STEAMOLOGY ®
zero emission power solutions

Red Diesel Replacement Phase 1
Zero Emission Red Diesel Replacement

BEIS Project

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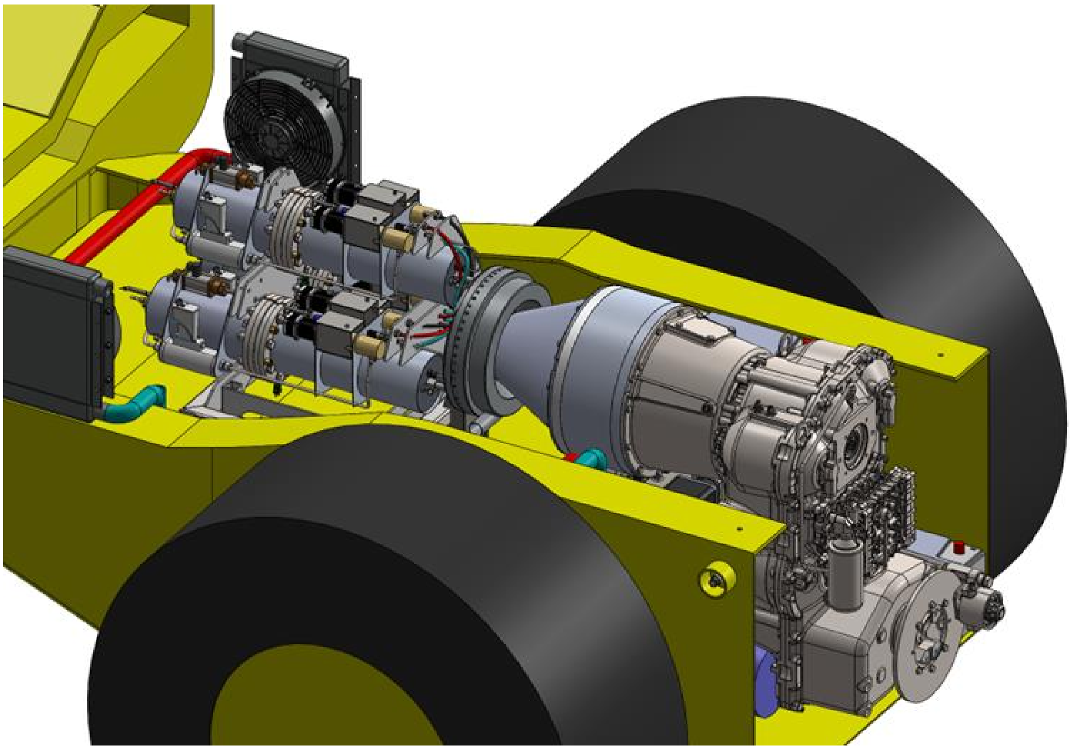
Company name: Steamology Motion Ltd
Phase 1
Period 23/03/2022 to 24/02/2023



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1.0 Project Summary

This project has set out to investigate the feasibility of replacing a diesel engine in a Non-Road Mobile Machinery (NRMM) vehicle used within the construction, mining and quarrying industries with the Steamology turbine engine. The project was split across 5 Work Packages during Phase 1:

- WP1 System Front End Engineering Design (FEED) Study
- WP2 Component Design & Analysis
- WP3 Component Test and Development
- WP4 System Compliance
- WP5 Business & Phase 2 Planning

This report summarises the Phase 1 project and focusses on the concept of packaging the turbine engine in to a JCB 457 wheel loader, or a similar construction vehicle within its class, such as the CAT 950GC. Build and demonstration in Red Diesel Replacement (RDR) would take place in a Phase 2 project.

This report presents the findings of the Phase 1 project and highlights the key benefits of this particular technology as well as considers the potential challenges for RDR in Phase 2 and beyond.

The technical, commercial and certification findings from Phase 1 will be used to deliver a long term
integration plan to re-power existing diesel assets as well as being used to approach OEMs with a view to new build vehicles in the construction, mining and quarrying sectors. In addition, Steamology will be able to demonstrate and present possible ‘spinout’ applications to decarbonise other diesel fleets in road freight, passenger and freight rail and marine industries as a truly multi-modal zero emissions solution.

2.0 Company Overview

Steamology zero emission energy solutions address three markets with common technology:

- Zero emission steam for industrial applications
- Zero emission diesel engine replacement power 200 kW to Megawatt scale, mechanical, electrical, hybrid drivetrains for trains, trucks, ships transport or static applications
- Renewable Energy (RE) storage and power generation

Steamology, founded to commercially exploit the technology legacy of a successful landspeed world record attempt, to explore the potential of clean green renewable hydrogen steam.

Steamology deliver scalable and modular solutions for industrial steam heat and power, embracing the hydrogen economy, eliminating emissions, replacing fossil fuels and fossil fuel engines.

Steamology has spent six years developing innovative hydrogen-based zero-emission steam systems for steam, heat and power turbines. The company's technical team have been working together for ten years on superheated steam engineering. Steamology has prioritised developing clean, energy-dense hydrogen and oxygen fuelled steam power for commercial applications. The closed steam system is emission free, combustion of hydrogen and oxygen in our steam generators creates high energy steam and produces zero carbon, NOx, sulphur or particulate emissions in a repeatable cycle. Steam is used to drive an impulse turbine connected to mechanical and electrical drive applications. Exhausted steam is recycled to the steam generator. Steamology high torque turbines are compact, robust, reliable with few moving parts, suitable for static and transport applications.

Compared to hydrogen fuel cells and battery solutions we have three distinct advantages for high power applications in the 200kW -1MW range:

More energy dense
Fuel cell and batteries have a linear increase in volume occupied as the power increase.
Steamology only require the addition of compact 100kW generators
Longer life
Steamology solutions have no charging loses and with few moving parts extended service and component life with ‘spanner friendly’ infield maintenance
More cost effective
The same turbine is used to 1MW, high-power installations are more cost competitive to diesel engines than fuel cells or battery

2.1 Technology Summary

Steamology has been developing an innovative hydrogen based zero emission steam generator for powering turbine applications. For over a decade the technical team have been working with superheated steam turbine engineering. Following a successful world land speed record project for a steam turbine driven car the priority has been the development of an energy dense hydrogen and oxygen fuelled power unit for commercial applications.

The Steamology Water to Water (W2W) power system can be applied as a zero emission 'drop-in' diesel engine replacement 200kW to MW scale high torque steam turbine. The turbine can be connected to a conventional mechanical gearbox transmission, an electrical generator, a hybrid or hydraulic drive. Regenerative braking energy can also be stored if the increased complexity and component cost can be justified.

These drivetrains are suitable for construction & mining and quarrying sectors as well as road, rail and marine freight transport applications. Steamology have been developing concepts for the deployment of zero emission high torque turbines operating in closed loop for each of these sectors.
The W2W patent approved steam generator is fuelled by hydrogen and oxygen supplied from compressed gas storage. The hydrogen and oxygen combustion takes place inside the steam generator at high temperatures ~2500°C and combined with a water spray produces superheated steam at 40 bar pressure at 400°C in a compact controlled environment.

The high pressure, high temperature steam is passed through a DeLaval nozzle that exchanges the temperature and pressure for velocity. The two-stage impulse 'Curtis Wheel' turbine is driven by the kinetic energy of the steam at ~1000 m/s (three times the speed of sound) and relatively cold gas at 110°C. The turbine is made as a single component and rotates relatively slowly ~9,000 rpm in a relatively cold gas. This means that standard materials can be used and the component has a long service life with low maintenance.

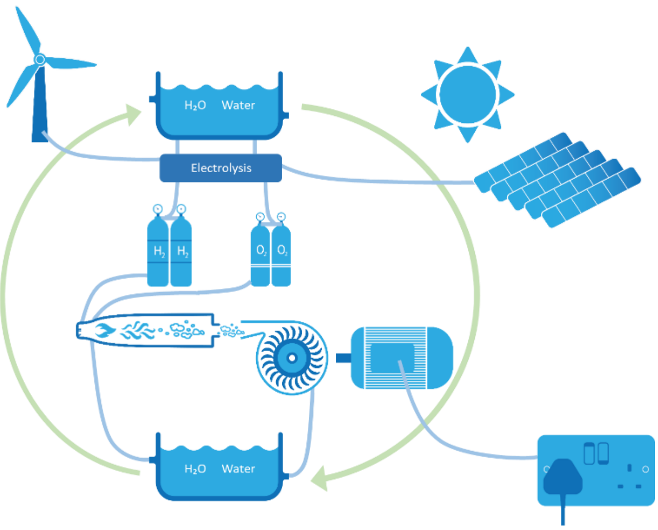

Figure 1 - Steamology W2W Closed Loop System

Steamology high torque turbines are compact, robust and reliable with few moving parts, suitable for transport and static applications, particularly in the power range up to 1MW. The Steamology zero emission hydrogen steam turbine drivetrains are believed to be genuinely novel. Use of hydrogen and oxygen as fuel generating steam, whose temperature and pressure are controlled to produce power and high torque response, displays innovation in approach, technology and methodology.

3.0 WP1 System FEED Study

3.1 Objectives

This work package focused on the specification of the engine and the sub-systems and the design of a Phase 2 demonstrator vehicle. The work package addresses the component and system design of a Steamology closed loop and high torque turbine engine as well as the fuel storage and transmission.

The deliverables:

1.1 Initial design layout for red diesel engine power train layout
1.2 Initial packaging of the power unit and ancillaries CAD drawings
1.3 Concept CAD of the power unit and ancillaries, packaged for installation
1.4 General Arrangement drawings of proposed Phase2 power unit
1.5 Specification of power unit detailing torque, power life cycle maintenance

3.2 Outputs

The deliverables are laid out in incremental steps resulting in the final concept design of the RDR Phase 2 demonstrator power unit.

Steamology has and continues to develop connections with a number of largescale companies in the construction, quarrying and mining industries such as Costain, Farrans, Gallaghers and Tier 1 supply chain for example, ZF Transmissions, Parker Hannifin and Luxfur gas cylinders.

Working with stakeholders, the design team shortlisted red diesel-powered assets used by the construction, quarrying and mining industry as well as a broad commercial addressable market.

The vehicle selected for the demonstrator concept design is a JCB 457 wheel loader. This vehicle and similar vehicles within its class, such as the CAT 950GC, are commonly used in an industry with a market valued at 5 million USD.

Figure 2 - Typical Wheel Loader Class Construction Vehicles

3.3 Concept Design

The concept design work involved the specification and mechanical integration of the engine with all ancillary equipment and fuel storage to enable operational demonstration of a NRMM vehicle for RDR Phase 2.

The steam turbine engine doesn't experience traditional issues relating to Noise Vibration and Harshness (NVH) factors that diesel internal combustion engines experience. Therefore, the working environment for the operator is dramatically enhanced with low noise and no particulates, NOX or air pollution. We have redeployed some of the space used for the diesel engine ancillaries such as air filtration, exhaust gas treatment, silencing and diesel fuel tank. The Steamology turbine engine operates in closed loop. The product of combusting hydrogen and oxygen gas fuel is water. This adds to the water volume being used in the work flow. The excess water is suitable for safely discarding or suitable for returning as purified water for electrolysis. Closed loop operation means that no air filtration or exhaust treatment required.

Alternative technologies, such as hydrogen in ICE or fuel cell technologies do not return the water. Therefore, the water used to generate green hydrogen is single use and requires significant water abstraction, unlike the Steamology engine.

To reduce the complexity and engineering risk for the demonstrator all pumps are electrically driven. Production units will utilise mechanical water and lubrication pumps driven by the turbine.

Industry standard Type 3 hydrogen and oxygen cylinders have been specified for the demonstrator. Luxfur are the selected supplier due to their experience in transport applications with hydrogen and oxygen cylinders. A limited number of tank sizes are currently available so these demonstration cylinders are specified on price and lead time rather than optimised packaging. Cylinders can be supplied with all the appropriate hardware for fill, discharge and pressure regulation.

The condenser system, enabling closed loop running, has been a key part of the Phase 1 development. This has informed the packaging and development of the Phase 2 demonstrator.

Importantly, Steamology has the inhouse skills, experience and capacity to develop all of its own controlling hardware and software. Many electro mechanical projects fail due to a lack of understanding of the electrical and mechanical control requirements, characteristics and specifications. Frequently, subcontract partnerships are required to bring together these two essential skill-sets in the delivery of engine developments. Steamology is fortunate to have the mechanical and electrical team sufficient for the full development of an industry leading control system.

Figure 3 and Figure 4 show the outline mechanical assembly design for the Phase 2 demonstrator.

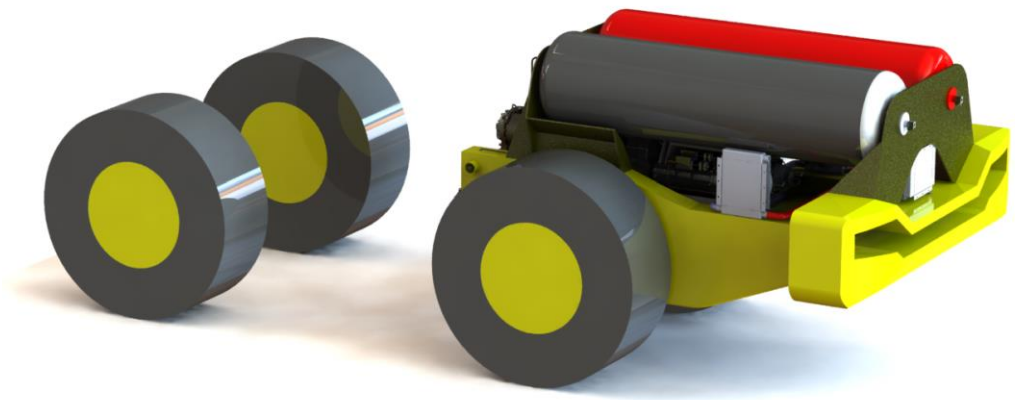

Figure 3 - 3D Rendered View of Phase 2 Concept Design

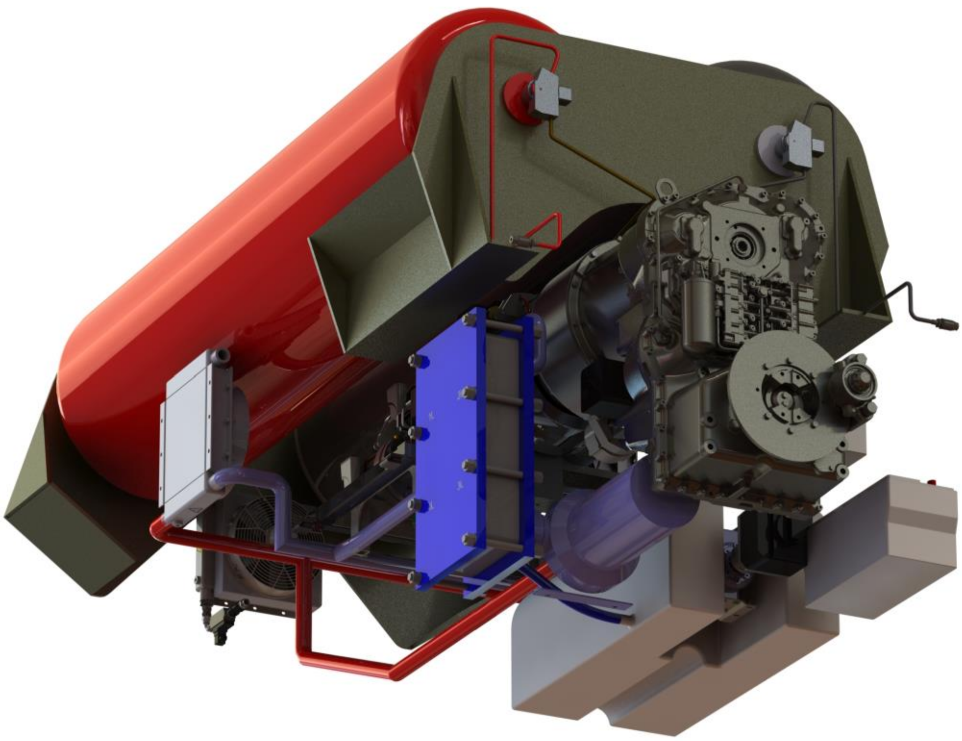

Figure 4 - 3D Rendered View of Phase 2 Concept Design

3.3.1 Drive Train

- The turbine has a top speed of: 15000 RPM
- The reduction gearbox ratio is 6:1
- Standard mechanical connections have been selected for serviceability and testing development
- The existing ZF gearbox and existing drive train will be utilised for the Phase 2 demonstrator

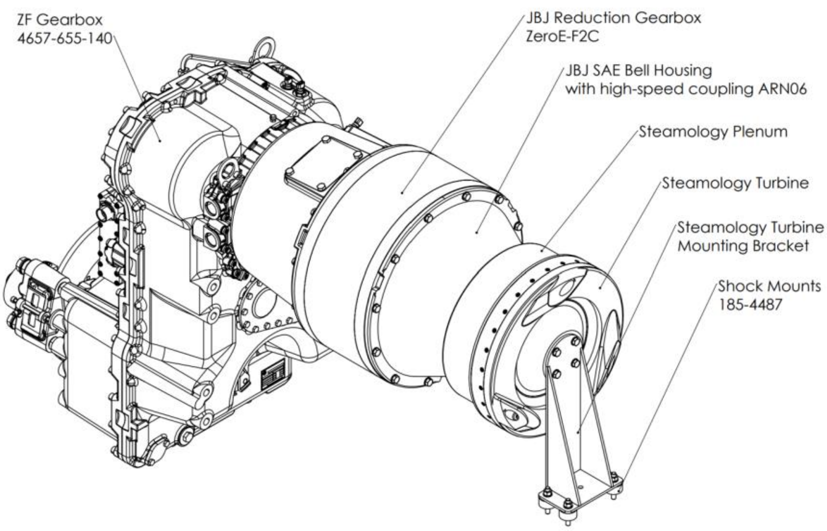

Figure 5 Phase 2 Demonstrator Concept design – Drive Train

3.3.2 Steam Generator

- The steam generators have no moving components
- Each steam generator and associated valving are modular
- Component and subassembly section has been informed by readiness for certification requirements, affordability, availability and proven robustness

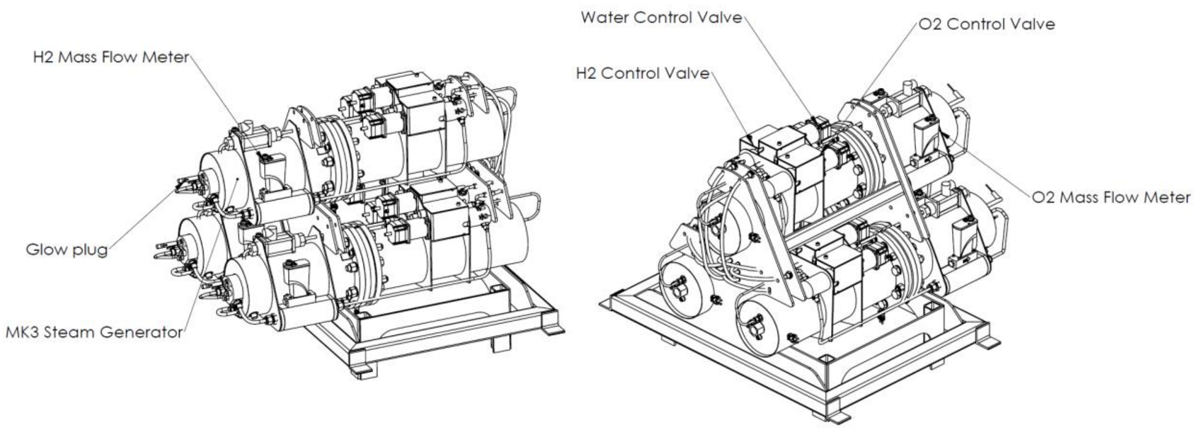

Figure 6 - Phase 2 Demonstrator Concept design – Steam Generation

3.3.3 Water System

- Nominal water tank 100 L for filter water is required
- Fixed displacement water pump driven by 24V DC motor

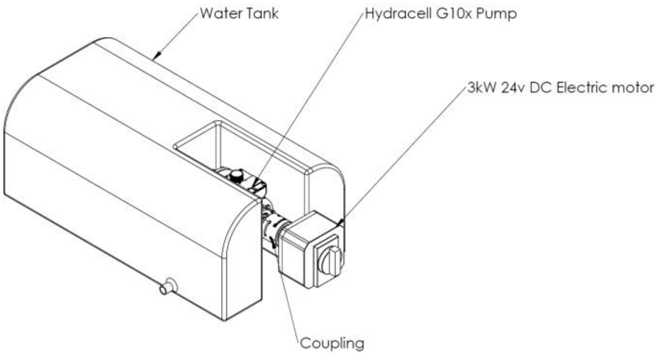

Figure 7 - Phase 2 Demonstrator Concept design –Water System

3.3.4 Fuel Storage

- Industry standard Type 3 cylinders (composite wrapped aluminium liner)
- Concept has used the recommended mounting procedure
- WEM refill ports specified

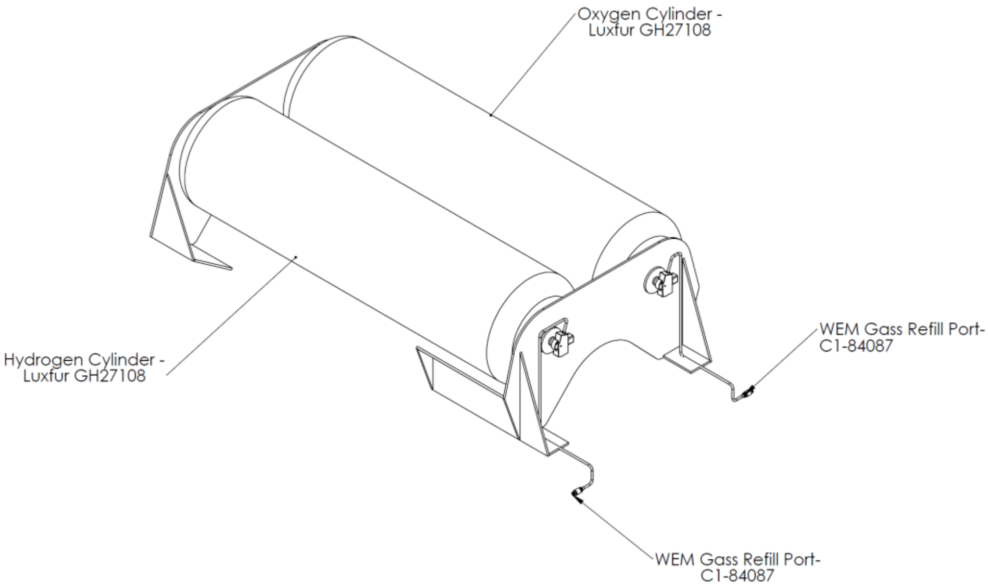

Figure 8 - Phase 2 Demonstrator Concept design – Fuel Storage

3.3.5 Steam Condenser System

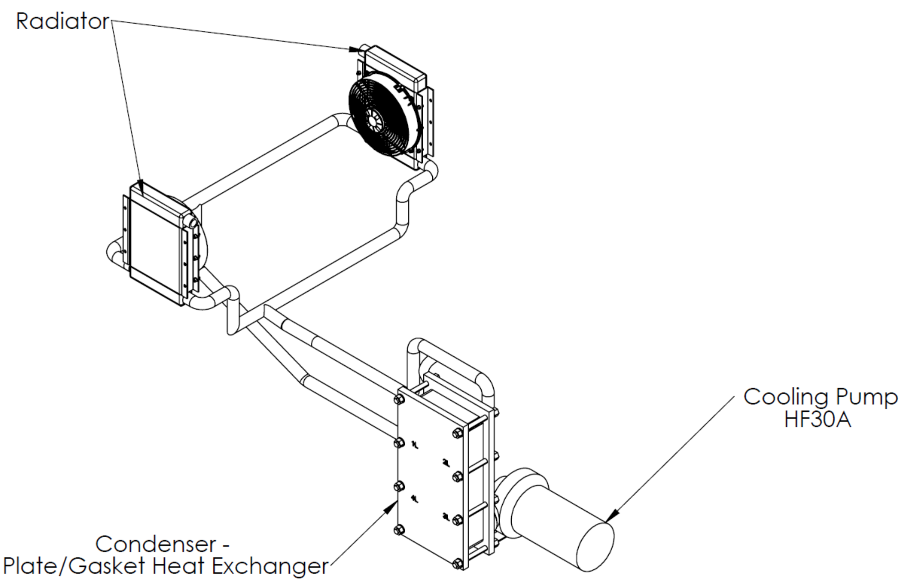

Figure 9 - Phase 2 Demonstrator Concept design – Steam Condensing System

3.3.6 Electrical/Control System

- Standard batteries selected for startup
- Custom designed ruggedised IP rated CAN compatible Engine Control Unit (ECU)

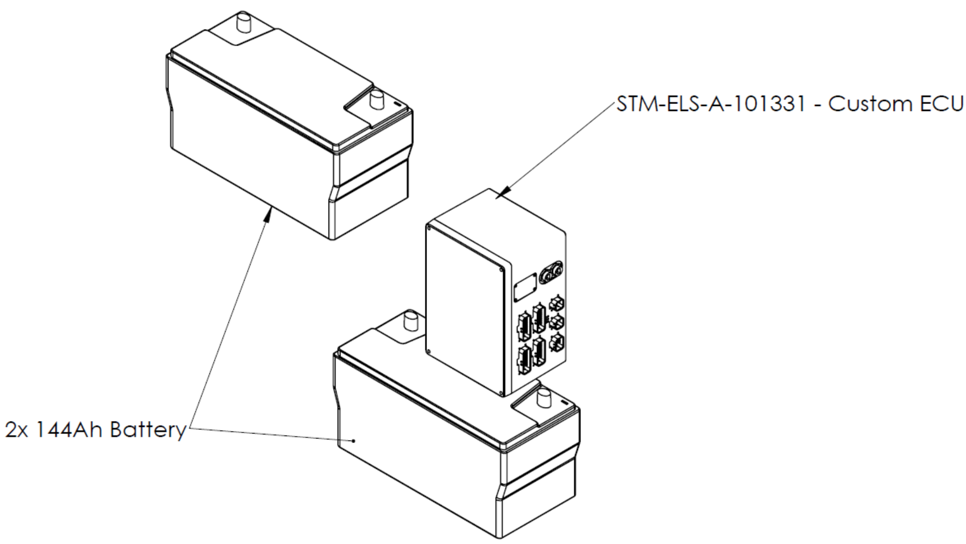

Figure 10 - Phase 2 Demonstrator Concept design –Electrical/Control System

3.4 Power Unit Specification

Multiple manufactures, such as CAT and JCB, manufacture wheel loader vehicle addressing the approximate 200kW power range. Operators run these machines in a wide range of environments and duty cycles.

Representative data from Costain for a CAT 950GC wheel loader has been used to check the Steamology bunkering data and it has been concluded that it is reasonable to expect a demonstrator vehicle as outlined in schematics will deliver a representative daily duty cycle with daily refuelling.

The Steamology turbine engine was specified to match the output of the existing diesel engine so the vehicle demands could be met and the existing vehicle transmission could be used. This also minimises the impact of the engine swap on the vehicle and therefore helps to de-risk the demonstrator vehicle. However, this does not optimise the drive train.

Table 1 shows the engine characteristics of the existing engine next to the output of the Steamology turbine engine that has been designed.

	JCB 457	**Steamology Demonstrator**
Engine	6.7l Cummins	Steamology Turbine
Transmission	ZF 5 speed Ergopower 5WG210	ZF 5 speed Ergopower 5WG210 with 6:1 transfer gearbox
Peak Power	210kW	210kW
Peak Torque	1350Nm	1400Nm (after transfer gearbox)
Speed Range	800-2000 rpm	800-2500 (after transfer gearbox)

Table 1 - Engine Specification

Duty cycle data of a CAT 950 GC wheel loader was provided by Costain. The CAT950 GC is a very similar vehicle to the JCB 457 and has a very similar duty cycle. Taking the data provided we can calculate the amount of hydrogen needed to fulfil the duty cycle daily requirement. This includes the idle time of the diesel engine.

The hydrogen cylinder specified for the Phase 2 demonstrator holds 19.5kg (16kg usable to 50Bar). The oxygen cylinder can be pressurised to 200bar and can hold 228kg (173 to 50Bar). The mass ratio is 8:1 and therefore the hydrogen cylinder is the limiting factor. Table 2 below shows how many estimated hours the demonstrator would be able to operate, assuming the same operating conditions as the CAT 950 GC.

Vehicle	Operating Hrs	Idling Hrs	Total Hrs	Utilisation %	Fuel L	CO2 Emmissions t	Fuel L/hr	Fuel Per Day L	Fuel Per Day kg	Energy per day MJ	kg of H2 per day	Demonstrator operating hours
CAT 950 GC Loading Shovel	72:54:00	57:06:00	130:00:00	56.1	1289	3.40	9.92	79.3	66.6	3031.7	25.3	5.1
CAT 950 GC Loading Shovel	96:47:00	185:45:00	282:32:00	34.3	2206	5.82	7.82	62.6	52.6	2391.9	19.9	6.4
CAT 950 GC Loading Shovel	160:47:00	284:18:00	445:05:00	36.1	3075	8.12	6.91	55.3	46.4	2112.8	17.6	7.3
DOOSAN DL380-7 Loading Shovel	24:11:00	14:11:00	38:22:00	63.0	353	0.93	9.29	74.3	62.4	2840.3	23.7	5.4

Table 2 - Demonstrator Fuel and Duty Calculation

It is evident that for a significant portion of the day the diesel engine is idling therefore using fuel, creating noise and air pollution. This also accumulates service hours without delivering useful work. Comparatively, the Steamology turbine will not require significant idling. At this stage there is a lack of detail on operational service and duty cycles but Steamology have sufficient confidence to say that the standard 20kg fuel storage cylinders that are currently available and specified will deliver useful daily testing.

3.5 Service & Maintenance

Due to the vast reduction in components and moving parts, the scale of servicing the engine and required frequency of service is reduced. Crucially, the tools and technical skills required are the same.

JCB457 Service Procedure	Light Service	Heavy Service
Replace enginer air filter		■
Change engine oil filter	■	
Replace crankcase ventilation (CCV) Filter		■
Replace fuel filter	■	
Replace serpentine dive belt		■
Flush engine cooling system		■
Replace automatic transmission fluid & filter	■	
Replace manual transmisson fluid	■	
Replace case fluid	■	
Replace front differential fluid	■	
Replace rear differential fluid		■
Check & adjust valve lash		■

Steamology Engine Service Procedure	Light Service	Heavy Service
Replace water filter	■	
Replace oil filter	■	
Replace coolant		■
Sensor recalibration	■	
Sensor replacment		■
Turbine Bearing replacment (30,000 hrs)		■

Table 3 - Service Requirements

3.6 Further Development

The turbine's characteristics offer multiple opportunities for increasing efficiency and effectiveness of power delivery in future vehicles beyond RDR Phase 2, when an opportunity is available to design from first principles. Examples of these opportunities are:

Low speed torque

The Steamology ø365 turbine will rotate at 800rpm (at interim gearbox) to provide peak torque, whereas the Cummins diesel engine will rotate at 1500rpm to achieve peak torque. The availability of rapid high levels or torque means that some of the components in the conventional diesel engine driveline, such as the torque converter and multiple reduction gears, will become redundant.

Hydraulic

Turbine power delivery is suitable for a large hydraulic pump and many vehicles in the construction sector that are similar to wheel loaders and operate with primary hydraulic power, driving the wheels and ancillaries. The turbine power characteristics shown in Figure 22 can match the demands of a hydraulic pump.

Electric

The turbine speeds are well suited to modern axial flux electrical generators, for example the Danfoss Editron range. An all-electric drive can be achieved or ancillary electrical power can be generated for vehicle hotel loads. Therefore, decarbonisation of diesel electric vehicles is in scope. Steamology has rail and marine projects exploring electric drivetrains.

Mechanical

Steamology impulse turbines lend themselves to mechanical drivetrains. Hybridisation of these mature technologies will also be explored beyond Phase 2

The current Phase 2 design maintains the torque converter, ZF gearbox and ancillaries. This has been done for simplicity and to reduce the risks to the programme. Future development will remove the torque converter and simplify the gearbox. This represents a more ambitious and longer-term engineering development programme.

4.0 WP2 Component Design & Analysis

4.1 Objectives

This work package focused on the engineering analysis, design and specification of components and systems used in Phase 1.

Four Deliverables were laid out across the project:

2.1 Computational Fluid Dynamics simulations
2.2 Steam generator design general arrangement assembly
2.3 Condenser design general arrangement assembly
2.4 Electronic controller PCB assemblies

Design iterations of the steam generators and the condensing system were developed using Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) studies.

The design studies considered the compliance and certification requirements for pressure vessels operating in the NRMM, construction, quarrying, mining environment. The CFD study covered gas flow, water nozzles and steam nozzles.

Following the design and development stage, the steam generator components, condenser system and subassemblies were designed, purchased and manufactured.

The electronic controller hardware and software was developed during the work package. The PCB design was updated to increase compatibility to the operational environment of NRMM equipment. Software was also developed to incorporate the ability to communicate with CAN bus in preparation for integration into a machinery system.

4.2 Outputs

4.2.1 CFD Simulations

Water Nozzle

The system needs to reliably produce a water pressure and flow rate to ensure the steam generator does not overheat and also provides enough water to meet the steam mass flow requirements.

Multiple nozzle hole patterns were run through the CFD model and then validated in the test cell. This has produced a look-up table that allows the selection of an appropriate water nozzle based on the pressure and flow requirements. This same process will be applied to any future iteration on the water nozzle design.

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Total Back Pressure (Bar)	Number of Holes														
Mass Flow Rate (kg/min)	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
3	25.1318	24.9868	14.5848	13.3943	10.372	7.9773	6.4555	7.5917	6.2551	4.8067	3.6492	3.3396	3.4267	2.866	2.6421
4	0	0	25.9193	23.8149	18.4331	14.1818	11.4721	13.5216	11.1404	8.5365	6.4883	5.9327	6.084	5.0922	4.6943
5	0	0	0	0	28.8018	22.1571	17.9209	21.1387	17.4208	13.3307	10.1395	9.2696	9.4926	7.9555	7.3358
6	0	0	0	0	0	0	25.7996	30.4716	25.1131	19.1992	14.5984	13.3459	13.6622	11.4513	10.5663
7	0	0	0	0	0	0	0	41.46	34.1787	26.1332	19.8534	18.1684	18.583	15.582	14.3837
8	0	0	0	0	0	0	0	54.1773	44.6282	34.1324	25.9387	23.7376	24.2799	20.3441	18.7847
9	0	0	0	0	0	0	0	68.5492	56.477	43.1663	32.8108	30.029	30.7157	25.7438	23.7537
10	0	0	0	0	0	0	0	84.6352	69.7581	53.3007	40.4964	37.0665	37.916	31.7725	29.3316

Table 4 - Water Nozzle lookup Table

Steam Nozzle

The De Laval nozzle used as the turbine steam inlet works to increase the velocity of the steam to >1000m/s. In doing so the pressure and temperature of the steam is reduced.

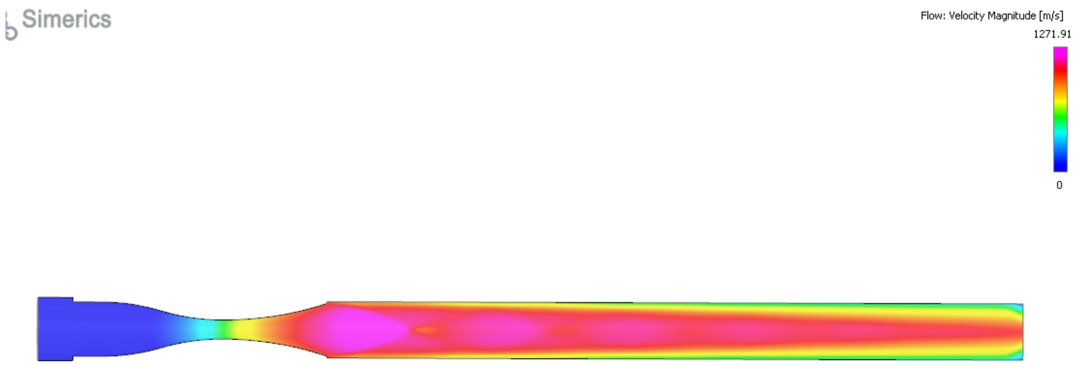

Figure 11 - Example of steam flow through a De Laval Nozzle CFD simulation

The velocity of the steam on the turbine is an important aspect to running the turbine efficiently and increasing mass flow which will increase the output power. The CFD model has been created and run to produce a look-up table of nozzle sizes to enable nozzle selection based on the running conditions.

Velocity Matrix

Max Velocity (m/s)		Mass Flow Rate (kg/min)								
		3	3.5	4	4.5	5	5.5	6	6.5	7
Throat Diameter (mm)	4.4	1275.04	1307	1335.24	1360.7	1383.66	1404.67	1424.17	1442.37	1459.37
	4.6	1252.7	1284.16	1312.06	1336.95	1359.48	1380.23	1399.47	1417.32	1434
	4.8	1231.38	1262.5	1289.85	1314.27	1336.58	1357.05	1375.92	1393.45	1409.83
	5	1210.99	1241.66	1268.51	1292.72	1314.7	1334.79	1353.33	1370.56	1386.66
	5.2	1196.46	1225.62	1251.46	1274.7	1295.85	1315.29	1333.28	1350.06	1365.77
	5.4	1171.51	1201.13	1227.37	1250.75	1271.91	1291.36	1309.46	1326.24	1341.9
	5.6	1159.61	1187.91	1212.98	1235.54	1256.06	1274.92	1292.38	1308.66	1323.91

Table 5 - Steam Nozzle Lookup Table

Water Transfer Hub

The water transfer hub is part of the steam generator that channels the flow of the water jacket to the central spray nozzle. The part has 3D printed channels to ensure efficient flow and heat transfer. A CFD model was created to analyse the design. Picture A shows how one of the initial designs had area of "dead water". This would result in these areas heating up and causing the hardware to overheat and potentially fail. The final design shown in Picture B shows even flow around the channels. This has since been run in the test cell with no issues.

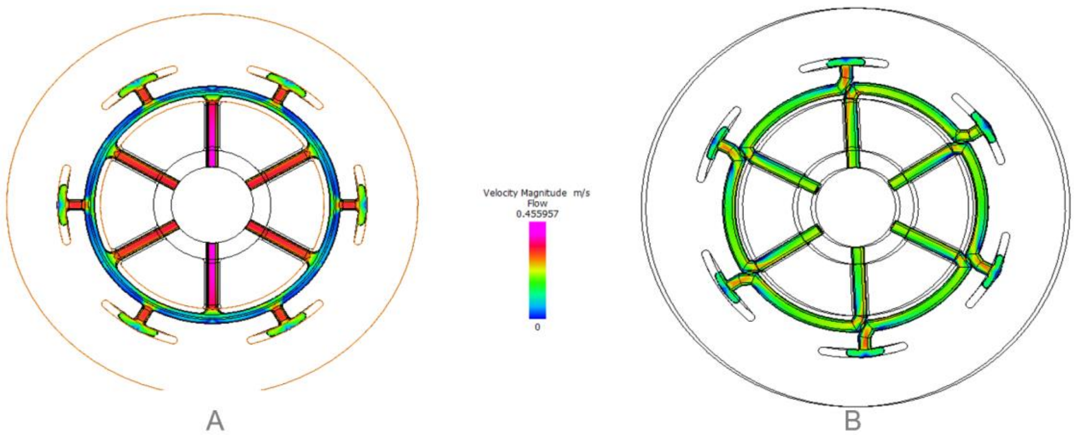

Figure 12 - Flow through Water Transfer Hub

4.2.2 Steam Generator General Arrangement

The steam generator general assembly has been developed to include all valving for the hydrogen, oxygen and water systems downstream of the fuel tanks.

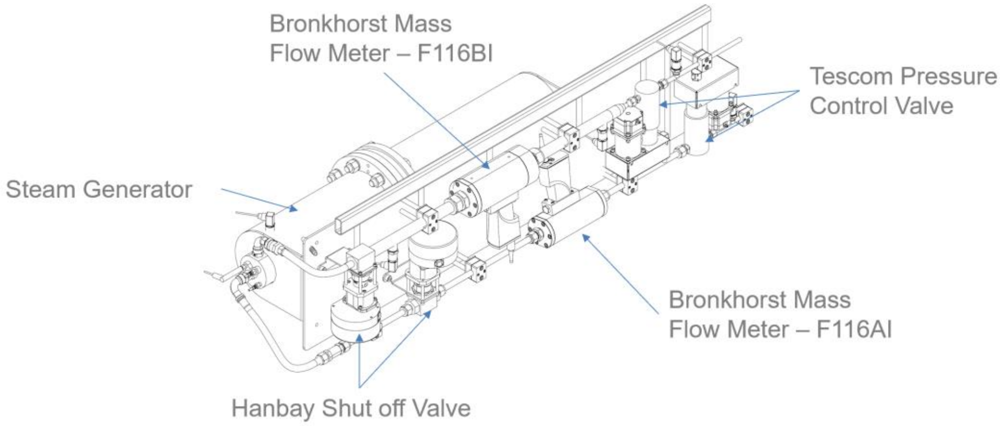

Figure 13 - Steam Generator General Arrangement

One of the key challenges in the supply chain is finding components suitable for the system that are ATEX certified. Steamology are aiming to have all valving, instrumentation and fittings certifiable to ATEX Zone 2.

4.2.3 Condenser General Arrangement

The exhaust from the turbine is low temperature and low-pressure steam. The addition of a condenser closes the loop on the system and allows the condensed steam to be reused in the water system. Therefore, sensible heat is recovered. Recovering the sensible heat in the system provides an improvement in efficiency and fuel economy. Hot condensate water can be returned to the steam generator at 80-90°C rather than ambient temperatures resulting in a fuel saving.

Extra water generated from the combustion of the gases is very pure and can be fed back in to electrolysis with no treatment required. This is a very important feature of the system in areas where water for electrolysis is difficult to source.

Steamology engaged with suppliers to understand the different types of condensing systems available, such as steam to air and steam to water.

Condenser Specification:

- Steam Mass Flow: 60kg/min
- Steam Temperature: 115°C

Steamology chose to go with a steam to water system as this has the smallest packaging footprint and is more flexible for testing and development.

For a steam to water condenser system the key component is the steam to water heat exchanger. The two main types in the industry are 'shell and tube' and 'plate and gasket' heat exchangers.

The schematic below (Figure 14) shows how the system is configured:

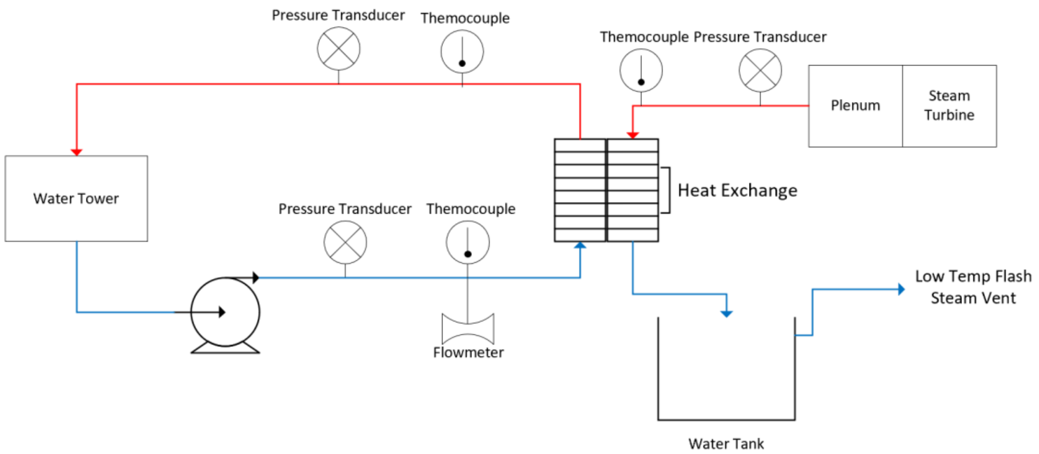

Figure 14 - Condenser system Schematic

Due to packaging and cost a plate and gasket heat exchanger was specified and purchased from Kelvion.

The heat exchanger heat load capacity can be increased or decreased by the addition or removal of plates. This allows the condenser to be matched to different load profiles or duty cycles.

The plate and gasket heat exchanger cools and condenses the steam by passing a coolant (water) thought one side and steam through the other side.
As shown in Figure 14 the sensors were specified and fitted. The instrumentation specified enabled Steamology to calculate the heat load being absorbed at different running states. This data will help to optimise a vehicle condenser system design. Additionally, the condenser data will help indicate issues with the turbine. For example, if the steam going through the condenser system produces a higher heat load this can indicate a performance reduction in the turbine/ nozzle.

Figure 15 - Condenser System – Plenum

Figure 16 - Condenser system – Kelvion Plate & Gasket Heat exchanger and Nixon Flowmeter

Figure 17 - Condenser system- High flow coolant Pump

4.2.4 Controller

Steamology has the inhouse capability for the development of not only the software but the hardware used in the ECU (Engine Control Unit). The functionality and capability of the Steamology ECU has been upgraded during RDR Phase 1. The images below show the latest specification of hardware which has consolidated the design in to one unit that has been packaged with suitable IP protection for a demonstrator programme.

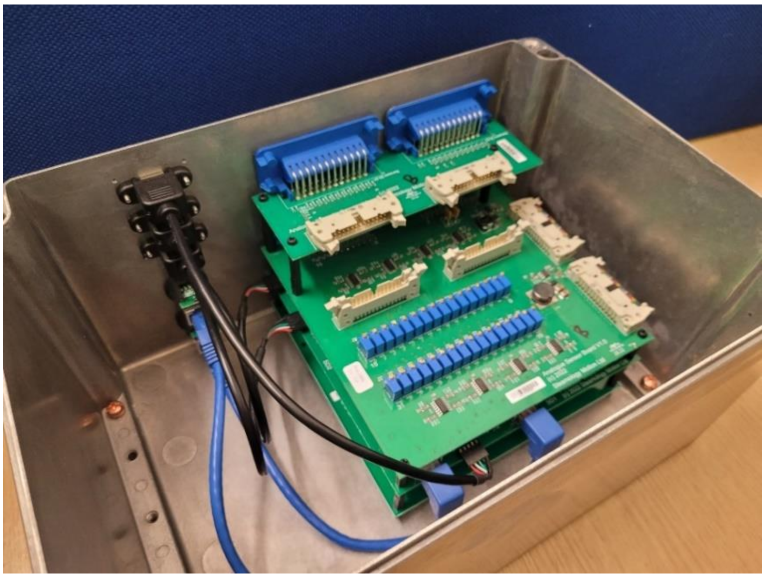

Figure 18 - Steamology ECU

The PCB was designed to increase compatibility of the system for the operational environment of NRMM equipment. Software was developed to incorporated the ability to communicate with CAN bus in preparation for integration into a machinery system. Initial NRMM demonstrators will use an existing OEM donor vehicle. The CAN bus protocols facilitates the retrofit of the power unit whilst maintaining the majority of the vehicle systems.

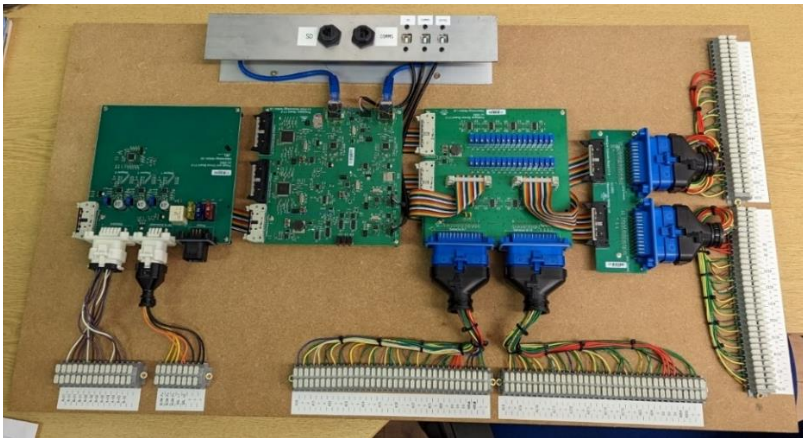

Figure 19 - Steamology ECU – on Test “Bread Board”

The controller is configured to run the Steamology Turbine Engine as well as functioning as a data logging device. Steamology is currently investigating the option for developing the inhouse controller design or adopting a pre certified outsourced design.

5.0 WP3 Component Test & Development

5.1 Objectives

The main aim of this work package was to build and commission the Phase 1 full scale power unit demonstrator and undertake full scale closed loop testing. The system and supporting test cell ancillaries have been assembled and commissioned and full-scale testing has been carried out. The technology will continue to be develop outside of the RDR programme.

Deliverables:
3.1 Steam test data from test cell test programme
3.2 Condenser hardware
3.3 Power unit primary movers, ancillary equipment built as subassemblies in preparation for system assembly
3.4 Power data from turbine running using dynamometer test cell
3.5 Analysis of power and torque data overview of system efficiencies and specification

5.2 Outputs

The Steamology Turbine Engine developed and tested during the Phase 1 block diagram is laid out in Figure 20. The system is closed loop and full scale. The engine is run against a dynamometer to absorb the load generated by the turbine.

This report will present the findings from the test programme and highlight where improvements can be made.

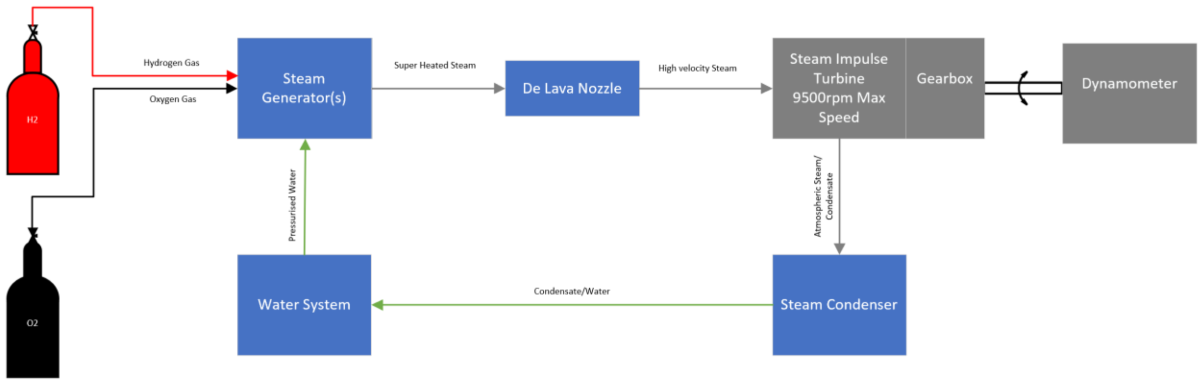

Figure 20 - Steamology Turbine Engine Block Diagram

5.2.1 Steam Generator

Figure 21 below shows the pressure, temperature and mass flow of the steam being produced by a single steam generator. It is worth noting the response time of the steam generator. Cold starting from ignition to 35 bar, 370°C Steam at 8.5kg/min mass flow is currently less than 60 seconds. A number of developments are in hand to reduce this to less than 30 seconds. The ambition is that once the turbine is warm transient power settings will be achieved in the same time as existing diesel engines.

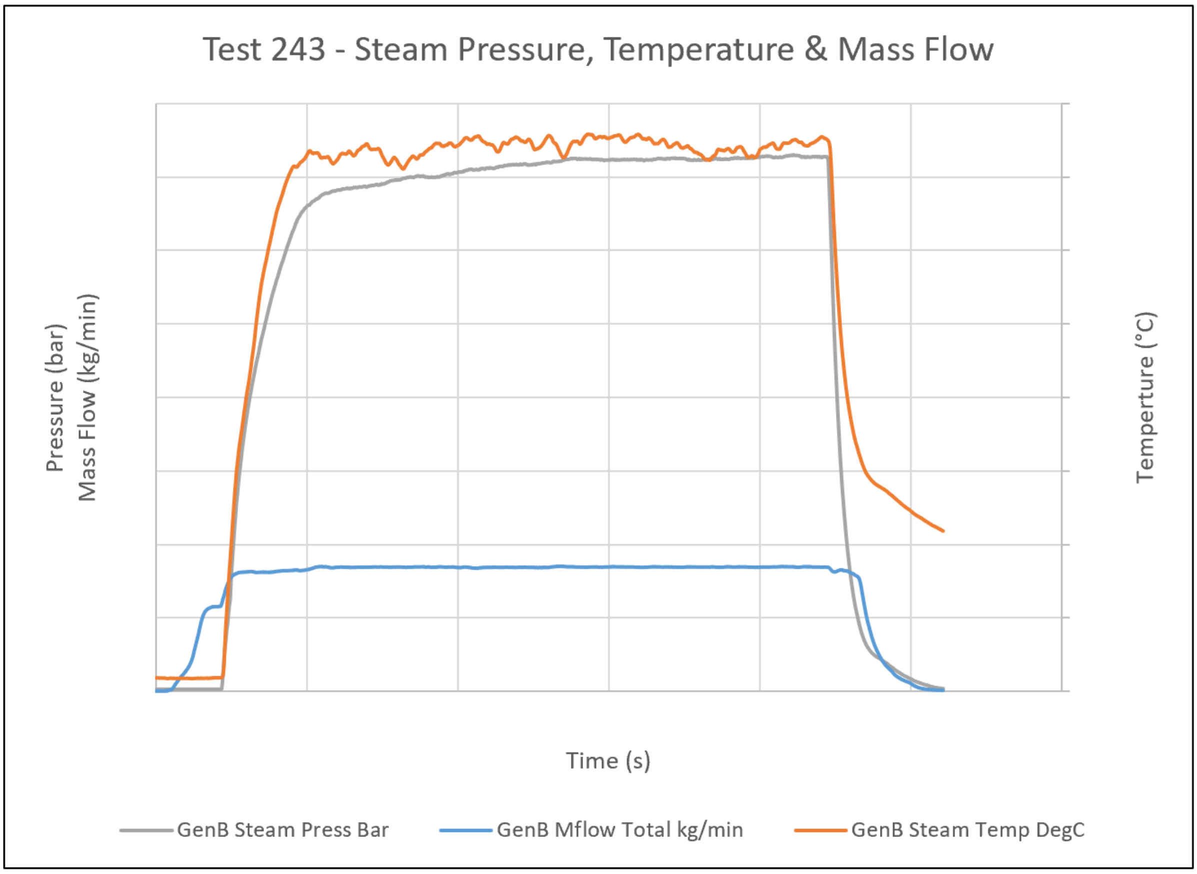

Figure 21 - Graph to Show Steam Generator Pressure and Temperature

5.2.2 Engine Power & Torque

Figure 22 shows the power torque characteristics of the turbine with 1, 2, 3 and 4 steam generators running. The varying speed was controlled using the dynamometer.

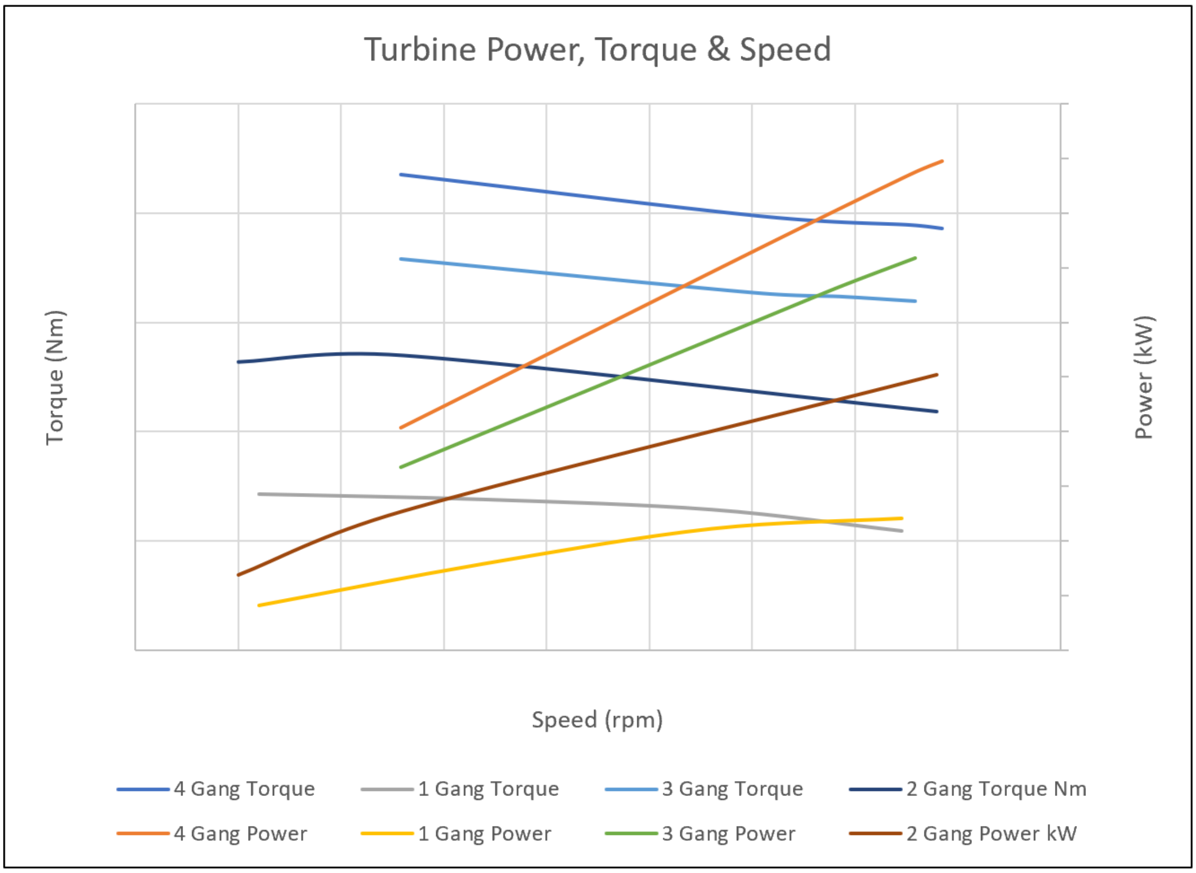

Figure 22 - Graph to Show Turbine Power, Torque & Speed

The torque profile detailed in the graph show the low-speed high torque characteristics which is to be expected with an impulse turbine. The torque increases with the increase of steam mass flow. Modulating the steam generators on and off is an important part of the system throttling. Each steam generators represents a course throttling "notch".

5.2.3 Condenser System

Figure 23 shows the data taken from the condenser system. The data shows the energy transferred from the exhausted steam in to the condenser coolant.

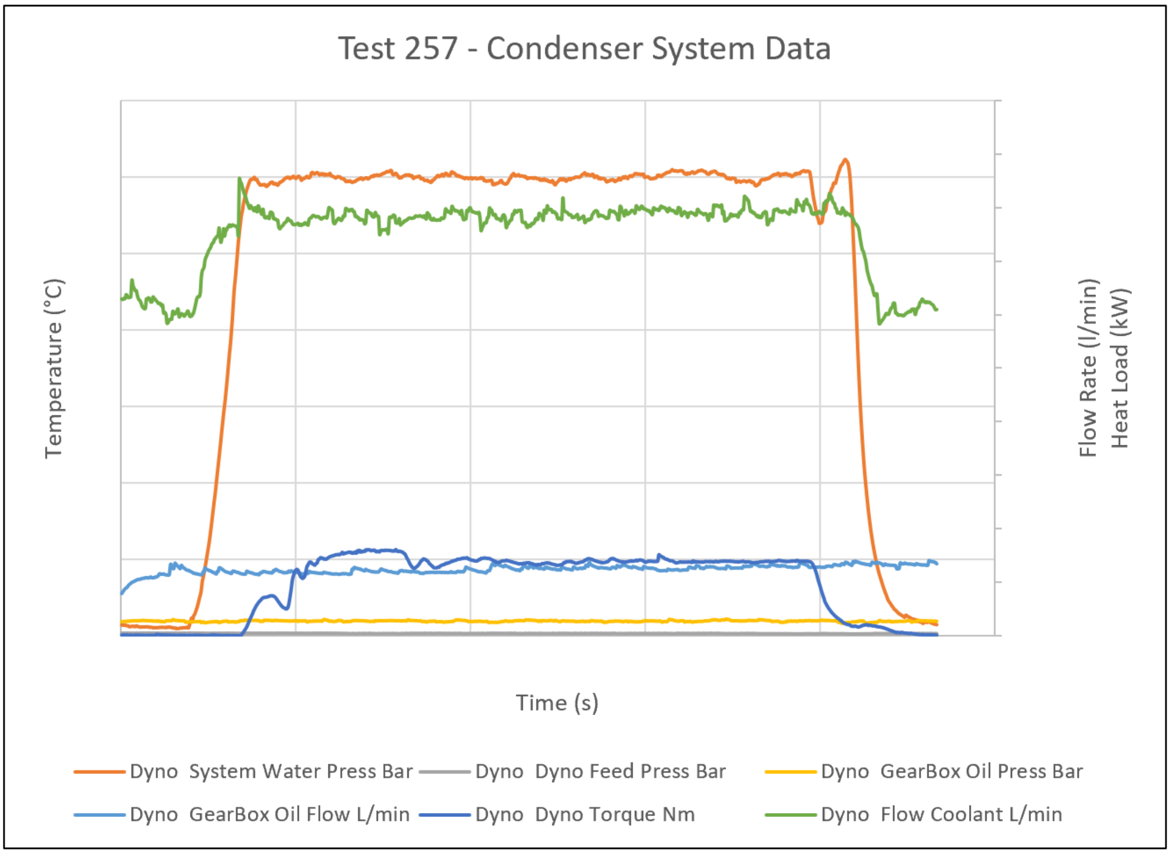

Figure 23 - Graph to Show Condenser System Data

Future optimisation of this system will be to reduce the cooling on the exhausted steam to bring he condensate temperature up from 20°C to 80°C. The 80°C water can then be used to feed the steam generators therefore reducing the amount of energy required to turn the water into steam ultimately resulting in a fuel saving. This also reduces the load on the condensing system and therefore low specification hardware can be used resulting in a lower system cost and greater packaging savings.

The testing has shown that the engine is able to deliver the power and torque required to replace the diesel engine. The turbine behaves very much more like an electric motor than a traditional diesel engine.

This means that a number of components that are in a traditional diesel engine driveline can be reduced or eliminated. For example the low starting torque of a diesel engine requires a torque converter to be fitted and many gearbox ratio's in order to deliver satisfactory power and torque. Once it is possible to create a fully optimised Steamology Turbine Engine driveline there will be considerable cost, volume and weight savings from the reduced number of components. The end result is a reduction

6.0 WP4 System Compliance

6.1 Objectives

This work package sets out to further develop Steamology's certification road map and increase the inhouse understanding of the technology and system requirements to comply with the relevant standards. Development in this area of the project is a crucial for planning and costing future stages of work to allow the technology to advance through TRL and MRL.

6.2 Outputs

Building on previous work Steamology, re-engaged with certification experts to define a program of work developing the system compliance roadmap specifically for NRMM assets in the construction, mining and quarrying industry.

The team has developed an improved level of understanding at a component, subassembly and system level. This work is also informing the business planning to ensure that the correct level of certification can be in place for the international markets that have been identified.

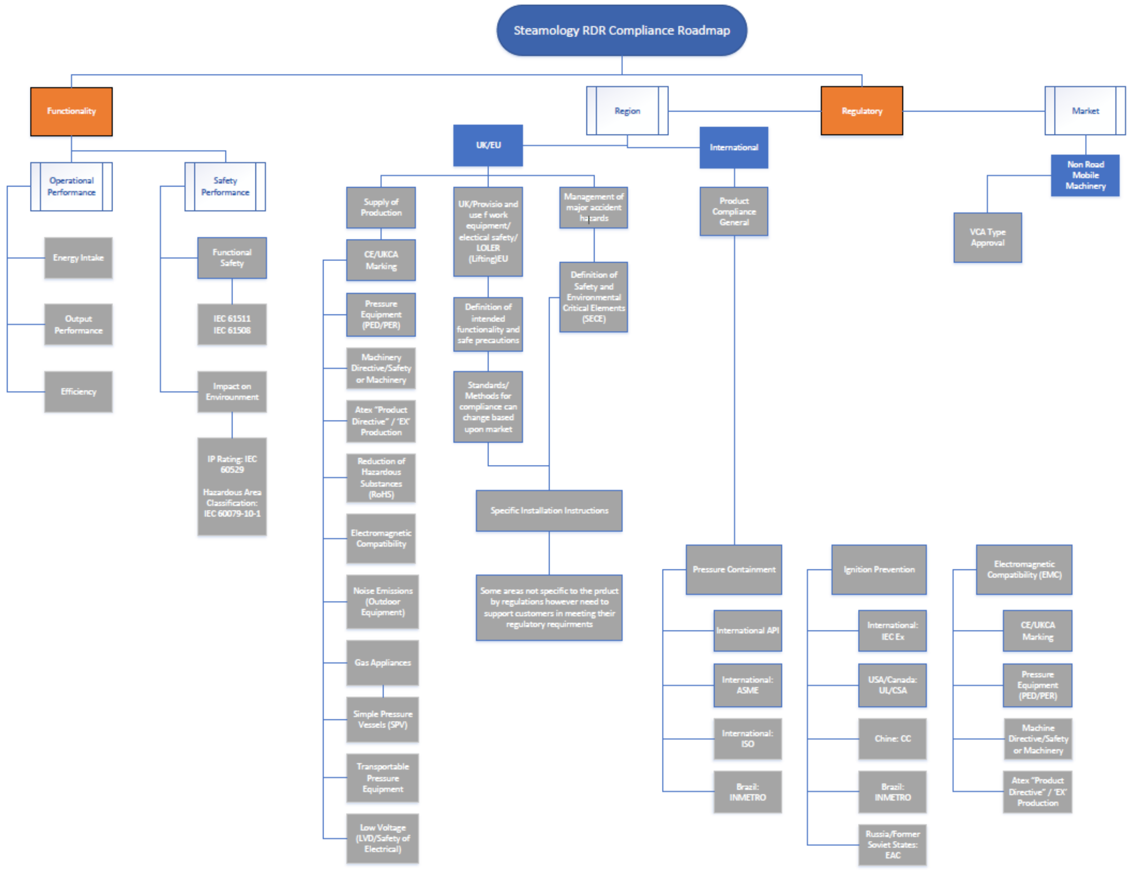

Figure 24 - Compliance Roadmap

The knowledge and understanding gained from Steamology's work with these organisations informed the system boundary diagram shown in Figure 25.

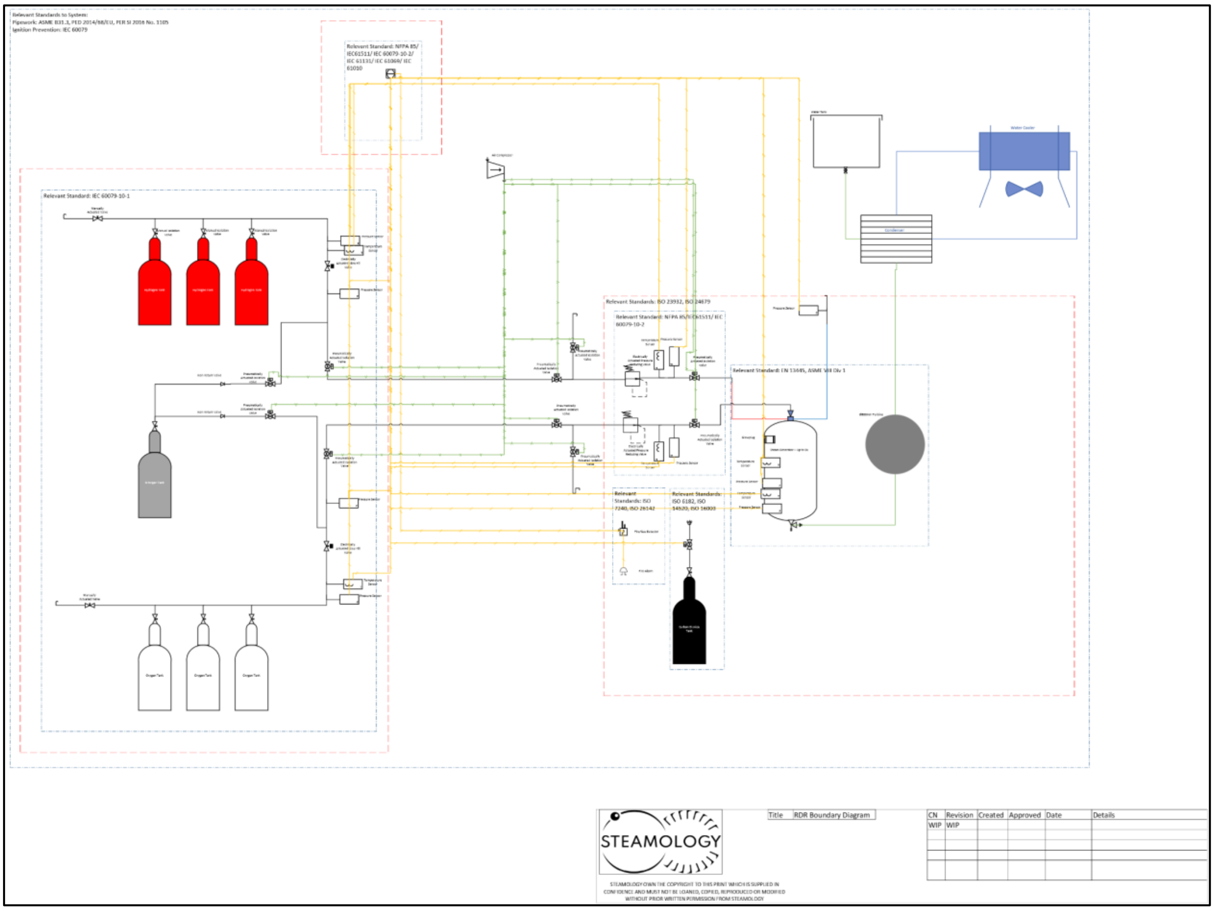

Figure 25 - RDR Phase 1 System Boundary diagram

In planning for end-to-end demonstrations, the system boundaries between fuel generation, bunkering, refuelling and end use are critical.

Steamology reviewed the system boundaries and completed formal HAZID sessions with external consultants. Compliance work has focused off the steam generator as the novel part of the drive train. Two of the key standard categories are the Press Equipment (Safety) Regulation (PER) and ATEX explosive atmospheres directive. Detailed work with the appropriate standards has governed the mechanical design and development of the pressure vessels as well as the specification of control and sensing components.

7.0 WP5 Business Planning

7.1 Objectives

RDR Phase 1 has enabled the design, development and full-scale demonstration of the Steamology turbine engine operating in closed loop as a fuel to power driveline.

This work has developed the following engine components:

- Gas valve
- Water valve
- Steam generator
- Steam nozzles
- Steam turbine
- Condensing system
- Controller
- Ancillary equipment

RDR Phase 1 has underlined the cost effectiveness of the turbines in comparison to alternative zero and low emission technologies.

The business planning confidence have been increased by reinforcing the understanding that all of the key components are ready for mass manufacture at readily available tolerances with readily available materials. All of these components in the demonstrator engine are already at full size and full scale which means that there is a high level of confidence in the timescale for commercial deployment.

Steamology is currently pre-revenue and will require significant further private investment and grant funding before being a commercial entity.

The key business planning objective for Steamology is to maintain the momentum of the technical development by raising sufficient funds to grow the engineering team and develop the commercial team. The RDR Phase 1 demonstration activity has provided Steamology with a technical platform that can be demonstrated to key stake holders.

Dissemination and demonstration activities are now taking place with key OEM’s and Tier 1 diesel engine manufacturers as well as being used as a platform for further grant funded projects and a range of pitching activities targeted towards private and venture capital investment.

In order to rapidly scale up commercially and therefore make a meaningful contribution to decarbonisation, Steamology plans to develop licencing and joint venture agreements with companies that already have the scale and global reach that is required. The diesel engine industry was worth 212 billion USD in 2021 and the industry faces uncertainty in the next decade. Current and future decarbonisation legislation is calling for the global removal of diesel engine assets between 2030 and 2050. The hydrocarbon subsidies such as the UK government red diesel incentives are being removed. Historically operators have been able to operate with fuel at below market cost. As subsidies are removed, decarbonisation legislation is being introduced and further potential tightening of ULEZ and carbon tax regulation are brought in, the market demand for long-life diesel-powered assets is being disrupted. OEM’s are responding by offering alternatively fuelled products.

Steamology technology can utilise all of the human and capital resource deployed in the diesel engine industry for manufacturing, sales, service, spares and maintenance for steam turbine drivelines. This prevents the existing diesel engine manufacturing sector facing numerous stranded assets - not only of capital equipment but also in terms of human resources.

Establishing the manufacture of battery and fuel cells fully electrified drivelines involves the creation of completely new supply chains at scale.. An example of the challenges faced are show in UK by Britishvolt and the length of time it is taking to establish Giga factories. Companies are faced with the challenges of green and brown field development, planning infrastructure, skills and investment. Whereas the supply chain and infrastructure for volume manufacture of the Steamology turbine engine already exists.

Steamology commercial sales are planned within 24-36 months for drop-in engine unit.

A blend of grant and investment funding is expected to bridge the famous technology “valley of death” until commercial traction can be established.

The 11-month RDR Phase 1 project has already provided Steamology with the opportunity to engage a growing network of potential commercial and funding partners. Steamology has a number of exciting project proposals across a wide range of multimodal transport applications sharing the common ambition to repower existing diesel assets with zero emission technology.

7.2 Technology Assessment

7.2.1 Benefits

- Mechanical, electrical or hydraulic drive

Steamology turbine engines rotate between 9000 and 15000 rpm in the 200kW to 1MW range and reduction gearboxes have been designed to bring the output shaft speed down to match existing conventional mechanical gearbox transmissions and electrical generators. These speeds are also suitable for driving a hydraulic system. This flexibility of output, combined with high torque characteristics at a wide power range, means that the turbine can be deployed in a wide range of applications traditionally using red diesel. The fuelling infrastructure expenditure required to switch away from diesel can be spread over a wide range of applications. Battery and fuel-cell alternatives require electrification of the drive-train and do not offer the application flexibility.

- Repower existing assets

Many diesel-powered assets have an extremely long lifetime up to 30-50 years. The asset owner is keen to use the full working life and capacity of the asset. Electrification of existing diesel assets is not always practical or financially viable. Decarbonisation legislation, carbon taxation and ULEZ initiatives can foreshorten asset life creating “stranded assets”. Steamology turbine engines can be used as “drop-in” diesel engine replacements allowing the asset owner to fully utilise the hardware for its full commercial life cycle.

- Suitable for hybrid or single power drivelines for new OEM builds

Steamology turbine engines are scalable and modular. Turbines are particularly suited to high and rapidly changing power demands. New build construction mining and quarrying equipment may be suited to hybrid drive lines where base loads are supplied from battery or fuel cell technology and transient peak loads from Steamology technology.

- Zero Emission – No tail pipe and no tail pipe emissions

The product of hydrogen and oxygen combustion is water and Steamology turbine engines operate in a closed loop without a traditional exhaust pipe and associated emissions. Therefore, having no impact on air quality. The turbine engine is also very low noise when compared with ICE further improving the operator’s working environment.

The water generated in the closed loop system is captured and stored and can then be potentially returned for electrolysis. With the growing global concern about water scarcity this aspect of the engine is incredibly beneficial when compared with alternative hydrogen technologies which are total loss for the water used to generate the hydrogen.

- Scalable and modular power - 200kW to 1MW

The wide operational range of Steamology turbines and the application flexibility means that fleet operators have an opportunity to utilise the same infrastructure for bunkering and refuelling for a much larger range of vehicles.

- Wide range of fuel purity

Currently less than 5% of the world hydrogen is green and economic sources of blue hydrogen are available to support early roll out of hydrogen projects while the scale up of green hydrogen takes place. Steamology turbine engines can use hydrogen fuels for a wide range of sources without the need to wait for better green hydrogen technologies to be developed tomorrow. Oxygen can be readily made from local renewable energy. Fuel cells typically require 99.999% pure hydrogen whereas Steamology steam generators can operate with much lower fuel purity. Electricity savings can be made when producing the fuel from electrolysis by having high quality water available as well as lowering the gas fuel purity requirement.

- Existing diesel engine manufacture maintenance service skills (transferable skills/limits training)

Many alternative low and zero carbon technologies require fundamental change in skills. For example, electrification of a mechanical driveline leaves mechanical engine fitters, service and maintenance skills redundant requiring significant retraining. Steamology Turbine engines are familiar mechanical devises and can make use of the existing skilled work force across the supply chain.

- Operation in low/high temp environments

Battery systems can reduce output by up to 40% at -7°C and lose performance over a relatively short life cycle of 3-5 years. Fuel cell and battery systems suffer operational challenges in high ambient temperature conditions usually requiring temperatures not to exceed 80°C. High operation temperatures impose challenges on the required balance of plant when temperatures reach 50°C. However, Steamology turbine engines operating in closed loop will deliver similar performance in hot and cold work environments and will deliver the consistent performance at the beginning and end of a long life.

- Air intake and exhaust

Steamology operates in a closed loop and therefore does not require any air inlet or exhaust outlet. This reduces the space and cost of an air filtration unit and an exhaust system equipped with noise suppression, particulate removal and gas treatment. There is a considerable reduction in part count and servicing cost’s whilst improving the operability and user experience in dusty and harsh environments.

7.2.2 Challenges

- First adopter – race to be second

Steamology turbine engines are significantly different to the alternative low and zero carbon power trains. Steamology must demonstrate and validate performance of the technology in order to gain customer confidence. This is typical for disruptive technology hardware.

- Infrastructure
  - Electricity for electrolysis
  - Electrolysis at scale (capture and storage of both oxygen and hydrogen gas)
  - Compression and gas storage

The fossil fuel hydrocarbon industries have extensive sunk capital costs and assets with over 100 years of maturity. Emerging hydrogen and low carbon alternatives face the enormous obstacle of creating an entirely new distributed energy infrastructure at suitable scale.

- Regulation, certification and compliance

The emerging hydrogen economy is facing the challenge of creating regulatory framework for new and high energy fuels that have characteristics that are different to the incumbent fossil fuel technologies. Antagonism exists between the need to comply with existing transport certification and the need to develop a new compliance strategy that effectively deals with the properties and characteristics of hydrogen and alternative fuels specifically. Certification development is a long term, collaborative and resource intensive process. Development of safe working practises is essential.

- Low TRL

Steamology technology is at mid TRL and has been granted a number of patents. Steamology has a product development roadmap over the next 12-24 months to increase the efficiencies of the engine and subassemblies. Many of the existing zero or low emission technologies already have considerable decades of research and development. It is important that we recognise the relative TRL of competing technologies.

7.2.3 CAPEX

- Steamology's "Cradle to Cradle" approach

The current steam generators are at full size and scale and the production process, finishing and inspection are relevant for low and high-volume production.

At low volume production the unit costs are in line with mature industry diesel engine manufacture and are a fraction of the cost of fuel cell.

- Low CAPEX compared with alternative
    - Diesel £200,000/MW
    - Fuel cell £1,00,0000/MW
    - Battery – fine cost per MW
- Long Life – 30,000 hours
    - Benchmarks well with diesel engineering
    - Batteries – 3-5 years life
    - Fuel cell's 10,000-15,000 hours

Steamology component count is a fraction of diesel engines and fewer rotating components. Therefore, the life expectancy for the limited rotating assemblies can be confidently predicted. Engine servicing and fitting of spares is straightforward compared to diesel engines.

7.2.4 OPEX

- Electrolysis life extension and running cost reduction due to recirculating high quality water and reduced need for high fuel purity
- Service life extension with limited idling hours (diesel engine typical 70% idling building service hours without delivering useful work)

It is estimated that the fuelling costs for the Steamology turbine engine are comparable with competitive hydrogen technologies. Steamology is a dual fuel solution requiring both the hydrogen and oxygen from electrolysis. However, the overall system efficiency the acceptance of low fuel purity and the reduction in water abstraction mean that overall OPEX will be on a par. As the global hydrogen economy scales up all hydrogen technologies will benefit.

7.2.5 Process Risk

Hydrogen and oxygen gas handling procedures and regulations are mature and exist in many different industrial sectors. Hydrogen and oxygen gases are hazardous and require strict adherence to safety protocols. Steamology is researching and collating modes of best practise from this wide range of industries and working with recognised certification bodies exploring the creation of safety frameworks of these known gases in novel applications.

Examples process risks throughout the Steamology system are:

- Gas Storage on vehicle
    - Oxygen
    - Hydrogen
    - Inerting and venting

The development of the certification planning includes separation of the gases until they are mixed in the steam generator. Gas storage volumes are assed for ventilation. There is a potential for storing compressed hydrogen and oxygen gas at a wide range of pressures typically 350bar and 700bar. In the future liquid hydrogen and oxygen systems may be used. A considerable supply chain for gas fuel transport applications is emerging. Steamology has engaged with a number of suppliers and is monitoring the development of process and safety regulations.

- Bunkering and infrastructure

Process risks are highlighted at the interfaces between the different system elements. The integration and safe transfer of equipment and control system delivering, storing and refuelling requires a great deal of oversight and understanding the interoperability of different systems.

- Steamology process is not widely understood

Knowledge of Steamology technology is not currently wide spread. It will take wide scale demonstration and pilot scale adoption to imbed the required work practices and develop the necessary training collateral.

- Dual fuel solution is perceived as more complicated than reality

Electrolysis has been used widely. Submarines typically use electrolysis to produce oxygen for breathing and exhaust the hydrogen rather than using the energy potential of the hydrogen. Using both gases from electrolysis is well understood but not currently widely practised in hydrogen fuel production.

- Dealing with high pressure and temperature steam (100°C+ of steam process and machine experience and regulation exist)

Steamology has engaged with a range of industrial steam experts to ensure best practice of steam handling and control.

- Fugitive gases

There is a highlighted awareness in the hydrogen community of the impact of fugitive gases in terms of safety and climate impact. Steamology is adopting best practices in line with the developing hydrogen industry.

- Zero emission

Steamology technology is genuinely zero emission with no tailpipe. Steamology circular economy approach meets ESG targets and reducing long term investment risk. Some low carbon/low emission technologies may not comply in the future with increasingly stringent emissions legislation as we target net zero.

- Materials

  Materials used in Steamology's technology are abundant, readily available and do not present any long-term recycling issues. Battery and Fuel Cell technologies have long term unknow legacy recycling responsibility for manufacturer therefore deterring investment.

7.2.6 Cost effectiveness

- Standard materials and manufacturing processes
- Capital means of productions already exist. No new factories required
- Means of production globally distributed

The Steamology demonstration equipment already being manufactured at low volume at competitive cost. There are no barriers to scaling production such as tooling, specialist processing or treatments. Low volume production from the 10's to the 100's can be extremely cost competitive with other more mature hydrogen alternatives. So, Steamology will be competitive before economies of scale are achieved.

7.2.7 Scalability

- Steamology steam generators and turbines already exist at full scale and full size
  - Many mid TRL projects incur challenges progressing from single kW to 1000's kW
- Even at mid TRL the designs are already cost effective. High volume manufacture can be achieved without significant tooling or production line investment. The technology is cost competitive in the short term and can be rapidly scaled to meet global demand.

Diesel engines are ubiquitous and multimodal. Diesel engines now face an extremely limited life due to increasingly globally adopted decarbonisation legislation. There will be many niche sectors for Steamology steam turbine engines once the company has started to demonstrate and disseminate the technology.

7.3 Route to Market Assessment

Key Steps to commercialisation:

- Steamology turbine engine is currently mid TRL 5/6. The TRL needs to be raised to 8/9 before commercialisation. The key next steps for successful commercialisation:
    - Real world demonstration engines operating outside of the test cell environment
    - Certification and regulatory compliance
    - Durability testing
    - Development of supply chain and manufacturing partners
    - Commercial joint venture licencing agreements with sales/maintenance/ distribution partners
- Steamology anticipate being able to build demonstration vehicles in the next 18 months followed by pilot fleet pre commercial vehicle trials and then full commercialisation in the next 3 years. Steamology is engaging with the grant and investment community to secure funding.

Barriers:

- Infrastructure cost of adopting a hydrogen economy
- Government policies on
    - Carbon taxation
    - Hydrocarbon fuel subsidies
        - Trust in dates for diesel engine removal

Risks

- Failure to achieve significant market penetration in a crowded hydrogen technology environment. Mitigation requires rapid deployment to demonstrator stage
- Government relaxation of ambitious decarbonisation targets
- Reduced appetite for new technology if carbon tax and legislation is not seen to be enforced
- Lack of global alignment in certification and safety regulation and standards

Potential benefits for other sectors:

- Steamology turbine engine operate in a wide range 200kW – 1MW and can deliver electrical and mechanical power and are therefore suitable for:
    - Passenger rail
    - Freight rail
    - ‘Yellow plant’ rail
    - Marine work boats
    - Marine crew transfer vessels
    - Port handling equipment
    - 40-44t HGV road freight

Steamology has engaged with major Rolling Stock Operating Companies (ROSCOs) and global Tier 1 transmission supply companies to explore these multimodal vehicle and freight opportunities.

7.4 Opportunities & Next Steps

The immediate next steps will be to continue test and development of the Steamology turbine engine as well as progressing the certification and compliance status of the technology.

The Net Zero Innovation Portfolio (NZIP) presents a number of appropriate grant funding opportunities for Steamology zero emission steam, heat and power applications. Steamology will investigate the forthcoming RDR Phase 2 alongside opportunities presented by the UK SHORE programme. These offer significant full-size vessel and vehicle demonstrator projects available to showcase real world deployment of the technology.

The accelerator support offered by RDR Phase 1 has allowed Steamology to meet and present to the investment community. The validation of government funding is proving to be helpful in these presentation in these presentations and negotiations.

7.5 Lessons Learned

- Considerable scope for high torque at low speed
    - Redesign of the vehicle from first principles could have dramatic cost savings and simplifications of the drive train
- Controller
    - Lack of appropriate off the shelf controllers
    - Steamology has developed the hardware and software of their 3rd generation controller. Importantly this has shown the dramatic time and cost saving of developing mechanical hardware and software within a small dedicated inhouse team.
- Closed loop
    - Condensing hardware is readily available and the team have gained considerable insights on how the system can be optimised and integrated for vehicle and vessel deployment
- Challenges of the weather
    - Steamology test cells are relatively low budget and situated outside the main workshop and prone to extreme weather. Particularly freezing events which requires extra planning and contingency in the management of the test programme
- Certification
    - The rapid increase in hydrogen economy is placing staffing and skills pressures on regulatory bodies to meet demand for new standards and standards advice
    - Steamology has learned to include longer lead times and consultation within project planning.
- Supply chain
    - Increased interest in hydrogen and hydrogen projects is placing pressures on the supply chain and placing pressures for gas and components