BRAMBLE
ENERGY

DESNZ Net Zero Innovation Portfolio
Red Diesel Replacement Programme
Phase 1

Gen-ZE: Fuel cell generator

Final Feasibility Report

19th August 2024

v2.2

Executive Summary

There are estimated to be approximately 1 million generators in the UK, which are responsible for emitting 1 $MtCO_2e$ annually[1] out of 400 $MtCO_2e$ emitted across the whole of the UK[2] . The construction sector is a large user of diesel generators and a range of construction companies have set ambitious targets to eliminate diesel plant from construction sites by 2035. There are currently hundreds of battery-electric construction vehicles / equipment commercially available and a growing need to recharge these vehicles in off-grid locations with a zero-emission power source. A hydrogen fuel cell generator can provide a zero-emission recharging option..

This document is a summary report from the Gen-ZE feasibility project delivered by Bramble Energy with funding from the Department for Energy, Security and Net Zero (DESNZ) through the Red Diesel Replacement (RDR) competition, which is part of the £1bn Net Zero Innovation Portfolio (NZIP).

The aim of the Gen-ZE project was to develop a prototype fuel cell generator leveraging Bramble's low cost printed circuit board fuel cell (PCBFC™) technology. This project has demonstrated the feasibility of a fuel cell generator using the PCBFC™. The fuel cell system has been developed, commissioned and installed on a trailer along with power electronics and sub-systems required to deliver power to electric construction plant. The next step is to demonstrate the fuel cell gen-set on construction sites to validate the generator, assess the performance in real world setting and gain feedback to develop the fuel cell technology for commercialisation.

Further work is also needed to develop this into a commercial offering. This would need wider support from stakeholders across the hydrogen supply chain, including hydrogen production and distribution to co-ordinate the deployment of hydrogen powered fuel cell gen-sets across construction sites in the UK.

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[1] ERM, 2023, Industrial Non-Road Mobile Machinery Decarbonisation Options: Techno-Economic Feasibility Study; https://assets.publishing.service.gov.uk/media/658443f3ed3c3400133bfd4d/nrmm-decarbonisation-options-feasibility-report.pdf

[2] DESNZ, 2024, 2022 UK Greenhouse Gas Emissions, Final Figures, https://assets.publishing.service.gov.uk/media/65c0d15863a23d0013c821e9/2022-final-greenhouse-gas-emissions-statistical-release.pdf

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Glossary

BEIS	Department for Business, Energy and Industrial Strategy
BoP	Balance of Plant
DESNZ	Department for Energy Security and Net Zero
MCP	Manifold Cylinder Pack
MEA	Membrane Electrode Assembly
MRL	Manufacturing Readiness Level
NRMM	Non-road mobile machinery
NZIP	Net Zero Innovation Portfolio
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
PCBFC	Printed Circuit Board Fuel Cell
PEM	Proton Exchange Membrane
RDR	Red Diesel Replacement
TRL	Technology Readiness Level
WP	Work Package

1. Introduction

Emissions from industrial non-road mobile machinery (NRMM) (excluding agricultural machinery) constitute approximately 6 million tonnes of CO_2 equivalent ($MtCO_2e$) per year, which is 1% of the UK's total greenhouse gas emissions[1,3]. The construction is responsible for approximately half of these NRMM emissions[1]. Red diesel used in the construction and infrastructure building sectors is also estimated to contribute to 7% of nitrogen oxide emissions and 8% of PM10 emissions in London[4].

To support the reduction in emissions across the construction, mining and quarrying sectors the Department for Energy, Security and Net Zero (DESNZ) funded the Red Diesel Replacement (RDR) competition through the £1bn Net Zero Innovation Portfolio (NZIP). The RDR competition was introduced to support the decarbonisation of these high-impact sectors affected by the partial removal of the entitlement to use red diesel and rebated fuels from April 2022. The aim of the RDR competition is to support the development and demonstration of low carbon fuel and system alternatives to red diesel for the construction, mining and quarrying sectors.

Bramble Energy led a feasibility project in round 1 of the RDR competition; the Gen-ZE: Fuel cell generator project. The aim of the project was to develop a prototype zero-emission hydrogen fuel cell generator based on Bramble Energy's innovative printed circuit board fuel cell (PCBFC™) technology. The fuel cell generator was designed to be ruggedised to deliver efficient, zero emission power for the next generation of electrified construction plant. This document is the final report from the Gen-ZE project and summarises the technical deliverables, the benefits and challenges of adopting fuel cell generators and recommended next steps.

2. Overview of the project

The construction sector has been addressing the challenge of climate change and reducing emissions through the design of zero carbon buildings during the operational life of the building and also during construction. This includes the use of low-carbon building materials and where possible, zero-emission vehicles and equipment on-site.

The Construction Leadership Council has set a target to eliminate 78% of diesel plant from construction sites by 2035[5]. To help meet this there are currently hundreds of battery-electric construction vehicles / equipment commercially available[6]. There is a growing need to recharge these vehicles in off-grid locations with a zero-emission power source. A hydrogen fuel cell generator can provide a

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[3] Climate Change Committee, Sixth Carbon Budget, Sector Summary: Manufacturing and Construction; https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Manufacturing-and-construction.pdf
[4] HM Revenue & Customs, 2021, Policy paper: Reform of red diesel and other rebated fuels entitlement; https://www.gov.uk/government/publications/reform-of-red-diesel-entitlements/reform-of-red-diesel-and-other-rebated-fuels-entitlement
[5] https://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2023/08/CLC-6th-Performance-Framework-V.03.pdf
[6] https://bellona.org/database-emission-free-construction-equipment-by-product-type

zero-emission recharging option to construction plant. By acting as a recharging point, the fuel cell generator can serve across multiple construction vehicle and equipment markets, similar to current diesel gen-sets.

The Gen-ZE project focuses on developing a zero-emission hydrogen fuel cell powered generator to support the adoption of zero emission construction equipment.

Within the Gen-ZE project Bramble has developed a prototype zero-emission fuel cell gen-set designed around the requirements from the construction industry. The scope of the project includes designing, building and testing a fuel cell gen-set. The ultimate aim of the Gen-ZE project is to provide a fuel cell gen-set that can charge a battery electric powered crane (see Figure 1)[7].

Alongside the technical development of a prototype Bramble reviewed the requirements for hydrogen supply, infrastructure, certification and conducted a hydrogen cost analysis and business case for the fuel cell gen-set.

Figure 1: Battery electric crane the fuel cell gen-set is designed to charge[7]

The project was split into multiple work packages including:

Requirements specification: Within this work package Bramble reviewed the end user requirements based on the MoSCoW (Must / Should / Could / Won't) methodology for the commercial product and prototype. A review was also conducted on the regulatory requirements including review of electrical safety, electromagnetic compatibility, restriction of Hazardous Substances (RoHS), fuel storage and environmental legislation. An in-depth review against the International

[7] Select Plant Hire; https://www.selectplanthire.com/product-catalogue/battery-powered-crawler-cranes-lr1160-unplugged/

Electrotechnical Commission standards “IEC 62282-5-100 Fuel cell technologies: portable fuel cell power systems. Safety” was also undertaken.

System design: The system design included fuel cell stack design modifications and the concept and detailed fuel cell system design for the gen-set trailer. This included power electronics for the electrical output at relevant power for use on construction site.

System build and testing: This work package involved the build and test of the fuel cell stack followed by the fuel cell system build and test. The fuel cell system was testing was carried out at a third party test facility, which also validated the fuel cell system software.

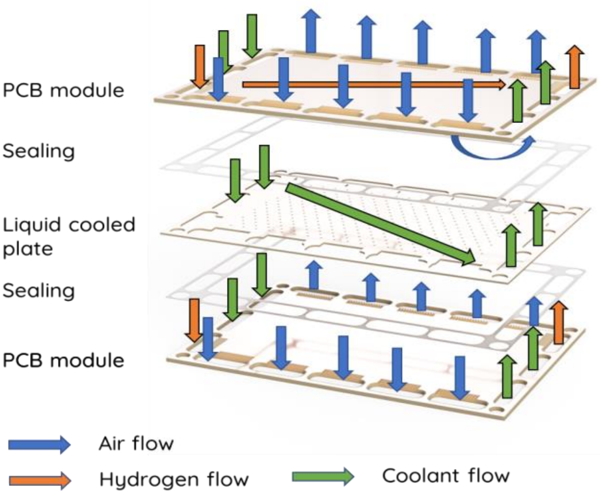
Trailer integration and electrical system: The fuel cell system was then integrated into a trailer for use on construction sites, the trailer also incorporated power electronics to provide a three phase electrical output at 400 VAC, as well as cooling for the fuel cell system and control system.

3. Technical development

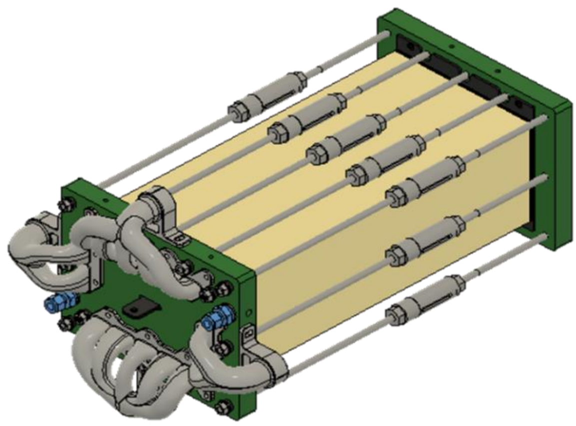
3.1 System design

3.1.1. Fuel cell stack

Bramble has a unique approach to manufacturing fuel cell stacks, which leverages the high precision and economies of scale established by the printed circuit board (PCB) industry to manufacture PCBFC™ modules. This approach brings advantages with manufacturing cost savings, design flexibility and the ability to quickly scale fuel cell manufacturing through the existing PCB supply chain.



a) Illustration of PCBFC™ modules stacked together with liquid cooling plate and sealing between modules



b) Illustration of PCBFC™ fuel cell stack comprising approximately 120 modules

Figure 2: Fuel cell modules and fuel cell stack

The PCBFC™ module incorporates a membrane coated with catalyst, known as the membrane electrode assembly (MEA). The PCB is manufactured to include flow fields for the air (cathode) to circulate on one side of the membrane and hydrogen (anode) on the other side.

Cooling of the fuel cell stack is achieved by circulating coolant through the plates between each layer in the stack. This requires the fuel cell stack to manage the fluid distribution of the coolant, air and hydrogen. Manifolding for air, coolant and hydrogen has been designed into one end of the fuel cell stack (see **Error! Reference source not found.**b).

The fuel cell stack is designed to provide the power output needed for Gen-ZE fuel cell generator with approximately 120 PCBFC™ modules designed to produce >11 kW output from the fuel cell stack (i.e. gross power output). Compression of the fuel cell stack is achieved by using spring washers mounted on tie rods between end plates. This provides mechanical compression to seal the individual PCBFC™ modules and liquid cooled plates.

3.1.2. Fuel cell system

The fuel cell system design incorporates the fuel cell stack, as well as the balance of plant that is necessary to operate the fuel cell. The fuel cell system design involved development of the piping and instrumentation diagram (P&ID), before mechanical and electrical design of the fuel cell system. The mechanical design is illustrated in Figure 3, including the subsystems that are within the overall system.

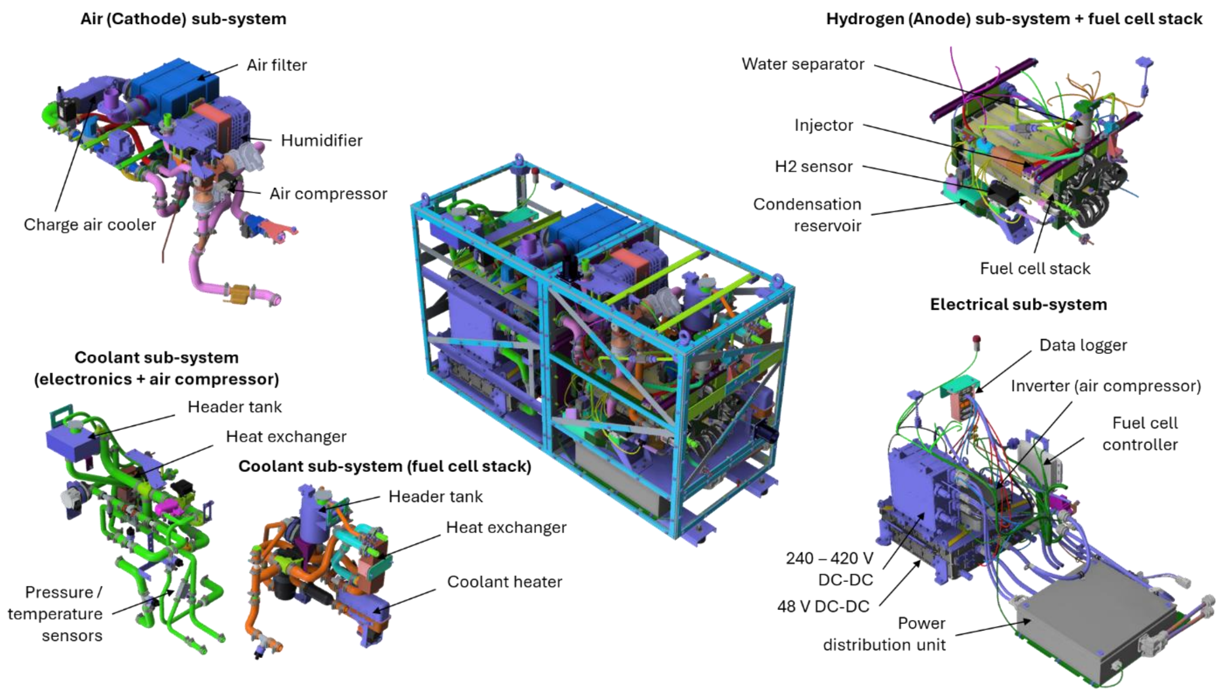


Figure 3: Fuel cell system CAD design showing the sub-systems within the overall system

Air supply system to the fuel cell cathode: The cathode air supply system filters the air intake into the fuel cell. The air filter specified was rated to remove >98% of particles in size from 0.2 – 10 µm. The air is then compressed up to 2.3 bar (absolute) and a charge air cooler is used to lower the air temperature before flowing through a humidifier. This sub-system controls the temperature, flow rate, pressure and humidity of the air circulating through the cathode side of the fuel cell stack.

Hydrogen supply system to the fuel cell anode: The anode hydrogen supply system includes an injector to control the hydrogen flow into the fuel cell stack and a hydrogen recirculation loop with water separator and ejector. The hydrogen recirculation improves the utilisation of hydrogen and overall system efficiency.

Cooling system (electronics + air compressor): The fuel cell system includes a low temperature cooling loop to provide cooling to the power distribution unit (PDU), inverter for the air compressor and DC/DC. This interfaces with a heat exchanger and external cooling loop to a radiator.

Cooling system (fuel cell stack): A high temperature cooling loop provides cooling to the fuel cell stack. Similarly to the low temperature cooling loop this also interfaces with a heat exchanger and external cooling loop to a radiator.

Electrical sub-system and control system: This includes a power distribution unit which interfaces the electrical output of the fuel cell stack with the rest of the fuel cell system and includes a 12 V DC-DC integrated into the power distribution unit and electrical safety aspects to isolate the fuel cell stack in the event of a fault.

The fuel cell system is controlled by a sophisticated controller, which manages the fuel cell system balance of plant components under different states to control the air, hydrogen and coolant flow into the fuel cell stack, monitor the performance of the system and provide alerts for any faults. The fuel cell system controller will interface with the control system in the gen-set.

3.1.3. Fuel cell gen-set

The fuel cell gen-set was designed to incorporate the fuel cell system and interfaces for power electronics to provide AC output power at the required voltage – 400 VAC to charge the electric crane. An outline of the concept for the trailer is shown in Figure 4. The trailer also includes several auxiliary systems to support the fuel cell system, these are summarised below.

Power electronics: To charge the battery electric crane three phase power at 400 VAC is required. The battery electric crane is designed to be operated either plugged (connected to mains or a genset) or unplugged (battery powered). The fuel cell gen-set will trickle charge the 196 kWh battery on the electric crane. The power electronics includes the following components:

- 3 x Victron MultiPlus-II 230V inverters, networked to provide 400V AC
- 4 x 12 V LiFePO4 870Wh (discharge rate <80A) (Lithium Iron Phosphate) batteries connected in series to provide power to start-up the fuel cell system and buffer for any immediate load demands.

- Orion-Tr DC-DC isolated DC/DC converters to provide 12 VDC power to the ancillary system in the fuel cell system.

Cooling system: Two radiators have been installed to reject 3 kW waste heat from the low temperature cooling circuit and 15 kW waste heat from the high temperature cooling circuit. The cooling requirement is based on an ambient temperature of 30°C to maintain a temperature for the low temperature cooling loop of 36°C and temperature of 70°C for the high temperature cooling loop. Radiators and fan sets from the automotive sector have been specified to provide the required cooling to the fuel cell system.

Hydrogen system: To simplify the build of the prototype the fuel cell gen-set will run directly from hydrogen manifold cylinder packs (MCPs). The hydrogen supply system in the trailer can be connected directly to MCPs and includes regulators to reduce the hydrogen pressure from >350 bar to 8 bar input into the fuel cell system. Each MCP contains 9 – 11 kg H_2 and would be able to operate the fuel cell gen-set for approximately 10 hours with an approximate electrical output of 160 kWh. This would provide enough power for a typical daily shift on a construction site. For longer operating hours or more arduous shifts, multiple MCPs can be manifolded together to provide extended hours of operation. The hydrogen system also includes vent lines and inline filters to protect the fuel cell from contaminants from the hydrogen supply.

Control system: A control system has been implemented into the gen-set. This will allow control via a human machine interface (HMI) screen on the external panel of the generator to control the output power from the fuel cell and notification of any alarms or errors from the fuel cell system controller. This will also be connected to a Crowcon Gas Master alarm panel for hydrogen and fire detection and will automatically shut down the fuel cell and hydrogen supply in the event of any hydrogen leakage or fire event.

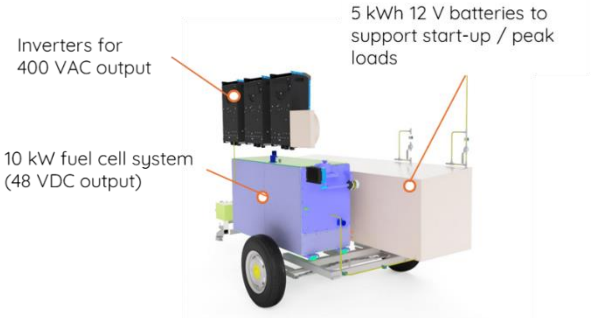


Figure 4: Fuel cell trailer gen-set concept design

3.2 System build and test

3.2.1 Fuel cell stack

The fuel cell stack was assembled from PCBFC™ modules manufactured through Bramble's supply chain. Bramble assembled the MEAs using materials from third party membrane and catalyst suppliers, these are then shipped to the PCB factory and placed into the PCBFC™ modules before PCB lamination of the anode and cathode half cells. The PCBFC™ modules are then sent to Bramble where further quality control tests are carried out before a sealant material is applied to each PCBFC™ module to ensure leak tightness when assembled into a stack. The fuel cell stack end plates and current collectors were designed and manufactured in-house and the stack was assembled and fitted with manifolding before fuel cell stack conditioning and testing.

The fuel cell stack testing included operating the fuel cell stack under different operational conditions and start-up and shut-down scenarios. The individual cell voltages of the 120 cells within the stack are monitored during testing, with the variance of the voltages as well as the minimum cell voltage key parameters to indicate the performance of the fuel cell stack. A polarisation curve of the fuel cell stack from testing is shown in Figure 5. The relative humidity, inlet and outlet temperatures, pressures and flow rates were monitored and varied during sensitivity testing to understand the performance of the stack under different operational conditions. This included operating the cathode and anode pressure from 10 kPa(g) to 140 kPa(g) and flow rates (stoichiometry) of available oxygen / hydrogen. The aim of the testing was to verify that the stack could provide the required power output under the operational conditions of the fuel cell system and that the start-up and shut-down sequences allowed repeatable performance over multiple cycles.

This testing and in particular the start-up and shutdown procedures help to calibrate parameters in the fuel cell control system. Upon completion of the successful test plan the fuel cell stack is the ready to be integrated into the fuel cell system.

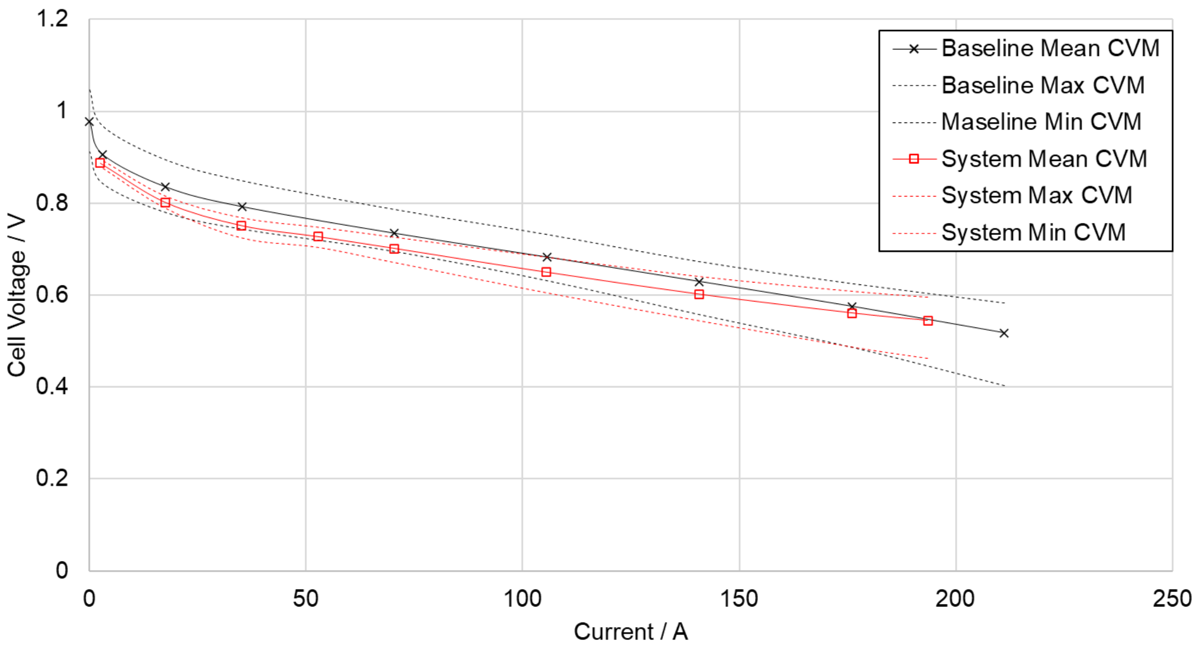


Figure 5: Polarisation curve from fuel cell stack testing

3.2.2 Fuel cell system

The specification of the ‘active’ fuel cell system balance of plant components (e.g. compressor, valves, DC-DC) was completed in the earlier stage of the project, which allowed for the packaging design to be carried out in parallel to procurement of these components. Once the design was completed the bespoke components, including mounting brackets, manifolds and housings for sensors were manufactured. These were machined or 3D printed, some of which was completed in-house at Bramble.

The fuel cell system was initially commissioned without the fuel cell stack to leak check the system and verify the control system without the risk of damaging the fuel cell stack (through over-pressurising the stack). This commissioning allowed verification that the system components worked together as expected, such as the operation of the valves, pumps and compressor under different set points. The output from this testing was the data from the sensors and components within the system (including mass flow rate, temperature, pressure and humidity) to verify the system design and control software.

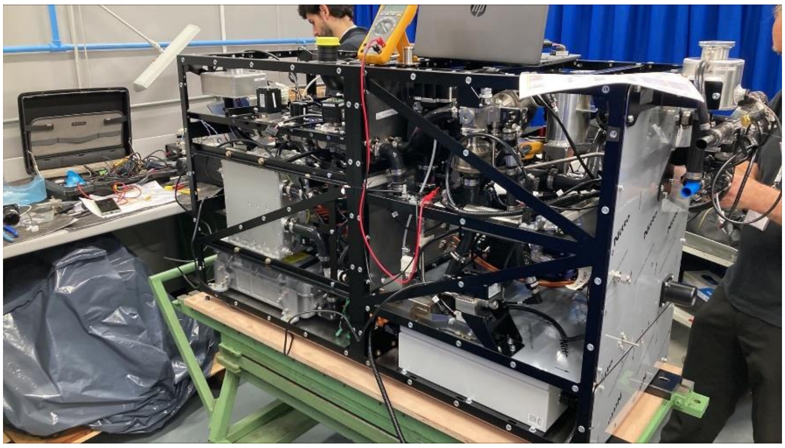
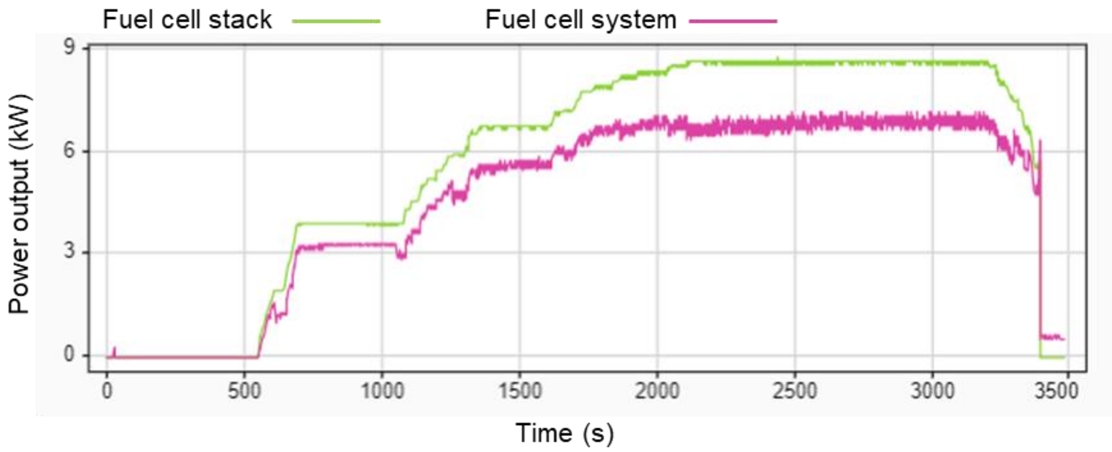


Figure 6: Fuel cell system build and commissioning

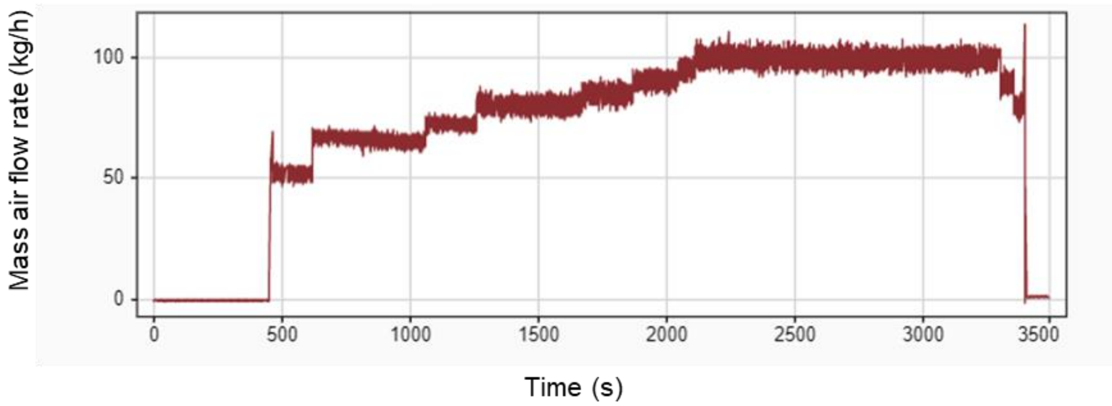
Once initial commissioning was completed the fuel cell stack was integrated into the fuel cell system. Further leak checks and commissioning with the fuel cell stack in the system was completed before the fuel cell system was moved to a test cell. The fuel cell system underwent three weeks of testing at third party facilities to verify the performance of the system with many of the components in the fuel cell system operating together for the first time.

During the test the fuel cell stack showed good response to demand. The testing ran through the basic checks, which included testing of the: injector, coolant pumps, coolant control valves, purge valves, back pressure and humidifier bypass valve.

The fuel cell system test plan was successfully completed, with an example run of the fuel cell system shown in Figure 7. This data shows the fuel cell power output from the stack (gross power) and the net power output from the system. The main power draw within the system is the air compressor, with the flow rate from the air compressor into the fuel cell stack shown in Figure 7b. In the test run shown, the fuel cell stack produces approximately 8.6 kW, resulting in a net power output from the system at approximately 6.7 kW. The learnings from the fuel cell system test have fed into how the fuel cell system is controlled during the demonstration phase.



a) Fuel cell power output from the stack (gross power) and system (net power)



b) Air mass flow rate into fuel cell stack (kg/hour)

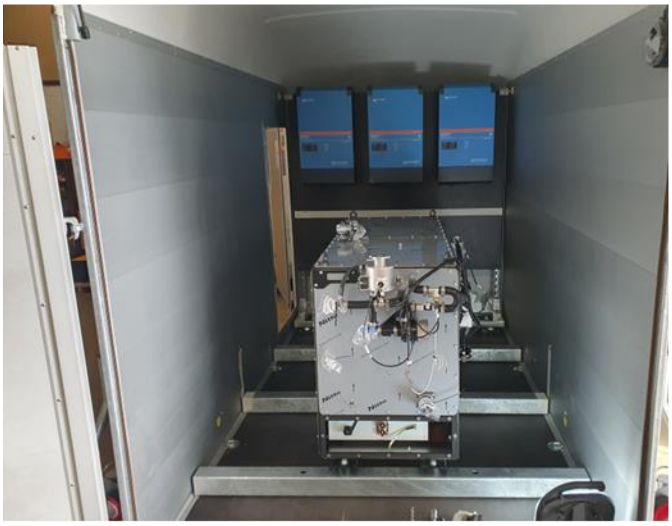
Figure 7: Fuel cell system data showing the power output and air mass flow rate

3.2.4 Fuel cell gen-set assembly

The fuel cell system is designed to provide trickle-charge to a battery electric crane and other electric plant. The crane includes a 196 kWh battery, the battery state of charge is recommended to be kept within 10% and 90% of the capacity. The crane has a maximum power output of 255 kW and maximum lifting capacity of 250 tons. The battery capacity allows for 4 hours of lifting operation.

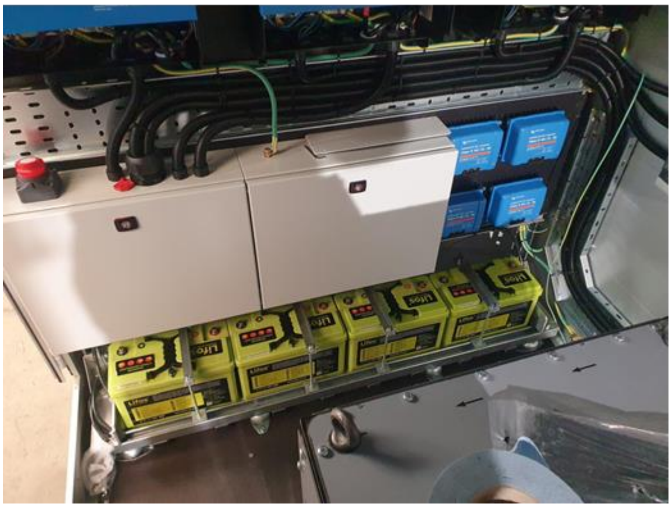
The fuel cell system would be able to charge the electric crane in 15 hours. The crane is able to be operated whilst charging (i.e. in plugged mode) with a 32 A CE plug. The battery electric crane can be charged whilst operating by the fuel cell system or the fuel cell system can be run to charge the crane battery overnight.

Following the completion of the test plan the fuel cell system was then installed into the trailer along with the power electronics, hydrogen system and cooling system (as shown in Figure 8). The trailer was commissioned with initial leak checks, control system verification and purging the fuel cell system with nitrogen before testing the completed fuel cell gen-set system.



a) Fuel cell system installed in trailer

b) Hydrogen fuel supply connections



c) Batteries, DC-DC and power electronics

d) External power connections

Figure 8: Fuel cell system installed in trailer during trailer fit-out

The fuel cell system was successfully commissioned and installed in the trailer. The gen-set will undergo further commissioning checks and design verification testing before demonstration on a construction site to charge a battery electric crane.

4. Benefits and challenges

The integration of a low-cost fuel stack integrated into a system and trailer for replacement of diesel gen-sets is targeted at a sector where the current price point of incumbent diesel gen-sets is approximately £300 - £400/kW. The PCBFC™ gen-set offers a range of advantages, including low-cost manufacturing through the PCB production pathway, however there are also benefits and challenges that will be common amongst other hydrogen and fuel cell technologies. Some of the key benefits and challenges are outlined below:

4.1 Benefits

+ **Zero emissions:** The fuel cell generator only emits water at the point of use and the GHG emissions will be mainly associated to the production / transport of hydrogen. The operational emissions could be fully decarbonised in the future through the production of green hydrogen from renewable electricity and the transportation of hydrogen using zero-emission vehicles. Fuel cell technologies also benefit air quality as unlike diesel gen-sets they do not emit pollutants such as NOx, PM and SOx. This is of particular benefit to construction sites in urban areas or close to populations where air quality is already an issue.
+ **Low-cost PCB platform:** With unique, proprietary technology leveraging the PCB manufacturing route Bramble is able to significantly bring the cost down of fuel cell stacks. This cost saving is realised by manufacturing through the already established PCB manufacturing supply chain, as well as bill of materials savings due to the lower cost of the composite materials used in Bramble's fuel cell technology. As a result of this, Bramble's fuel cell cost targets of $100/kW for a production capacity at 100 MW/year is market leading at this volume (equivalent to >6,500 GenZE fuel cell stacks/year). This is compared to incumbent technology, which is often quoted above $1,000/kW[8].
+ **Extended operation time:** Unlike batteries, fuel cells and hydrogen storage dissociate energy from power. This means that additional energy storage can be supplied to the fuel cell by adding more hydrogen tanks or MCPs. Hydrogen offers a lower cost way to increase the energy storage capacity than batteries, as a battery cost is approximately £200/kWh[9] compared to hydrogen tank cost of approximately £40/kWh[10] (based on electrical output and assuming 50% fuel cell efficiency). The fuel cell and hydrogen solution can therefore be the lower cost zero-emission option when longer duration energy storage is needed (e.g. when multiple days of energy storage are required on site).
+ **Low noise operation:** Low noise operation is a benefit fuel cells and batteries have compared to diesel gen-sets. This improves working conditions and reduces noise nuisance to neighbouring sites.
  Scalability: Another particular benefit the Bramble PCBFC™ technology brings is the scalability of fuel cell stack manufacturing. A single large-scale PCB facility has a throughput of 400,000 panels/month, this translates to approximately 900 MW of PCBFC™ modules each month. Prototypes, pilot scale and production-ready module designs can also be manufactured on the same PCB production line, reducing the risk of teething issues during the manufacturing scale-up phase to high volume production. This is a benefit to

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[8] Bramble Energy, 2023, The pathway to the lowest cost fuel cell; https://www.brambleenergy.com/resources/whitepapers/discover-the-pathway-to-the-lowest-cost-fuel-cell/
[9] Tesla Megapack, 2024; https://www.tesla.com/megapack/design
[10] Based on quotations for 10 kg H_2 type III hydrogen tanks

the fuel cell stack and the fuel cell system components would still be sourced from third party suppliers. It is worth noting that different manufacturing routes would be used for the production of some of the components used in the prototype system (e.g. some of the manifolds would be injection moulded rather than 3D printed at scale).

4.2 Challenges

- **Low carbon supply of hydrogen:** One of the challenges of rolling out fuel cell technology is sourcing low carbon hydrogen in the UK. This is due to the nascent supply chain for green hydrogen, which is being established through initiatives from DESNZ such as the Hydrogen Allocation Rounds[11]. This means that the majority of hydrogen available for use is currently produced from fossil fuels. The benefit of deploying fuel cell gen-sets is dependent on the reduction of GHG emissions compared to diesel gen-sets and this can only be realised through the supply of low-carbon hydrogen. The main driver for adopting fuel cell gen-sets is the reduction in GHG emissions, therefore the supply of low carbon hydrogen that can demonstrate this reduction is critical. There is a risk that these demonstrations are inhibited by the lack of low-carbon hydrogen, which could stifle the development of technology that relies on the supply of hydrogen, such as fuel cell gen-sets.
- **Hydrogen storage on site and safety considerations:** Hydrogen has a low volumetric density and needs to be compressed into high pressure tanks (e.g. at 350 bar) for practical transport and storage. The location of hydrogen storage cylinders on construction sites needs to be carefully considered more so than storing diesel. Hydrogen cylinders need to be stored in an exclusion zone to ensure safety distance from buildings, ventilation intakes, ignition sources etc… The safety zone applied will be dependent on the type of storage and the quantity of hydrogen stored. The hydrogen MCPs would also typically be required to be stored in a compound for security and safety reasons and the space requirement to site the MCPs can be challenging to find on construction sites with limited space.
- **Cost of hydrogen supply:** In addition to the challenge in sourcing a supply of low carbon hydrogen, the cost the low-carbon hydrogen supply needs to be at a level for fuel cell technology to be adopted more widely. As of 2024, there are hydrogen supply quotes to supply to UK sites of £100/kg for delivered MCPs, which is not a sustainable cost for wide spread adoption of hydrogen and fuel cell technology. The hydrogen supply cost needs to reduce closer to £10/kg H_2 to be comparable on a total cost of ownership basis with diesel. As the hydrogen supply chain matures and competition between hydrogen suppliers increases the cost of hydrogen production will reduce. However, there is still a challenge to reduce the cost of distributing hydrogen particularly for the distribution of smaller quantities, where the logistics and distribution costs are expected to remain high.

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[11] Department of Energy Security and Net Zero, Hydrogen Allocation Rounds; https://www.gov.uk/government/collections/hydrogen-allocation-rounds

- **Demonstrated durability:** The long-term operation of fuel cells in a construction site environment has not yet been demonstrated. There is therefore need to prove out the operation of the fuel cell for real-life duty cycles for extended period of time. This includes long-term operation in a high dust environment. This will inform the maintenance requirements (e.g. frequency of air filter replacement) to meet the lifespan needed for fuel cells on construction sites.

5. Costed development plan

A high-level breakdown of the development plan to take the alpha prototype of the fuel cell gen-set into a product at TRL 8 is shown in Table 1. There are also multiple routes to market for the development of the Bramble fuel cell stack / system / trailer gen-set. The following costs assume that the complete trailer gen-set is developed as a product. This is an option which Bramble would need partners to develop further, with Bramble predominantly focused on commercialising fuel cell stacks at power level >1 kW. The costs for these steps are estimated and would need further detailing before any financial investment commitment would be made.

The high-level cost estimate of the development phase to move from TRL6 to TRL8 is between approximately £2 - £4 million. It should be noted these are only estimated values based on similar developments for other applications and more detailed planning of the product development process and discussions with suppliers would be required to provide a detailed development plan.

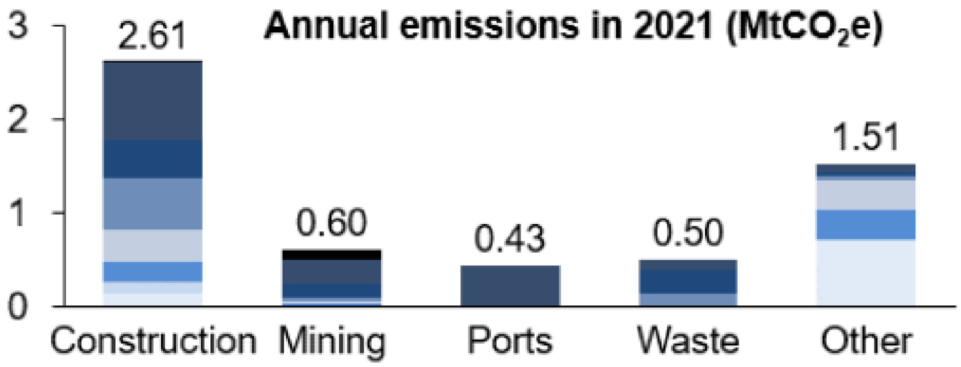
Table 1: Summary of high-level costed development plan for commercial development

Development step	Estimate	
1. Design for manufacture		
Supplier engagement	£50,000- £100,000	Initial discussions with suppliers are for one or two components, the costs of higher order volume of components and cost reduction would need further negotiation. Bramble would need to strengthen internal procurement team to deliver this.
Mechanical design review	£300,000 - £500,000	The design for manufacture has not been considered in detail for the prototype build. There are also further design integration aspects which could be considered between the fuel cell system and the trailer gen-set system.
Electrical design review	£200,000 - £400,000	There is also further opportunity for electrical integration and optimisation between the fuel cell system and the trailer gen-set system. This would also include multiple electrical outlet options.
Controller & software design review – integration with gen-set	£300,000 - £600,000	The fuel cell system includes a controller, which interfaces with a control unit on the trailer gen-set. There is scope to reduce cost by integrating the controller into one unit, which controls the fuel cell system as well as the hydrogen regulator and valves, the radiator control valves, the power electronics and the user interface.
Compliance / certification review	£50,000 - £150,000	A certification review was conducted as part of the feasibility project. This was incorporated into the design requirements for the fuel cell system, however full review of the trailer certification requirements would need to be undertaken and fully captured in the design updates.
2. Beta prototype		
System component level test	£200,000 - £300,000	To incorporate third party components into a product would require a higher degree of confidence in the components and testing of components would be required to verify performance and reliability. This would be needed before a warranty could be defined for the system.

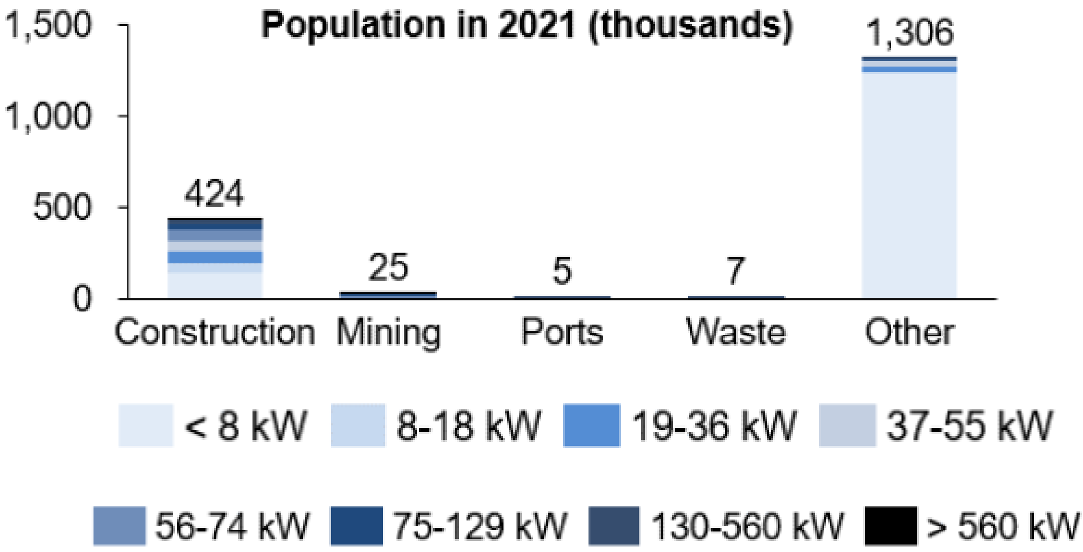
	Stack durability test	£300,000 - £500,000	In addition to the confidence of the system components the fuel cell stack should undergo additional testing for durability and replicate duty cycles from the end use application. This would advance the technology maturity of the fuel cell stack and the system control strategy.
	Beta prototype build	£150,000 - £400,000	Multiple beta prototypes would need to be built and commissioned. This would also validate the build and commissioning process and ensure that the assembly and build process could be carried out reliably.
	Beta prototype test	£100,000 - £250,000	More rigorous testing of the fuel cell system and gen-set system would need to be carried out to verify the system meets the design requirements. For instance, this would include cold temperature testing, testing under different vibrational loads and in different test conditions. This would verify system performance in a controlled environment before more extensive site testing could be carried out.
	Certification	£100,000 - £200,000	A series of certification tests would need to be carried out on the system (e.g. electromagnetic compatibility testing) to fulfil regulatory requirements. Testing would need to be undertaken to confirm and provide evidence that the fuel cell system meets required certifications.
	Customer trials	£100,000 - £300,000	Multiple units would then be deployed across customer trials to validate the fuel cell system meets the needs of the customer in an operational environment. This would validate that the fuel cell system meets its intended purpose and look to confirm initial customer orders for the units.
	Preparation for manufacture	£150,000 - £300,000	This would include the fit out of a manufacturing facility with tools, jigs and fixtures to complete the assembly of the fuel cell system and gen-set. This would also require sufficient storage of parts and facilities for end of line testing of the system.
	Marketing and publicity	£100,000 - £200,000	There would also be costs associated with the marketing and commercialisation of the system. This would include preparation of user manuals, videos and publicity to launch the product to the market, including the exhibition at trade shows and events.
Total		£2,100,000 - £4,200,000	

6. Route to market assessment

Analysis by ERM for the Department for Energy Security and Net Zero conducted in 2023 shows that the UK construction sector has the largest GHG emissions from NRMM of any sector (shown in Figure 9). Across the NRMM fleet, which includes forklifts, excavators, telehandlers, generators make up >60% of the fleet and approximately 18% of the fuel use[1].



a) GHG emissions from non-road mobile machinery



b) Fleet size of non-road mobile machinery

Figure 9: GHG emissions and fleet size of non-road mobile machinery in the UK by sector and power rating**Error! Bookmark not defined.**

The Construction Equipment Association is the trade association that represents the UK construction equipment sector and data from the CEA shows the UK is the largest producer of construction equipment in Europe and fifth globally[12]. The UK is a net exporter of industrial NRMM, with the European Union (43%) and the USA (28%)

[12] Construction Equipment Association, The UK's construction equipment sector report, 2023; https://thecea.org.uk/wp-content/uploads/2023/07/CEA-Report-2023-Final-Download-3.pdf

representing the key export markets in 2022 (HMRC, 2023)[13]. The NRMM export market is worth £1.9 billion to the UK economy[14] and the UK therefore has an opportunity to lead on the transition of low-carbon NRMM technologies.

The report from ERM recognises that the majority of UK industrial NRMM is not owned by its operators, with 67% of construction NRMM either leased or hired by the operator[1]. This highlights that lease and hire companies have a larger impact on the UK market and are a more significant stakeholder for decarbonisation than elsewhere in Europe.

The construction sector is a key target market with incentives to decarbonise. In addition to the construction sector there are multiple markets the gen-set could be targeted, including EV charging, events and festivals as well as general use as a diesel generator replacement as illustrated in Figure 10.

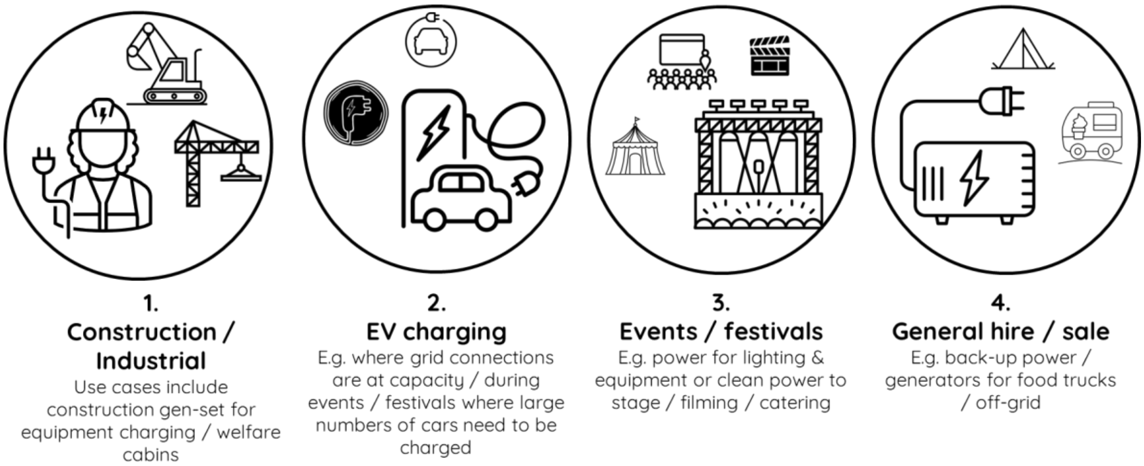


Figure 10: Use cases for hydrogen fuel cell gen-set

Table 2 summarises the stakeholders required for commercialisation of the fuel cell gen-set product. As discussed in section 4.2 there are challenges around the supply and storage of hydrogen. This is across multiple use cases, and incentives are required to support the adoption of zero-emission gen-sets over incumbent diesel powered units. Bramble's core intellectual property is on the fuel cell stack, based on the low-cost PCBFC™. This could be marketed as a product to integrators and original equipment manufacturers (OEMs) developing fuel cell gen-sets, or licensed with manufacturing routes from the PCB supply chain. The range and the number of stakeholders shown below shows the complexity in commercialising fuel cell gen-sets.

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[13] HMRC, 2023, Overseas trade data table; https://www.uktradeinfo.com/trade-data/ots-custom-table
[14] Mission Zero: Independent Review; https://assets.publishing.service.gov.uk/media/63c0299ee90e0771c128965b/mission-zero-independent-review.pdf

Table 2: Summary of stakeholders required for commercialisation of fuel cell gen-set product

Stakeholder	Role	Suggested actions and approaches
Hydrogen Producer	Produce low-carbon hydrogen at price point that is viable for use in fuel cell gen-sets to compete with other zero-emission technologies.	Low-carbon hydrogen production is critical to the fuel cell gen-set business case. Provision of filling MCPs / smaller refilling units, either on-site or with trailer capable of refilling into smaller cylinders would support different off-takers of hydrogen.
Hydrogen Distributor	Transport hydrogen from producer to end user – this could include provision of hydrogen cylinders / MCPs.	Logistics to supply hydrogen to construction sites. There is a supply risk with varying hydrogen demand / geographic locations of construction sites. This could be de-risked as part of a wider hydrogen logistics solution, or for flagship longer term, larger construction projects.
End user	End customer (e.g. construction company) who will operate zero-emission gen-set and define requirements for product	Support technology developed and hydrogen suppliers in defining requirements for product and support zero-emission targets and deployment of new technology through trials.
Service Provider	Supplier of equipment to end user, for construction sector the business models tend to be hiring of equipment for specific phase of construction project. This could also include logistics for hydrogen supply to site.	Support through the definition of requirements for product and support zero-emission targets and deployment of new technology. This role could also encompass the hydrogen distribution to site through a direct contract with the end user for fuel supply.
Solution Integrator / OEM	Integration of fuel cell component (either stack or system) into gen-set system (e.g. trailer unit).	Engage with supply chain and review further integration options to solve specific needs, e.g. lighting towers.
Component Manufacturer	Bramble Energy – developer fuel cell stack / system and supply to solution integrator / OEM.	Develop reliable, affordable technology that meets user requirements for adoption in wider market.

7. Lessons learnt

There have been a wide range of lessons learnt from the feasibility project, including many technical developments of the fuel cell stack / system integration. Some of the main lessons learnt from the project are summarised below:

Engagement with end users: This includes engagement across a wide range of stakeholders, including the end user. A clear definition of end user requirements for the commercial and prototype demonstration is important and understanding of the safety aspects for demonstration are critical. Regular communication with end user and in-person meetings has also helped to improve their understanding of the technology and the constraints and challenges to trialling new technology on site.

Communication with suppliers and subcontractors: Clear communication between suppliers and subcontractors to ensure expectations are aligned and responsibilities and roles are fully understood is crucial to ensure successful project delivery.

Support testing with simulations: The fuel cell system was modelled using a 1D system model, which improved the efficiency and productivity during the commissioning of the fuel cell system. This enabled the simulation of different software states to understand the impact of changes to the system before real world testing. This also streamlined the calibration of the fuel cell system during commissioning.

Testing to replicate real world conditions: It is generally simpler and easier to test at component level than at full system level. Throughout the testing ensuring that the test plan will verify the performance in close to real world conditions is important. Testing should replicate real world conditions and duty cycles where possible.

Management of risks and delays: Given the research and development nature of the project there can be a high level of uncertainty in the project planning stage. When R&D activities are on the project critical path, this results in a high risk of delays to deliver the project against the timeline. There is also a challenge in planning contingency as this can lead to a high variance dependent on the outcome of different R&D scenarios. Regular and rigorous review of project risks and flexibility in the approach to deliver the project would help to maximise the benefit of the project.

8. Policy recommendations

Following the feasibility project key policy recommendations include:

Support technology trials that enable zero-emission: Sourcing low-carbon hydrogen supply is currently a challenge and the demonstration of new technologies may not always be possible alongside immediate emission savings (i.e. if low-carbon hydrogen is not available). However not testing or demonstrating the technology on sites will restrict its development. Supporting the trial and demonstration of technology that can enable emission savings is important and will strengthen technology development in the UK.

Support local supply chains: To maximise economic benefit and job creation in the UK the use of local supply chains, particularly in clean technology sectors is important. This will also help with the maintenance of equipment, where a local supplier should be able to provide quicker response to a site when needed.

Skills: Future jobs for clean technology need a wide range of skills, with a limited supply chain currently in the UK there is a skills gap across many areas. Working with industry and educational institutes to identify and support a long-term plan to address these skills gap will help build a sustainable cleantech industry in the UK.

9. Conclusions

The construction sector is a large user of diesel gen-sets and therefore a large emitter of CO_2 through the use of gen-sets. Ambitious targets to reduce the use of diesel on construction sites have been set by the industry and the Government is providing incentives and regulations to restrict the use of diesel, including the removal of the red diesel rebate for construction sector. There is a large market potential for zero-emission generators, with a willingness from industry to deploy zero-emission technologies. However the commercial viability of zero-emission gen-sets and the technical demonstration still need to be further validated.

The aim of the Gen-ZE project was to develop a prototype zero-emission hydrogen fuel cell generator based on Bramble Energy's innovative printed circuit board fuel cell (PCBFC™) technology. The fuel cell generator needed to be ruggedised to deliver efficient, zero emission power for the next generation of electrified construction plant.

Within this project Bramble has developed a prototype fuel cell generator which incorporates Bramble's low cost PCBFC™ modules and will reduce the cost of fuel cell gen-sets. This involved the design, build and testing of the fuel cell stack, system and control software. The next steps following this feasibility project will be to demonstrate the prototype system on a construction site to gain valuable feedback from site trials. This will then feedback into what is needed for a commercial system. Further work is needed to develop the gen-set into a more mature product and to develop the commercial case, particularly considering the complex range of stakeholders that would be required to deploy hydrogen powered fuel cell gen-sets across construction sites in the UK.