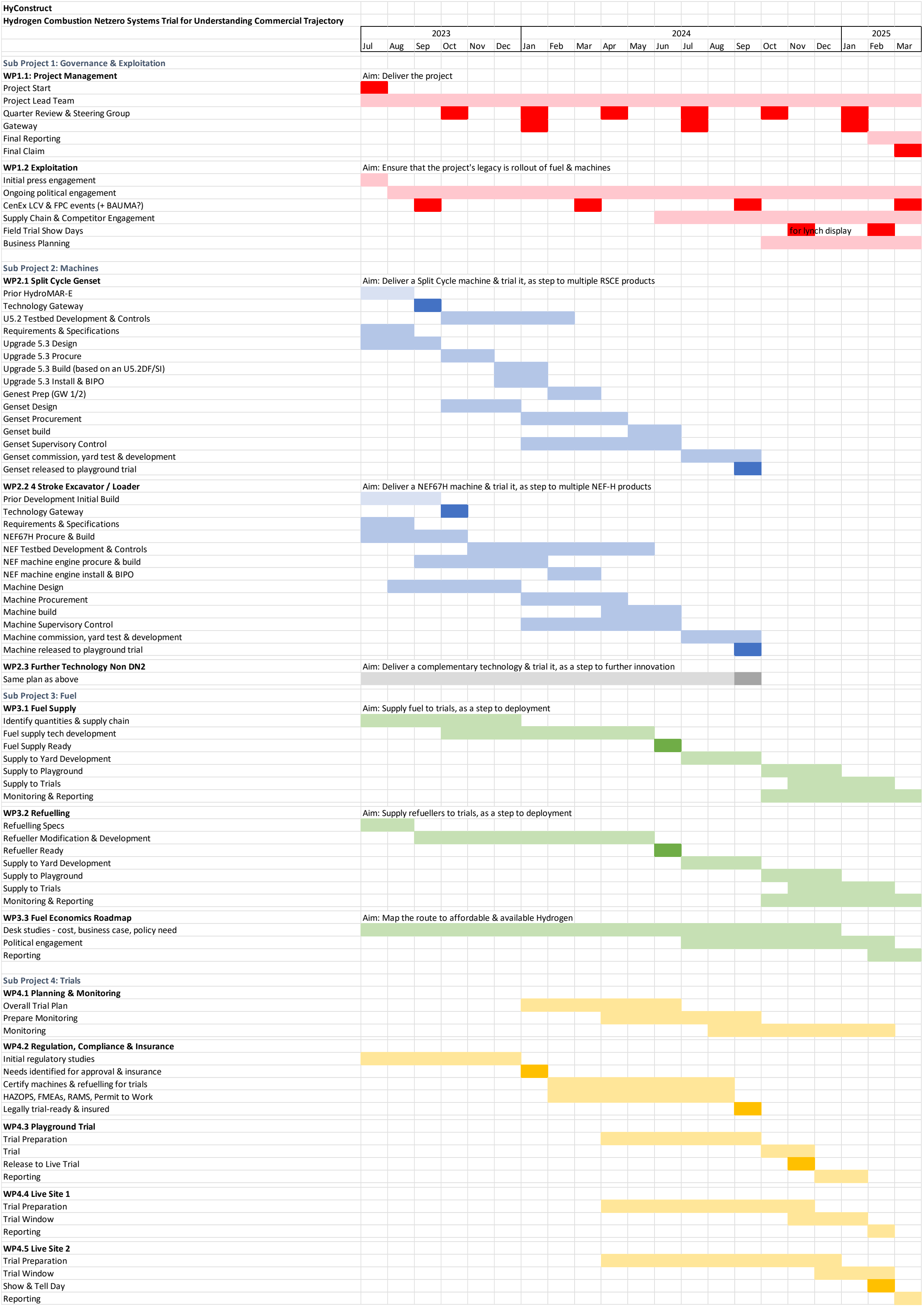
5.5.5 Demonstration Project Plan

An RDR Phase 2 proposal called HyConstruct was developed. In the end this was not submitted, as the technology development was falling behind and a suitable OEM could not be engaged.

The plan (Figure 48) brought together many elements, with work packages including:

- Development of a RSCE Genset (as the lowest-risk option for the RSCE)
- Development of a 4-stroke Hydrogen ICE loader or excavator (utilizing other Hydrogen ICE development work by Dolphin, as a lower risk way of doing a vehicle)
- Development of a third Hydrogen technology by another developer
- Development of a fuel supply and refueling
- Creation of a fuel economics roadmap
- Planning of trials, regulatory compliance, and insurance
- “Playground Trials” at a test site
- Two live site trials
- Post-project planning for wider exploitation and roll-out

The project would run from mid-2023 to 31st March 2025, with trials in the final 6 months.


HyConstruct
Hydrogen Combustion Netzero Systems Trial for Understanding Commercial Trajectory

2023: Jul Aug Sep Oct Nov Dec
2024: Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
2025: Jan Feb Mar

Sub Project 1: Governance & Exploitation

WP1.1: Project Management – Aim: Deliver the project
Project Start
Project Lead Team
Quarter Review & Steering Group
Gateway
Final Reporting
Final Claim

WP1.2 Exploitation – Aim: Ensure that the project's legacy is rollout of fuel & machines
Initial press engagement
Ongoing political engagement
CenEx LCV & FPC events (+ BAUMA?)
Supply Chain & Competitor Engagement
Field Trial Show Days – for lynch display
Business Planning

Sub Project 2: Machines

WP2.1 Split Cycle Genset – Aim: Deliver a Split Cycle machine & trial it, as step to multiple RSCE products
Prior HydroMAR-E
Technology Gateway
U5.2 Testbed Development & Controls
Requirements & Specifications
Upgrade 5.3 Design
Upgrade 5.3 Procure
Upgrade 5.3 Build (based on an U5.2DF/SI)
Upgrade 5.3 Install & BIPO
Genest Prep (GW 1/2)
Genset Design
Genset Procurement
Genset build
Genset Supervisory Control
Genset commission, yard test & development
Genset released to playground trial

WP2.2 4 Stroke Excavator / Loader – Aim: Deliver a NEF67H machine & trial it, as step to multiple NEF-H products
Prior Development Initial Build
Technology Gateway
Requirements & Specifications
NEF67H Procure & Build
NEF Testbed Development & Controls
NEF machine engine procure & build
NEF machine engine install & BIPO
Machine Design
Machine Procurement
Machine build
Machine Supervisory Control
Machine commission, yard test & development
Machine released to playground trial

WP2.3 Further Technology Non DN2 – Aim: Deliver a complementary technology & trial it, as a step to further innovation
Same plan as above

Sub Project 3: Fuel

WP3.1 Fuel Supply – Aim: Supply fuel to trials, as a step to deployment
Identify quantities & supply chain
Fuel supply tech development
Fuel Supply Ready
Supply to Yard Development
Supply to Playground
Supply to Trials
Monitoring & Reporting

WP3.2 Refuelling – Aim: Supply refuellers to trials, as a step to deployment
Refuelling Specs
Refueller Modification & Development
Refueller Ready
Supply to Yard Development
Supply to Playground
Supply to Trials
Monitoring & Reporting

WP3.3 Fuel Economics Roadmap – Aim: Map the route to affordable & available Hydrogen
Desk studies - cost, business case, policy need
Political engagement
Reporting

Sub Project 4: Trials

WP4.1 Planning & Monitoring
Overall Trial Plan
Prepare Monitoring
Monitoring

WP4.2 Regulation, Compliance & Insurance
Initial regulatory studies
Needs identified for approval & insurance
Certify machines & refuelling for trials
HAZOPS, FMEAs, RAMS, Permit to Work
Legally trial-ready & insured

WP4.3 Playground Trial
Trial Preparation
Trial
Release to Live Trial
Reporting

WP4.4 Live Site 1
Trial Preparation
Trial Window
Reporting

WP4.5 Live Site 2
Trial Preparation
Trial Window
Show & Tell Day
Reporting

Figure 48: HyConstruct project plan

5.6 Conclusions

Work Package 5 concluded that:

- The Hydrogen ICE is an attractive technology, especially for larger machines and in situations where battery or umbilical electrification are infeasible.
- The Recuperated Split Cycle justifies its extra purchase cost versus a standard Hydrogen ICE via lower consumption of expensive Hydrogen fuel and potential for better air quality.
- An integrated trial of an end-to-end hydrogen system (fuel production, distribution, and use) is feasible and should be pursued.
- There is great interest in this type of trial, from construction companies, machinery leasing companies, landowners, fuel suppliers and machine makers, with multiple of each expressing interest.
- Significant environmental benefits can be delivered to the mutual benefit of all construction sector stakeholders.

With some regret, the consortium decided not to progress to a bid for Phase 2 funding, for a variety of reasons including the relative immaturity of the H2-RSCE as a laboratory engine. However, as Section 6 shows, the case for UK construction as an early adopter is very strong indeed; discussions continue, and it is likely that the technology will be demonstrated in the construction sector as soon as it can be.

6. Development Plan & Route to Market

6.1 Shared Heavy-Duty Technology

Current machinery power solutions – Diesel engines - tend not to be bespoke to the construction sector, instead leveraging the economy of scale available if the same base unit is also used in road vehicles, agriculture, marine propulsion and gensets. A rule-of-thumb used for mass-production is that for every doubling of annual product volume, the manufacturing cost is 5% lower. In reality, this is an over-simplification, but it illustrates the importance of shared product volumes.

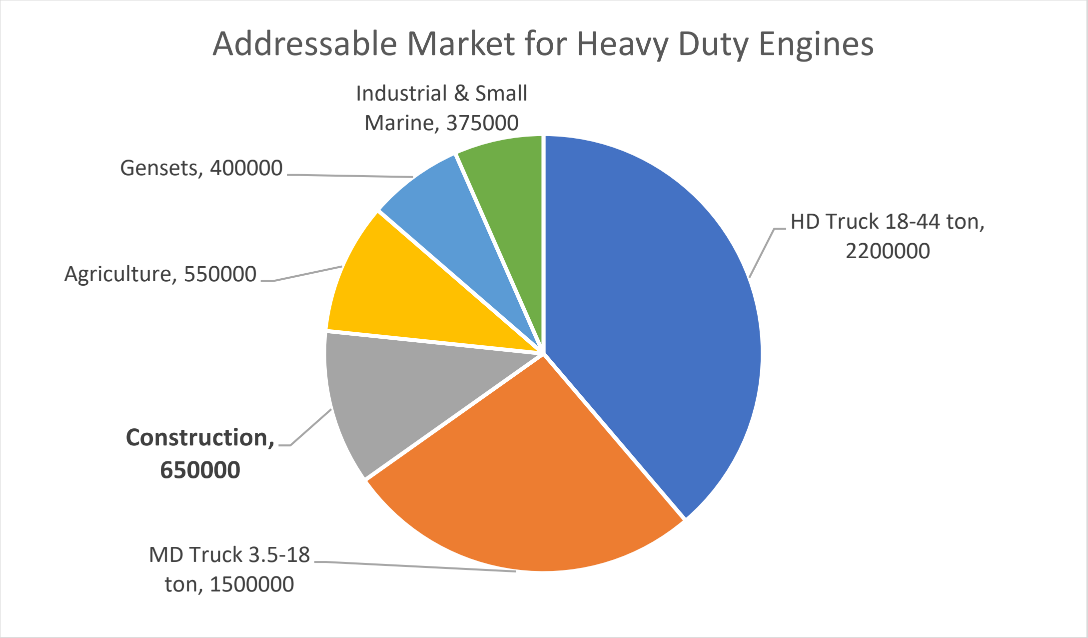


Figure 49: Global heavy engine market <1MW

The global addressable market for heavy duty engines is over 5 million units per year, of which trucks make up the largest share – hence, Construction powerplants tend to be adapted truck units, not the other way round. However, Construction is by no means insignificant in this context – this sector and Agriculture, plus much of the Genset market, tend to use "medium duty" size engines, of 100-200kW; together, these sectors more than equal the MD truck volume. Nonetheless, if the rule of "5% cost saving per doubling of volume" applies, then a shared engine would be 15% cheaper than one bespoke to the construction sector.

6.2 Future technology pathways

It is therefore relevant to consider which of these markets is likely to purchase an advanced Hydrogen ICE. Of course, the route to market would not require conquest of the whole market – a typical individual heavy duty engine product has a sales volume of less than 100,000 units per year. However, it is relevant to consider which markets would actually find the technology attractive in future.

6.2.1 On Highway

Starting with trucks, the European Commission has recently published its proposed regulations for the heavy-duty sector to 2040 and beyond. This proposal is innovative in that it is genuinely technology agnostic, requiring that any truck meet the following two criteria:

1. Emissions meet the Euro 7 standard, which covers not just "tailpipe" exhaust emissions, but also dust from brakes and tyres – so any vehicle, even electric, must comply.

2. Emissions of Greenhouse Gases should be below 5 grams per ton-km on a “tank to wheel” basis – which excludes carbon-bearing fuels from anything other than an ignition-pilot as used in HYDRATE.

The implication of these proposed rules is a “level playing field” for electric, fuel-cell and Hydrogen-ICE trucks, a point explicitly acknowledged by the Commission. In contrast, UK policy for trucks has tended to stipulate “zero emissions”, but does not specify how this is measured (in terms of what is measured, how, or a threshold for “zero”); the reality of this is that (a) even an electric truck would not meet that criterion if tyres are measured, and (b) as the UK takes identical truck products to the EU, it would disadvantage UK operators if the Hydrogen ICE were excluded.

The future truck market is likely to adopt a mix of solutions, in that:

- A battery truck is attractive where its mission profile permits a smaller battery, and overnight depot charging (which is both kinder to the battery, and substantially cheaper than a fast charge en-route) are available; here, the disadvantage of high purchase cost is overcome by lower operating costs.
- A fuel cell is an attractive means of providing electrical power where the very lowest emissions (in particular, of noise) are required and a battery is unsuitable; however, it remains more expensive than an ICE, and requires higher Hydrogen purity.
- A Hydrogen ICE offers a solution that is cheap to make, rugged and familiar to the supply and servicing value chains. Unlike the two solutions above, it is compatible with a conventional manual gearbox / transmission, although in a future mixed market an operator may prefer a hybrid (electric traction) drive for ease of operation; this is relevant, as it requires a smaller engine, closer to the size of the HYDRATE prototype.

We do not forecast market shares here, but the assumption is made that there will be future on-highway H2-ICE products in the same size ranges as off-highway.

6.2.2 Off Highway

Off-highway emission regulation has traditionally been considered more lenient than on-highway, although this is changing; it is probably safe to assume that the two will converge, especially with regard to GHGs. In the off-highway sectors, there is less in the way of clear regulation to phase out fossil fuels, and more diversity of favoured choices:

- In construction, fuel for machinery makes a relatively small contribution to the total project cost, yet the machinery is very visible; this creates an environment where initiatives like pop-up solar farms on a site can be attractive. Smaller or intermittently-used vehicles may adopt battery-electric power. For larger vehicles, and power generation where solar or a grid connection are unavailable, Hydrogen is establishing itself as a preferred fuel, as showcased by JCB in machines, and some Costain-operated sites for stationary power backup. As an interim step, HVO has been widely adopted in the UK since the “red Diesel ban”, but in the longer-term scarce bio-resources may be diverted to aviation, as discussed in section 1.
- In agriculture, even intermittently used machines tend to work hard when the season to use them arrives, so fast refueling, ideally in the field, is desired. This sector could favour “home grown” resources; perhaps bio-Diesel (HVO) in the short term, but bio-methane from fugitive sources (7) being a very attractive option. This latter has a very high commonality with the H2-ICE in either 4-stroke or RSCE form, to the point that the same engine could run on either fuel with calibration changes, or flex between fuels or blends.

- In the marine sector, missions tend to be longer, with safety critically dependent on range. Battery electrification will again be most successful for short, predictable missions such as ferries. Hydrogen and Ammonia are being considered as long-haul fuels; again, an Ammonia ICE has much in common with a Hydrogen one, especially with pilot (dual fuel) ignition.

So, it is again reasonable to assume that these off-highway markets remain open to the Hydrogen RSCE. Of all of them, Construction is interesting, as it has all the right ingredients to be an early adopting "hydrogen community", as it is self-contained with predictable needs and highly managed logistics.

6.3 Construction as a Hydrogen Early Adopter

The vision described in the sections above, applied to a post-2040 environment, anticipates the widespread use of Hydrogen as a fuel across multiple heavy-duty sectors, supporting a mix of ICEs and fuel cells according to which suits the individual need better. The question is, "how do we get there"? Any transition needs early adopters, to both build the confidence of the wider market, and build the volume of more affordable product and its supporting infrastructure.

Early adopting "Hydrogen Communities" have been the subject of much study because the fuel (especially paired with fuel cells) has a history of political interest (pre-dating the recent rise of electrification). For example, the Roads2HyCom project (9) postulated four key metrics for a successful Hydrogen Community:

- **Technology Accessibility**: Meaning, access to hardware. The ICE is an affordable Hydrogen solution, with one manufacturer (JCB) already showcasing a range of prototype equipment (10); small fuel-cell based generators have already been deployed as a backup to solar generation on construction sites (11). Construction sites are self-contained with a high degree of logistical management, meaning that delivery of Hydrogen to site can be managed. Therefore, it would appear that Construction scores well on this metric.
- **Public Acceptance:** As discussed above, construction sites tend to have high, and not always favourable, public visibility; the general perception of the sector is that "greener" construction equipment supports a more positive image. The high degree of logistical management on a construction site means that good safety practice can be actively managed. Therefore, Construction should score well for Public Acceptance.
- **Political Will:** The rationale for the Red Diesel Replacement R&D programme was mitigating the "ban" on Red Diesel, a clear indicator of Political Will in the Construction sector; the UK has a strong global position in this respect. Costain are clearly taking a strong position in response to political will; discussions with other construction contractors, project management firms and landowners suggests that Political Will, will only rise now.
- **Potential for Growth:** As described above, Construction accounts for over 10% of the Heavy-Duty engine market, which is itself enough volume to create a case for a new technology to become competitive; however, the real growth potential is that the technology spreads to other sectors, particularly trucks. As discussed in the preceding section, that potential is strong.

So, there is a good argument that Construction is a good Early Adopter for a wider transition from fossil fuels to Hydrogen, embracing Fuel Cells, conventional 4-stroke Hydrogen ICEs, and the Recuperated Split Cycle Engine. As shown in Section 5, the RSCE is strongly competitive in that field.

6.4 Route to Mass Market

In this report, confidential business plans are not discussed; however, based on the reasoning above, a speculative Route to Mass Market for the Hydrogen RSCE might be as follows:

Timeframe	RSCE	Other Hydrogen Technologies
2023-2025	Technology demonstration & development, for Hydrogen & other fuels e.g. Biomethane	Niche products in use with civic & other subsidies / incentives. Field trials such as RDR Phase 2 in Construction.
2025-2030	First Natural Gas / Biomethane product in a target market e.g. agriculture or food sector using wastes; First Hydrogen niche product e.g. genset targeting construction; other targeted H2 products e.g. construction machines.	4-stroke Hydrogen ICE construction equipment on sale; trials & low volumes in other niches such as trucks operating from depots or pilot Hydrogen Highways.
2030-2035	First higher-volume Hydrogen products serving multiple sectors.	Rising volumes across all sectors contributing to CO2/GHG targets.
2035-2040	Rising uptake as part of fleet mix, focused on long haul / high duty applications, potentially 10% of total market.	Hydrogen and Electricity displace fossil fuels by 2040 in regulated economies. Mix of technologies as befits each specific need.

Table 9: Illustrative Route to Market scenario

6.5 RSCE Development plan

6.5.1 Introduction & Approach

The detailed development plans for Dolphin N2 and their commercial parent FPT Industrial / Iveco Group are confidential and not able to be discussed here. Instead, a plan is presented based on a consortium bid for Advanced Propulsion Centre (APC) funding under their “APC18” funding call in 2021. The working assumptions used here were:

- The technology starting point was around TRL5 (laboratory demonstration of a complete integrated unit under a range of conditions simulating real use), which is the status targeted at the end of HYDRATE, delivered by WP3.
- The engine was based on the volume production facility for an existing unit (meaning mainly, the same number of cylinders and distance between bore centres, allowing existing machine tools to be used); however, major castings (block, head) and forgings (crank) are expected to change.
- Product introduction would be a niche unit after 5 years, and a volume product after 7 years. This remains a reasonable assumption, although we would aim to advance the niche product introduction to 3-4 years if possible.
- The product would be a Diesel unit with a Hydrogen derivative using a common cylinder head architecture launching after the end of the 7-year plan; this remains a potential route, but a Hydrogen-only product in the 5+7 year timeframe would contain all the same development elements, time and cost. As HYDRATE is a project dedicated only to the Hydrogen version, this is what is assumed.

6.5.2 Key development activities

There are three key areas of development required to take the engine to low or high-volume production:

- **Performance & Emissions:** Embraces targets for power, efficiency, air quality emissions, transiency, hot and cold operation, high altitude operation, and starting. These requirements are either legislated or a core user need, therefore a both low or high volume product needs to meet them. Typically, P&E development would occupy one or more engine testbeds for a period of 1-2 years, followed by a year of real or lab-simulated in-application work.
- **Durability:** Embraces both the integrity of the engine over its life (up to 20-30,000 hours), robustness to abusive environments (heat, cold, damp, salt, dust), and the continuing function of emission control equipment. Typically, Durability development requires multiple engine test-beds and component rigs simulating different aspects under accelerated-life conditions for 1-2 years (and this can only be concurrent with P&E and Cost activity if the item is well enough defined at the start of testing, including being made by a production-intent process), followed by field testing of a fleet of vehicles / machines; the latter can take the form of live operations with a “safe” customer.
- **Cost:** Areas of novelty on the engine are currently only made as prototypes; for each of these (discussed below) there will need to be an iteration of materials, design and production processes towards a manufacturing solution that is optimum for the product volume.

Typically, development may involve three prototype phases:

- **Alpha,** is a fully functional prototype to initiate P&E and some Durability work as above.
- **Beta,** is an evolved prototype with every aspect designed as it will be manufactured as a product, ideally the components come from their intended suppliers; durability work becomes meaningful at this stage.
- **Gamma,** has no design change from Beta unless absolutely necessary, but every part is “off-tools”, in other words made by the intended production process and tooling; final verification of all attributes, and homologation, is performed on Gamma prototypes.

Each phase typically takes a year, with extra “pre-Alpha” research being more likely in the case of a novel technology; hence the timescales proposed.

Areas of particular focus for development, where the split-cycle engine is unique (and therefore cannot directly read-across a solution) are as follows:

- **Combustion & Thermodynamics:** A primary focus of the P&E activity, this type of engine features a unique combustion system (4, 8), and unique requirements for starting and transient control; effort needed here will be significantly higher than for a conventional P&C program, driving the need for continuing “pre-Alpha” work; adoption of a battery supported Genset as first application simplifies this task somewhat.
- **Exhaust After-treatment:** So far, all laboratory work has been on an “engine-out” emissions basis; while after-treatment is not expected to present any showstoppers, the engine’s unique characteristics and novelty of Hydrogen as a fuel, plus the demands of future legislation, mean that this activity will need focus in P&C and Durability areas.
- **Recuperator & Plenum:** This is a unique component; performance has matched required specifications, but as this is a hot, high-pressure system currently fabricated by semi-manual processes from Inconel, significant work around cost reduction and durable safety will be needed in the industrialization process.

- **PSZ Thermal Insulation:** Again, this is not a feature of most heavy-duty engines; coatings were initially (before HYDRATE) durable for just a few tens of hours; a development program initiated in the RE-ARMD project gave durability sufficient for development, but this will be a major focus for full durability validation. Here it is manufacturing process control, rather than design, that is critical, so an early switch to “off-tools” is critical.
- **Cam Phase Control:** The RSCE has unique cam phase control requirements, meaning that off-the-shelf parts are not suitable. A very successful prototype system developed in the STepCO2 project has been applied in HYDRATE, but a lower cost concept or variant will need to be developed for production. Alpha-type performance testing will then need to feed a major cost & durability effort in Beta & Gamma phases.
- **High Pressure Hydrogen systems:** While the fuel injectors are based on off-the-shelf Liquid Natural Gas technology, that fuel can be pressurized in the liquid phase; Hydrogen cannot. The laboratory engines are supplied with fuel at pressure using a lab-type pump that is not directly suitable for mobile machinery. Prototype hydraulic-drive pumps exist, but are currently at TRL3-4, therefore significant development of performance, durability and cost is expected.

Areas that can adapt existing supply-chain technologies include:

- **Base engine:** While the design of major components (cylinder block and head, crank, cams, valvetrain) is different, all of these follow standard production processes and design rules; standard product development processes would apply.
- **Hydrogen Injectors:** As described above, the “Westport” dual fuel injector is an adapted Methane unit, also being considered for 4-stroke Hydrogen applications. Development of materials to resist Hydrogen embrittlement, and subsequent durability testing, is the major focus of effort; that is expected to occur in the same timeline as product development.
- **Hydrogen Tank & System:** Although by no means fully mature, there is a growing supply chain for 700bar tanks and onboard fuel handling parts.
- **Turbocharger:** The engine’s boost requirements are subtly different to a 4-stroke, but not out of line with the state of the art for higher efficiency and pressure ratio, in development in the supply chain but requiring tailoring to the correct trim.

6.5.3 Development Plan & Cost

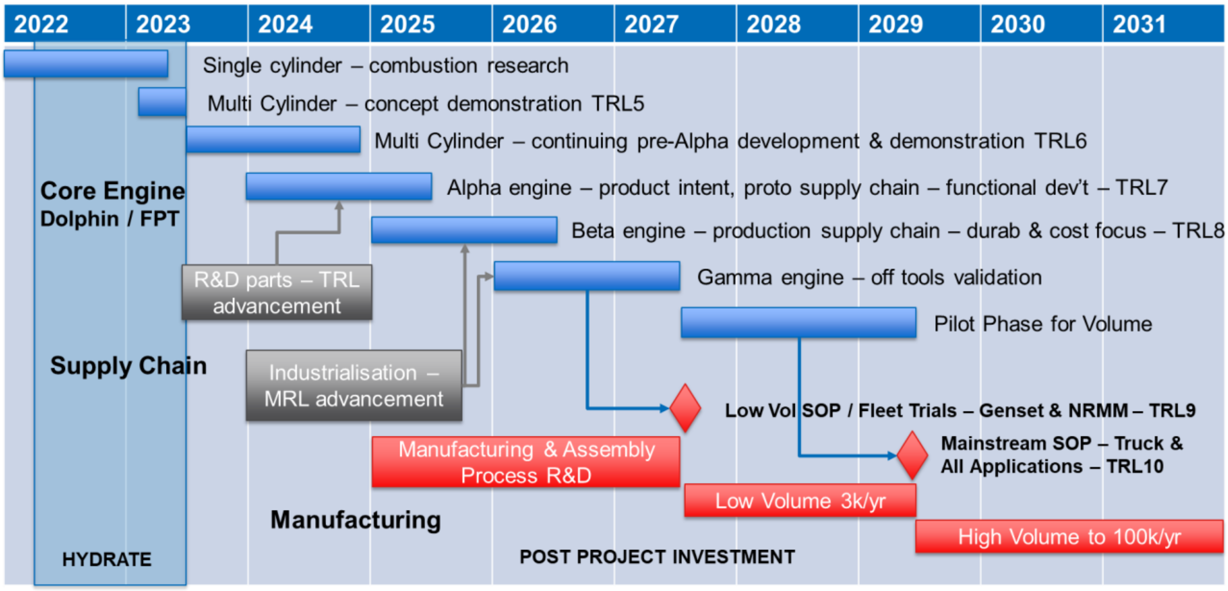


Figure 50: Illustrative Development Plan for Low & High Volume

The development activity described above is shown in Figure 50. Planning included illustrative budgetary estimates for the development pathway to a high-volume Diesel engine; for this report, Hydrogen component development costs have been added to reflect a pathway to a high volume Hydrogen engine. The assumptions here were:

- Niche product, 3000 units/year, but engineered to transition to a volume product.
- Volume product, suitable for up to 100,000 units/year.

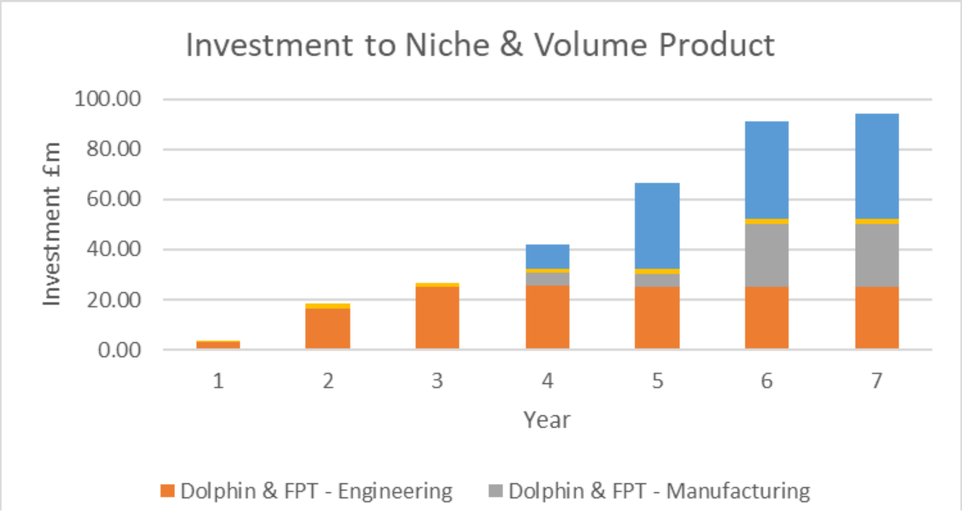


Figure 51: Illustrative investment costs for pathway to a volume product

In common with any other major ICE development (or indeed a major battery or fuel cell development), this requires a significant investment, of around £340m for all engineering and manufacturing "up-front" costs (excluding working capital once production starts). Around £130m is needed to get to the niche volume, but this is loaded by the assumption that it is engineered to move from low to high volume. A niche-only product could be created for lower investment cost (indicatively, £60-100m), but would effectively be a "series-built Beta prototype" with higher sale cost and more limited validation of long-term durability. Such a unit could however be sold to extended subsidized trials.

6.6 Economic Benefits

6.6.1 Sales volumes, fuel & CO_2 saved

The same methodology was applied, adapting estimates from the "APC18" bid, to estimate sales potential, fuel & CO_2 savings, and a return on investment. Again, these are indicative rather than representing any actual business plan.

Sales volumes were estimated on the basis of the low volume – high volume introduction strategy previously described, then assuming that the technology would be repeatedly licensed to other engine manufacturers. The endpoint of the projection is 600,000 units per year in 2036, which would represent licensing to around 7-10 volume products. While this may appear ambitious, it represents little more than 10% of the global market, just four years before economies like the EU and UK outlaw fossil-fueled heavy-duty engines. The transition saves over 200 billion litres of fuel per year (worldwide) and saves 600 million tonnes of CO_2 worldwide. Around 5% of those savings are in the UK; around 2/3 are derived from off-highway equipment due to high utilization in larger machines.

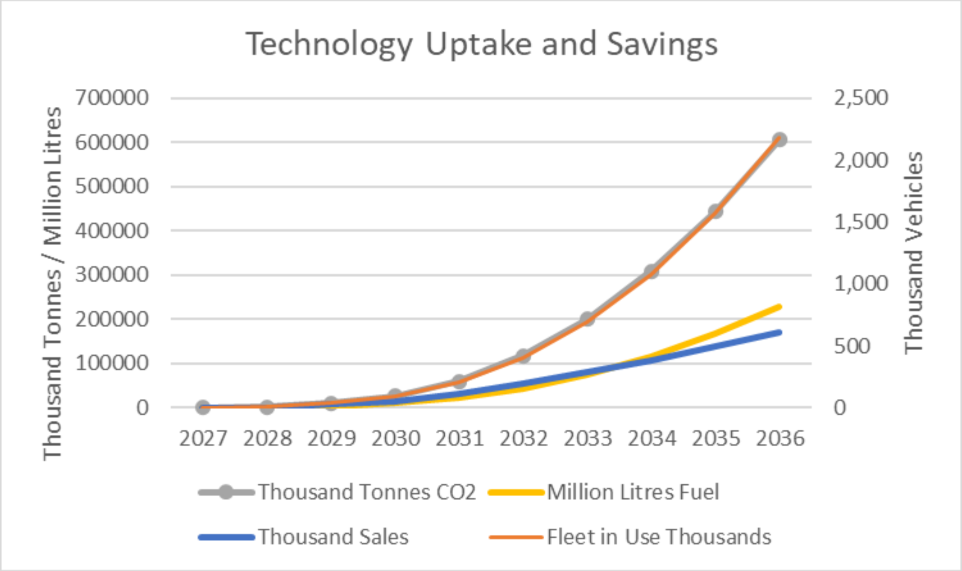


Figure 52: Global sales, fleet-in-field, fuel & CO2 savings

During the APC bid, an Internal Rate of Return was estimated. This is a measure of Return on Investment, and is equivalent to the interest rate earned on the money invested, as if placed in a savings account at that rate. With the sales projection above, IRR was estimated at 20-30% for both engine manufacturer and key suppliers, an attractive figure for investment.

6.6.2 Job Creation & Skills

The same assumptions for sales were used to estimate UK job creation. As Dolphin has been working with specialist UK suppliers in several previous collaborations, it was assumed that UK suppliers would provide:

- Low volume, and a proportion of high volume that declined over time as more competition became established, for the Recuperator (Hiflux), PSZ Ceramic Coatings (Zircotec), and one other key system such as Cam Phasers (Mechadyne), or Fuel Injectors & Systems.
- Most major parts for low volume production that were not carried over from a base 4-stroke engine; that low volume assembly being performed in the UK, and then serving as a pilot plant for other licensees and engine sizes.

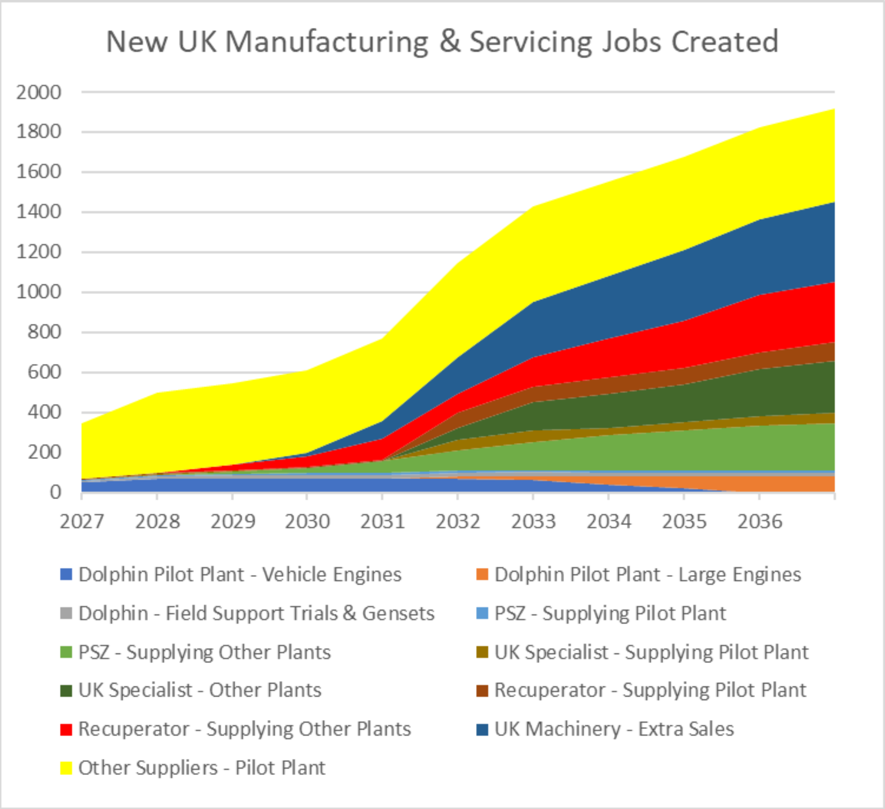


Figure 53: UK jobs created by illustrative route to market

The analysis showed potential to create over 300 UK jobs by 2027, and almost 2000 UK jobs by the late 2030s. It is worthy of note that (a) the role of the supply chain is much larger than that of the engine assembler, and (b) there are spin-off benefits, such as growth in sales and jobs by a UK vehicle or machine maker using the engine to secure market advantage (for example, New Holland in Basildon use the base FPT engines in tractors).

The type of skill created is very varied, from small but steady up-skilling in high-skill areas such as R&D and maintenance, to a much larger up-skilling of high-value manufacture. This provides a welcome boost in an area of the economy – ICE manufacture – where the UK has been strong, but where electrification creates a threat to those existing jobs.

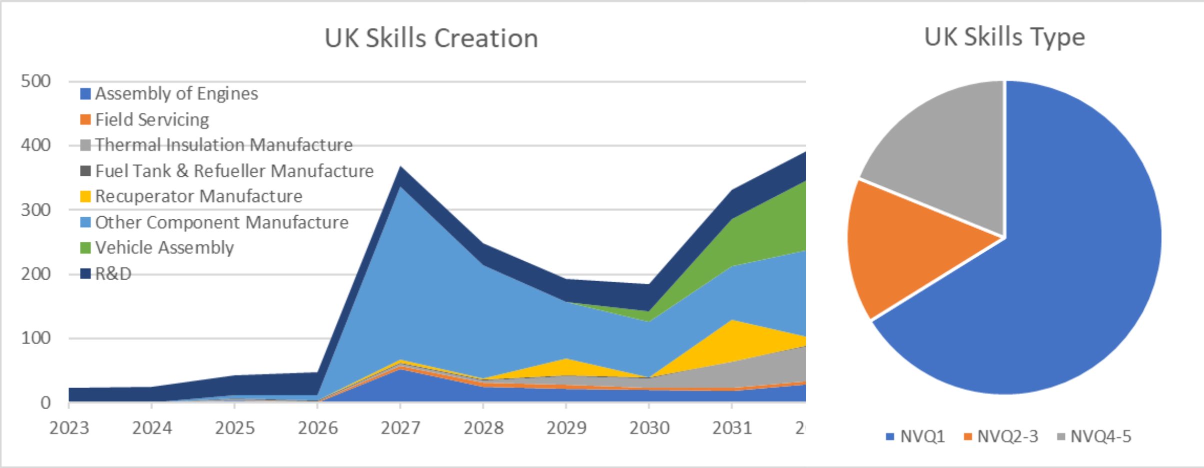


Figure 54: UK Skills Creation by Sector and Level (illustrative)

6.7 Conclusions

Significant study of the market opportunity and route to market has been made, both before and during the HYDRATE project, concluding that:

- There are multiple sectors where the Hydrogen Recuperated Split Cycle Engine is attractive, and that eventually addressing all of those sectors will lead to the most cost-effective product; the total addressable market of over 5 million units per annum worldwide is very attractive indeed.
- The UK's Construction sector is well placed to act as an early adopter of the H2-RSCE and other Hydrogen technologies, as it has all the attributes of a potentially successful "hydrogen community"
- A route to market is proposed whereby a low volume engine serving such early adopters, is followed by a high volume evolution serving all markets; the technology then spreads further via different sized products and licensing to other manufacturers
- Key system technologies requiring special attention have been identified, and in many cases supplier relationships (which are confidential) are already in place
- A development plan indicates that a low volume product could be on sale within 3-5 years, with rapid volume growth through the 2030s
- The business case for that plan is attractive both for the technology developers (manufacturer and suppliers) and for the UK as a whole, with potential to create 2000 high value UK jobs and reduce global CO2 emissions by over half a billion tonnes per year by the mid 2030s

Considering those factors, and the favourable user-perspective comparisons described in the preceding section, there remains a strong case for the technology as long as targets for performance, cost and durability can be met in the next phases of development.

7. Lessons Learned

7.1 Introduction

The project highlighted very clearly some of the challenges in delivering a high risk technology development project against an aggressive timescale. Ultimately, the project failed in its stated aim of outputting a multi-cylinder Hydrogen engine ready to start a RDR Phase 2 project. Yet in every other sense it succeeded: the single-cylinder engine ran successfully, demonstrating good Hydrogen combustion over a representative range of speeds and loads in this innovative engine type for the first time ever; studies around its application in construction showed a good technical, environmental and business case for its use. It just needed more time than was available.

Discussion of the reason for this is divided as follows:

- Technical challenges
- Supply chain challenges
- Partnership and people challenges
- Political challenges

The project team within lead company Dolphin N2 maintained a “Learning from Experience” register, which captured more detail issues within these headings, but is confidential. A summary is discussed here.

7.2 Technical Challenges

The Recuperated Split Cycle Engine is an innovative technology, requiring several fundamentally new systems to be developed, including the recuperation system, fast-acting valvetrain and thermal insulation. By the time of the HYDRATE project, these had been overcome in preceding Diesel engine research (grant-funded projects StepCO2 and RE-ARMD), but this left a legacy of late-running work whose knock-on effects impacted some aspects of program timing:

- A Diesel variant of the upgraded Titan engine was due to run before HYDRATE, being the first version of Titan to replace its original, rather experimental camless cylinder head with a more representative single unit of the multi-cylinder design;
- Because of these historic challenges, and issues relating to the supply chain and partners / people described below, this Diesel variant became so late that it was abandoned, leaving HYDRATE to pick up the mantle of being the first “Mk2 Titan” unit to run;
- This in turn introduced commissioning issues relating to oil supply and drainage, and valve system control, that were overcome but introduced a delay of at least a month’s lost testing time; while ultimately this lost time was not a critical factor, it didn’t help.

Ultimately, the Titan engine itself proved reliable, except for one issue with leakage of inlet valves. We were able to remove any contamination of data from this analytically, and the discovery of the problem represents an advance in our understanding. A single leaking valve out of 24 on the previous Diesel multi-cylinder engines is hard to spot in the data; one out of 4 on the Titan was more obvious.

Further technical challenges relate to the use of high pressure Hydrogen:

- Filtration on the initial system was based on Diesel principles of filtering only before the pressurization pump; with Hydrogen systems, the absence of lubrication generates wear debris and a post-pump filter had to be added after an injector failure. This issue has also been a learning-point for others in the industry, and is now addressed with minimal delay;

- Hydrogen safety is a new topic for many researchers; the natural process of learning from best practice, combined with staff changes discussed below, introduced uncertainty and significant delay while upgrades were applied to the laboratory's safety provisions. A Hydrogen Safety training course run by the Health & Safety Executive was employed to bring a common grounding of knowledge to the laboratory teams.

7.3 Supply Chain Challenges

The HYDRATE project's lifetime spanned some unusual events, including the aftermath of the Covid pandemic and the outbreak of war in Ukraine; in addition, some elements of the supply chain were never in a position to respond with timely or cost-effective solutions in the first place. Specifically:

- The cost of Nickel-based materials rose very significantly at the time the Titan engine was being procured, impacting the cost of Inconel parts used in the hot high pressure system. Work in a subsequent project, HydroMAR-E, has validated cheaper stainless steel alternatives for some of these parts;
- Hydrogen components are not available off the shelf; lead-times for the high pressure storage tanks and pressure pump used in the multi-cylinder test cell were appreciable and, added to other issues described below, created a delay that led to the multi-cylinder engine being unable to run;
- Likewise, specialized contractors to supply and fit hydrogen pipework are not numerous, meaning that fitting work had to be scheduled when the contractor was available; this introduced delays of around a month.

7.4 Partnership and People Challenges

Any collaborative project relies on cohesion of its partnership, and the input of key people. In the HYDRATE project, a specific set of circumstances led to major losses in the original research team, including the professor leading the research, his assisting senior lecturer, an experienced laboratory manager, and two experienced lab technicians. Contributing factors included personal circumstances, a major funding crisis that is impacting many universities in the UK, and a degree of resulting organizational turbulence. By the end of the project, a new team at the University was in place and delivered a successful final phase of testing in WP2, but before that could happen, a number of issues impacted the project:

- Both laboratories were the subject of two closures and a further testing pause related to safety, which might have been avoided with more staff continuity; no-one came to any harm, but with machinery and explosive fuels, safety risks cannot be taken. The resulting delays add to around 5-6 months.
- An issue with the multi-cylinder dynamometer arose before the start of HYDRATE, which again might have been avoided with more continuity; this was put right, but the disruption of extra effort and lost time impacted the project's early stages.

A number of senior-level meetings between Dolphin and the University led to new ways of working and a new team being put in place, which successfully delivered the test data of WP2; however, the result was a 10 month extension to an 11-month project, with these issues adding to the technical and supply chain ones described above.

7.5 Political Challenges

This section presents the view of the study authors and does not necessarily reflect the views of His Majesty's Government or DESNZ.

It is worth noting that HYDRATE was attempting to develop an innovative (and clean) Hydrogen ICE at a time when internal combustion was not viewed favourably as a future solution. Government policy is that all cars and vans sold from 2035 should have zero tailpipe emissions, often interpreted as an "ICE ban". There was stronger support for the ICE with sustainable fuels in the off-highway sector, where its proven ruggedness gives it an advantage against the fuel cell, while faster refuelling makes it workable in circumstances where batteries are not; Government policy does not set a "zero at tailpipe" requirement for de-carbonising Non Road Mobile Machinery.

However, the market for this size of engine is around 50% on highway, 50% off (section 6), so the on-highway market has a significant role to play in establishing a low cost base. The European Union is now proposing to accept the Hydrogen ICE as a zero-carbon solution for trucks [6]. The UK has historically taken a different approach for on-highway, with a focus on zero tailpipe emissions being driven by historic health effects from poor air quality. Going forward, a pragmatic approach would be to balance the rising risk to life from climate change against the diminishing risk from local air quality. A Hydrogen ICE can be adopted quickly and cheaply, leading to faster mitigation of climate change and more money to spend on further mitigations; while its residual air quality emissions (assumed to be properly controlled at Euro 6 or 7 standard, including real-world and through-life requirements) are of diminishing concern for human health versus other hazards [13,14].

The risk of an "ICE ban" was identified as high from the outset. Throughout and after the project, partners engaged in informed debate on this topic, including:

- Supporting the Advanced Propulsion Centre's technology roadmap updates
- Engagement with ZEMO's Heavy Duty working group
- Membership of a DESNZ working group on H2-ICE
- Promoting H2-ICE potential at conferences

As a result of this activity, it is the view of the study authors there is already now a shift of perception towards embracing a clean H2-ICE as part of a net-zero landscape.

7.6 Successes

Lessons can also be learned from what did work, as well as what did not:

- The engines themselves behaved well as far as it was possible to evaluate (single-cylinder extensively tested, multi-cylinder started), with previous known issues appearing to have been addressed
- Once the new Brighton team were in place, and with reinforced co-operation from Dolphin, the final phase of laboratory testing went well, with few failures, showing what can be achieved with de-bugged equipment and a motivated team
- The desk-based studies of WP4&5 delivered on-time, and added a great deal of insight to direct the future development of the technology
- The development of Hydrogen ICE skills within Dolphin led to the team being able to support their parent company in other, nearer-to-market 4-stroke Hydrogen ICE technology
- Finally but most importantly, Hydrogen has proven itself as a good RSCE fuel

7.7 Conclusions

Any high risk R&D leads to learning; as a result, the partnership is wiser after the project than before it. High level learning might be summarized thus:

- It is not possible to deliver good quality R&D both quickly and cheaply; closer attention to priorities at the planning stage would have tempered ambitions
- Co-developing a technology and the infrastructure or tools to test it, is too risky and should be avoided
- The importance of key people, and the increase of risk if they leave, should not be underestimated
- Sound data and reasoning should underpin any decision in technology or in politics

8. Conclusions & Recommendations

The HYDRATE project set out to develop the first Hydrogen-fuelled variant of the Recuperated Split Cycle Engine, and validate its use in the construction sector. HYDRATE experienced some significant delivery challenges, resulting in a 10-month extension and the curtailment of multi-cylinder engine testing. Despite these challenges, some very positive conclusions emerged, signalling that the technology has great promise in Construction and other sectors:

1. A single-cylinder engine was built and run on Hydrogen, demonstrating stable, controllable combustion over a range of operating conditions. The intended Dual Fuel operation is workable using the Diesel pilot either before or after Hydrogen injection, increasing flexibility for future calibration. The fuel can be made to auto-ignite, but does not do so in an unstable way as had been seen with Diesel. Hydrogen is confirmed as a fuel well suited to the Recuperated Split Cycle engine.
2. A multi-cylinder engine was built, commissioned and fired on its Diesel pilot fuel. Laboratory-related issues prevented testing on Hydrogen, but this work, plus a preceding test program with a Diesel version, provide very good confidence that the engine would have worked.
3. In the absence of further multi-cylinder testing, a 1-d performance simulation model was built to represent the engine; it was validated from the single cylinder's combustion characteristics, and prior Diesel work for the rest of the system. While this modelling highlighted that further development was needed to meet efficiency targets, it led to a roadmap whereby an efficiency of 50%BTE could be achieved with existing hardware with less than a year of development; a larger unit at 350-400kW could probably be developed to the 55%BTE "headline", but this is too large for most construction equipment.
4. Wheeled loaders, tracked excavators and large generators were identified as suitable construction-sector applications. The prototype developed, with limited modification, was shown to be package-feasible in a generator-set and a wheeled loader. Packaging solutions for fuel tanks, the most difficult part of the system, were developed.
5. The construction sector has all the right ingredients for adoption of hydrogen as an energy vector. There is a political will to de-carbonise construction, sites are captive, and the high value of what is being constructed permits some degree of tolerance of expensive fuel in the early days.
6. In a construction environment, the RSCE is strongly financially competitive against electrification, fuel cells and more conventional Hydrogen ICEs. While all are likely to co-exist, it clearly offers a promising route, especially for larger machinery where its efficiency offers most value against a higher purchase price. With the 50%BTE projected by the Roadmap once

the multi-cylinder runs, payback could be less than a year versus any other Hydrogen solution, depending on fuel cost.

7. A route to market is proposed, whereby the Hydrogen RSCE follows simpler Hydrogen-ICE technologies into the market; a Natural Gas/Biomethane version offers a further early market option, as that fuel is much more widely available.

The following are recommended:

1. Engine development should continue, aiming to implement the Roadmap described here in Section 3 and achieve 50%BTE at 180kW within 2024
2. Investment of time in addressing issues identified with the laboratories, their hydrogen supply, instrumentation and the leaking inlet valve issue on the engine, is a necessary precursor to the above
3. Field trials of Hydrogen-fuelled machinery should be supported, developing a common base of fuel infrastructure and user knowledge to cover standard ICEs, fuel cells, the Hydrogen RSCE and any other new technology
4. A gen-set is a suitable first application for the Hydrogen RSCE, and should be pursued when opportunity permits; meanwhile, more complex machinery can be demonstrated with simpler H2-ICEs and upgraded to RSCE later
5. The model of a single RDR Phase 1, followed by a single Phase 2 trial, does not work for higher risk technology; more competitions should be offered to fully promote all the opportunities offered by the replacement of red diesel
6. Co-operation between sectors, for example Construction, Agriculture, Marine and Trucking, should be encouraged to maximise use of knowledge and speed of uptake

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