UK Government

RYZE POWER

H2-to-Site: Comprehensive Hydrogen Supply-Chain Solutions for NRMM

The potential and challenges of a UK hydrogen-powered construction industry











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Executive summary

Purpose of the report

The UK construction sector is one of the country's most carbon-intensive industries, consuming 2.5 million tonnes of oil equivalent in diesel each year and emitting 7.7 million tonnes of CO_2[1]. The government's 2022 removal of rebate for sectors using red diesel created an urgent need for cleaner alternatives. Hydrogen has emerged as a particularly promising solution: it delivers zero greenhouse gas emissions at the point of use, which improves air quality compared to biofuels, and can power heavy machinery in complex, off-grid environments where electrification faces limitations.

The H2-to-Site project, was launched under the UK Government's Red Diesel Replacement (RDR) programme, running between July 2023 and October 2025. Led by Ryze Power with the support of iGAS, Wrightbus, and major construction site operators including Skanska, Mace Dragados, and Sizewell C, the project was part of the Department for Energy Security & Net Zero's £1 billion Net Zero Innovation Portfolio (NZIP), which provides funding for low-carbon technologies and systems and aims to decrease the costs of decarbonisation helping enable the UK to end its contribution to climate change. The project was awarded up to £3,212,280.99, with a budgeted project cost of £5,063,136.62: the project achieved its aims with a significant underclaim.

Project summary

With this support, the consortium developed, built, and tested a suite of first-of-a-kind modular hydrogen supply chain assets, including mobile refuellers, a semi-mobile compressor, construction-ready tube trailers, and a bespoke flatbed and Moffett system. These assets were evaluated through a combination of extensive quarry-based testing and demonstrations at live construction sites, comprising over 3,000 miles of on-road supply chain operation. The programme validated safe 350-bar refuelling for hydrogen non-road mobile machinery (NRMM), achieved deployment models meeting the Agreement Concerning the International Carriage of Dangerous Goods by Road (Accord Dangereux Routier – "ADR"), and established repeatable procedures, risk assessments, and training materials required for real-world operation.

In parallel, Ryze worked with project partners Sizewell C, Skanska, and Mace Dragados, to assess the integration of hydrogen supply chains into different site archetypes, ranging from highly regulated nuclear environments to remote earthworks and constrained urban stations. These case studies lay the groundwork for the safe future operation of hydrogen refuelling at diverse construction settings by identifying site-specific constraints, and outlining the enabling

[1] 'Zero diesel sites route map', Construction Leadership Council, Jun 2023

actions required for sector-wide rollout: including standardised refuelling protocols, workforce training, and clearer insurance frameworks.

Taken together, the project provides strong evidence that hydrogen can play a critical role in decarbonising UK construction. It shows that the equipment, operational practices, and supply-chain models needed for early adoption already exist; that major contractors are willing to deploy hydrogen where reliable solutions are available; and that the UK has a near-term opportunity to scale domestic manufacturing and secure economic, environmental, and industrial benefits. The H2-to-Site project demonstrates both technical feasibility and commercial readiness: laying the groundwork for the UK to become a global leader in hydrogen-powered construction.

Graphical abstract

Phase 1: Development




WP2 & 6: Mobile Refuelling equipment



WP5: Mobile compression



WP4: Tube trailer



WP3: Generator

Phase 2: Testing

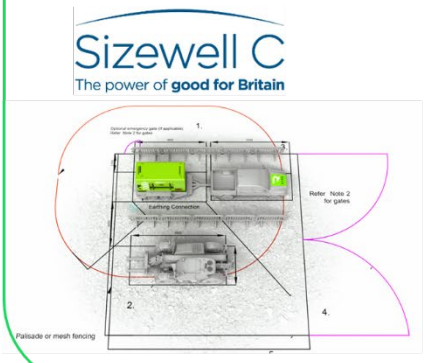


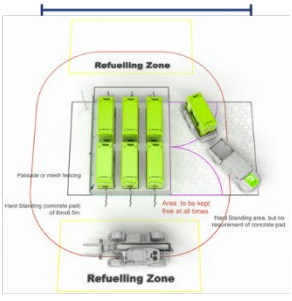
WP7: Quarry testing

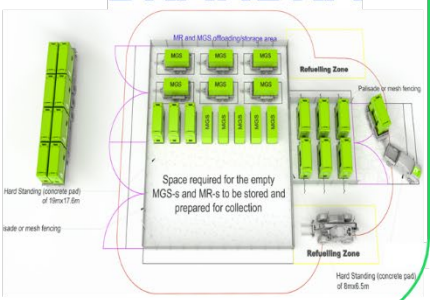


WP7a (extension): External site demonstrations

In parallel: Case studies







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Abbreviations

Table 1: List of abbreviations used in this report.

Abbreviations	**Full Term**
ADR	Accord Dangereux Routier
ATEX	ATmosphères EXplosibles
BCGA	British Compressed Gases Association
CIAB	Compressor in a Box
CO_2	Carbon Dioxide
COMAH	Control of Major Accident Hazards Regulations
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations
EDF	Électricité de France
FAT	Factory Acceptance Test
FC	Fuel Cell
FCIAB	Fuel Cell in a Box
FDS	Functional Design Specification
FEED	Front End Engineering Design
GHG	Greenhouse Gas
GFS	Gas Flow System
GRA	Generic Risk Analysis
GW	Gigawatt
H_2	Hydrogen
HAR	Hydrogen Allocation Round
HAZID	Hazard Identification

HSE	Health & Safety Executive
HS2	High Speed 2
HVO	Hydrotreated Vegetable Oil
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
JV	Joint Venture
kW	Kilowatt
LCHS	Low Carbon Hydrogen Standard
MEGC	Multiple Element Gas Containers
MGS	Modular Gas Storage
MJ	Megajoule
Mtoe	Million tonnes of oil equivalent
MW	Megawatt
NRMM	Non-Road Mobile Machinery
OEM	Original Equipment Manufacturer
P&ID	Piping and Instrumentation Diagram
PSV	Pressure Safety Valve
QRA	Quantitative Risk Assessment
RACI	Responsible, Accountable, Consulted, Informed
RDR	Red Diesel Replacement
SIL	Safety Integrity Level
TCO	Total Cost of Ownership
TRL	Technology Readiness Level
ULEZ	Ultra Low Emission Zone

WP	Work Package

1 Background

Since April 2022, the UK Government has removed the entitlement for most industries to use red diesel, a rebated fuel widely used in off-road vehicles and construction machinery. This decision was part of its strategy to decarbonise carbon intensive sectors. This policy shift created an urgent need for an alternative, cleaner energy source to be used in the construction sector. In response to this shift, the Red Diesel Replacement (RDR) programme has been developed by the Department for Energy Security & Net Zero (DESNZ), to support the development and demonstration of low carbon alternatives to red diesel currently used in off-road sectors, such as construction, mining, and quarrying sectors. Hydrogen, which produces zero carbon emissions at the point of use and has a cleaner exhaust profile compared to diesel, has been identified as a promising alternative, particularly for heavy-duty applications in challenging environments like construction sites.

1.1 Potential of a UK hydrogen construction sector

The UK built environment is responsible for around 25% of national greenhouse gas emissions, driven by energy-intensive processes, widespread diesel use, and carbon-heavy building materials.[2] Without decisive action, the sector risks undermining the UK's legally binding commitment to achieve net-zero emissions by 2050.

Pressure to decarbonise is mounting. Local authorities and private developers are increasingly expected to reduce carbon emissions and deliver sustainable projects. However, current practices, including reliance on diesel-powered NRMMs, continue to lock in high emissions and negatively impact air quality, especially in urban areas.

Transitioning to low- and zero-emission technologies has therefore become urgent. While battery-electric machinery shows promise, it faces significant barriers, including the need for large-capacity batteries, reliable grid connections, and long permitting timelines for temporary sites. This limits the number of construction sector applications which can be decarbonised using battery-electric technology alone. Hydrogen-powered solutions offer zero emissions at the point of use and thus deliver substantial air quality improvements, a critical benefit for construction in densely populated environments.

Hydrogen represents a scalable and sustainable pathway for the decarbonisation of the construction sector. The UK construction sector operates an estimated 300,000

[2] '[Building to net zero: costing carbon in construction]', House of Commons: Environmental Audit Committee, 26 May 2022

items of NRMM, which has a yearly diesel consumption of 2.5 million tonnes of oil equivalent (Mtoe).[3] This results in emissions of 7.4 million tonnes of CO_2 emissions per year.[4] To decarbonise this sector using hydrogen, more than 870,000 tonnes of low carbon hydrogen would be needed each year, equivalent to an electrolysis capacity of 9.3 GW.[5]

In addition to catalysing private investment, the hydrogen-powered construction sector can also create a large number of jobs. This is already happening in other parts of the world; the deployment of 2 GW in electrolyser capacity in Spain is expected to generate 17,000 jobs, based on estimates by Navigant.[6,7] It is estimated that manufacturing HYKIT supply chain equipment will generate up to 270 jobs to support the UK hydrogen construction sector, rising to up to 1,600 once export potential is realised.[8] Transitioning to hydrogen-powered equipment will help to retain the approximately 100,000 existing jobs in the NRMM sector rather than increasing them directly.[9] However, by retaining its leadership in hydrogen-powered construction machinery, the UK has the opportunity to export equipment to other countries seeking to decarbonise their construction sector and therefore increase the number of jobs in NRMM manufacturing.

[3] 'Zero diesel sites route map', Construction Leadership Council, Jun 2023
[4] This assumes an energy content of 41.7 GJ per toe, an energy density of diesel of 38.0 MJ/L, and 2.68 kg CO_2 per litre of diesel.
[5] This assumes a hydrogen energy content of 120 MJ/kg. For the electrolyser capacity 8,000 operational hours per year, an energy requirement of 60 kWh/kg hydrogen and a load factor of 70% are assumed.
[6] 'Betting on green hydrogen to fulfil employment growth', CIC EnergiGUNE, 24 Jan 2023
[7] Gas for Climate - Job creation by scaling up renewable gas in Europe, Navigant, 18 Nov 2019
[8] The number of jobs is based on the workforce required to supply the 300,000 NRMM currently operating in the UK construction sector over a 10-year period, and assuming that 83% of the UK NRMM manufacturing industry's output is exported.
[9] 'Powering Growth: The role of hydrogen internal combustion engines in non-road mobile machinery', HYDROGEN INTERNAL COMBUSTION ENGINE SUB-GROUP, Oct 2024

2 H2-to-Site: Project overview

While there has been considerable progress in the development of hydrogen fuelled construction machinery, there is a lack of hydrogen refuelling infrastructure tailored to construction sites, which poses a barrier to hydrogen adoption as fuel. To address the need for a scalable hydrogen solution to be used in the construction sector, Ryze Power, a leading hydrogen distributor based in the UK, has led the H2-to-Site project, part of the RDR programme funded through DESNZ's Net Zero Innovation Portfolio (NZIP). This initiative is a collaborative effort focused on proving the feasibility of hydrogen as an alternative, clean fuel for NRMM and developing new distribution and refuelling infrastructure to enable this.

The aim of the project was to develop and demonstrate equipment that is mobile, flexible, and provides hydrogen on-demand at construction sites. The H2-to-Site project resulted in a new range of mobile, flexible, and production-ready hydrogen refuelling equipment that can deliver fuel on demand directly to hydrogen-powered machines. The equipment ranges from mobile compression, allowing high-pressure filling of pressure equipment at production and customer sites; transportable pressure equipment capable of supplying low-and-high (350 bar) pressure hydrogen to a range of applications, and; transport equipment for supplying in bulk and last-mile deliveries to sites.

The demonstration was centred around a series of demonstration phases at a live quarry site, where a large number of different hydrogen-fuelled machines were tested, requiring up to 300 kg/day of hydrogen at the peak. These demonstrations generated critical data and conclusions, which will be used to inform best practices, including standard operating procedures, health and safety guidelines, and technical recommendations.

A major success of the project was the ability to extend these demonstrations to live construction sites: resulting in over 10 short-term demonstrations at a range of live working commercial sites, including housebuilding, wastewater treatment plans, and storage yards. These demonstrations allowed for significant safety and technical documentation to be developed, and prove the use of hydrogen under real-world conditions.

In parallel to these trials, the three major site operators conducted feasibility case studies in collaboration with the H2-to-Site consortium to assess their ability to adopt hydrogen technologies at specific construction sites. By validating hydrogen solutions in operational settings, the project will enable early commercial deployment, stimulate UK hydrogen production, and support domestic manufacturing of hydrogen-compatible equipment. Continued collaboration between industry and

government will be essential to unlocking hydrogen's full potential in the construction sector and delivering economic, social, and environmental benefits.

2.1 Project consortium

The consortium brought together stakeholders from across the hydrogen supply chain: ranging from OEMs, hydrogen supply, distribution and infrastructure, to site operators and potential end users of hydrogen NRMM:

- **Ryze Power** is a leading hydrogen supplier, distributor and infrastructure provider based in the UK, employing more than 30 people.

- **iGAS Technologies Solutions** is a UK-based engineering firm that designs and delivers turnkey systems for hydrogen and industrial gas filling, including high-pressure refuelling infrastructure.

- **Wrightbus** is a leading UK-based bus manufacturer and a pioneer in hydrogen fuel cell technology, having developed and commercialised the world's first double-decker hydrogen bus.

- **Sizewell C** is a 3.2GW new nuclear power station under construction on the Suffolk coast adjacent to the existing Sizewell B nuclear power station. The above-ground design will be a replica of Hinkley Point C in Somerset, creating thousands of UK jobs and apprenticeships and generating enough low-carbon electricity to supply over six million homes.

- **Skanska** is a Swedish global construction and development company with a major UK presence, is a leader in sustainable construction and an early

adopter of low-carbon technologies. Skanska employs more than 25,900 people worldwide.[10]

- **Mace Dragados** is a leading infrastructure and construction partnership, combining Mace's global construction consultancy with Dragados' heavy civil engineering capabilities. Primarily active on the UK's high-speed rail network (HS2), the JV is delivering landmark stations at Euston and Birmingham's Curzon Street, and will employ up to 3,000 workers during peak construction.[11]

2.2 Project outcomes

The project was awarded up to £3,212,280.99, with a budgeted project cost of £5,063,136.62: the project achieved its aims with a significant underspend of £2,377,636.81, against an estimated project spend of £3,690,866.06 .

With this support, it has successfully demonstrated a full end-to-end hydrogen supply chain for construction, from production and distribution to onsite refuelling and use in Non-Road Mobile Machinery (NRMM). Key achievements include the validation of equipment across 3,000 miles of on-road supply chain operation, ADR approval for transportable pressure equipment, and the demonstration of an off-grid refuelling solution, providing simultaneous power and refuelling of hydrogen.

Demonstration trials at quarry and construction sites validated new mobile refuelling technologies, supply chain equipment, and operational practices, proving that hydrogen can be deployed safely, reliably, and at scale.

3 Project workstreams and scope

The H2-to-Site project consortium has undertaken a series of trials, studies, and modelling exercises to develop and test equipment to supply hydrogen to construction sites and assess the potential of hydrogen in decarbonising the UK construction sector.

The project was divided into 9 work packages (WPs):

[10] 'Skanska', Forbes
[11] 'HS2 | Mace Dragados JV seeks subcontractors for £500M worth of Euston station work', New Civil Engineer, 11 Feb 2022

- WP1: Project Management (during the whole project)
- WP2: Mobile Refueller development (month 1-12)
- WP3: Fuel Cell generator development (month 1-16)
- WP4: Construction-ready tube trailer development (month 1-12)
- WP5: Compressor in a Box development (month 1-14)
- WP6: Distribution equipment development (month 1-16)
- WP7: Equipment demonstrations (Month 13-19)
- WP8: Feasibility studies (Month 9-19)
- WP9: Dissemination



Figure 1 - Gantt chart of planned project development timelines

The work packages can be broadly grouped into the following activities and outputs:

- Project management and output work packages: reporting, and developing outputs including TCO modelling, workshops, etc (Work packages 1 and 9, spanning the length of the project)
- Technology development of a suite of hydrogen supply chain equipment, designed for the full range of construction sites (Work packages 2-6, spanning Q3 2023-Q4 2024).
- Trials of both hydrogen machinery and hydrogen distribution equipment at an existing quarry sites (Work package 7, Q3 2024 – Q1 2025).
    - These trials were then extended to a number of short-term demonstrations at live construction sites: leading to over 10 demonstrations of hydrogen used in construction equipment doing real

work, from housebuilding to storage yards (Work package 7 extension, Q3 2024 – Q1 2025).

- Case studies with leading construction site operators Skanska, Mace Dragados, and Sizewell C to assess and prove the feasibility of hydrogen distribution supply chains and construction equipment at existing sites (Work package 8, Q2 2024 – Q2 2025).

3.1 Project management

Overall project management was shared between Lee Roberts (project management, outputs, and case studies) and Pratik Nayek (technology development, and trials/demonstrations). Individual work packages were further assigned a work package lead, along with supporting staff from Ryze Power. A full list of consortium project contributors by work package can be found in Appendix A.

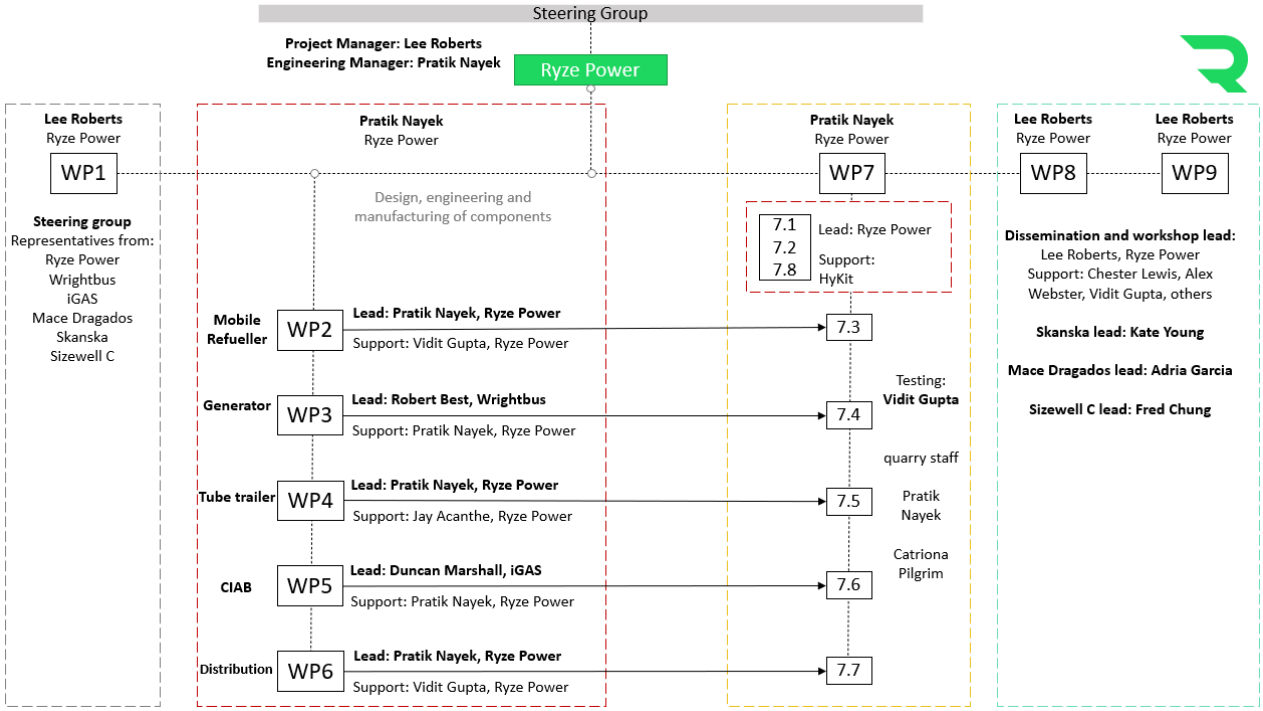


Figure 2 - H2-to-Site organogram

4 Design considerations, technical development, and challenges

The following sections provide an overview of the development work packages: including design considerations, development highlights, and lessons learned.

4.1 Hydrogen supply to construction sites: design principles

The project team identified several important requirements for Transportable Pressure Equipment (TPE) to be suitable for off-road applications such as construction sites: these principles fed into the design of the suite of equipment developed on the H2-to-Site project.

Physical site constraints: Construction sites are often faced with space limitations, with frequent movement of NRMM and vehicles around the site. Multiple machines are on site at any one time, particularly for large construction sites. Any refuelling equipment must be mobile, capable of being deployed in space constrained areas.

Site environment: Environmental conditions at construction sites are highly variable, and can significantly impact the safety, reliability, and performance of hydrogen equipment and supply infrastructure. Weather and temperature extremes can influence gas pressure, thermal management, and material behaviour, while dust and debris can be an issue for radiators, valves, and seals. Ground conditions pose a further challenge, with uneven or muddy surfaces posing safety hazards. Equipment must therefore be tailored to the unique requirements of construction sites, requiring alterations to designs when compared to traditional mobility or industrial solutions.

Dynamic layouts and operation: During the construction process, the layout, topography, accessible areas, and types of machines are subject to change. The refuelling equipment must therefore be not only mobile, but be easy to move, flexible in its deployment and operation, and ideally be capable of being driven to equipment across a range of terrain as needed, similar to diesel bowser operations today.

Safety and regulatory compliance: Hydrogen is subject to a range of regulations in the UK, including the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) and Health & Safety Executive (HSE)/British Compressed Gases Association (BCGA) guidance. All refuelling equipment and operation must meet these regulations and safety standards: including Transportable Pressure

Equipment Directive (TPED) and the ADR treaty (International Carriage of Dangerous Goods by Road) for transportable pressure equipment.

Usability: Importantly, for hydrogen to be accepted onto sites and used in a widespread way, the equipment must be user-friendly and be capable of being operated by staff on-site with appropriate training.

4.1.1 Hydrogen supply chain equipment

Based on the above constraints, the project team settled on a suite of modular hydrogen supply equipment: where equipment can be added or swapped out depending on the constraints and requirements of the site:

Construction-ready tube trailer

- Where site demand for generators is extremely high (e.g. 400kW and above), a tube trailer may be the most economical way to supply a site. Ryze have worked with a tube trailer OEM to alter the design of its standard tube trailers, with a pneumatic valve system to support a primitive cascade refuel. This system can be used to maintain uptime, by being taken to a mobile compressor site to fill Mobile Refuellers and Mobile Gas Storage where production sites are not available. The trailer also supports a decant refuelling strategy for partial fills of 350 bar equipment in emergency situations as part of site resilience. These tube trailers can store up to 650 kg of hydrogen.



Figure 3 - Ryze construction-ready tube trailers at the Quarry test site

Compressor-in-a-box (CIAB)

- To be able to compress hydrogen as needed at construction sites, the H2-to-Site consortium has developed a compact, self-contained compression unit. This system is referred to as a Compressor in a Box (CIAB) and enables onsite compression of hydrogen to higher pressures (up to 700 bar),

improving fuelling flexibility and supporting applications that require pressures beyond standard delivery levels (typically 350 bar and below).

Mobile Refueller

- The HYKIT Mobile Refueller is a modular mobile cascade refueller, used for refuelling mobile plant equipment with 350 bar on board storage requirements. Each Mobile Refueller unit developed for the trial phase of the H2-to-Site project contains 60 kg of hydrogen storage at 500 bar, of which 40 kg is usable. The units intended for commercial scale-up will offer increased capacity, storing 75 kg of hydrogen at 635 bar with 50 kg being usable. The Mobile Refueller can be transported by road and on construction sites using a flatbed truck or using a telehandler at construction sites.



Figure 4 - Compressor in a box (CIAB, left), refilling a HYKIT Mobile Refueller (right)

Mobile Gas Storage (MGS)

- HYKIT has also developed a Modular Gas Storage (MGS) system capable of storing hydrogen at 635 bar or 380 bar, designed to enable filling of generators with low-pressure hydrogen (selectable outlet pressure between 5 bar and 40 bar). The MGS can be transported by road and on construction sites using a flatbed truck, or using a telehandler at construction sites. This system offers mobile, modular storage, with flexible capacity based on 4 or 8 tank configurations, and can dispense hydrogen to mobile generators.



Figure 5 - HYKIT Modular Gas Storage

Distribution equipment

- A modified 40ft flatbed, with ISO container locks to support the transport of up to eight HYKIT Mobile Refuellers or up to twelve MGS at a time: allowing for asset deliveries to multiple sites with a single driver shift. The flatbed is paired with a Moffett, to allow for loading and unloading at customer sites.



Figure 6 - Prototype flatbed (left) and accompanying Moffett loading a test frame onto the flatbed (right)

4.1.2 Hydrogen supply chain

The H2-to-Site project sought to expand the current hydrogen supply chain. The conventional supply chain compresses hydrogen to 350 bar at a central hydrogen production site and delivers this via tube trailer to the construction site. At the construction site, the hydrogen can be directly delivered to mobile generators via a manifold using this equipment. However, for high-pressure equipment or for mixed-pressure deliveries (i.e. a mix of generators and 350bar NRMM on-site), alternative supply chains may be necessary.

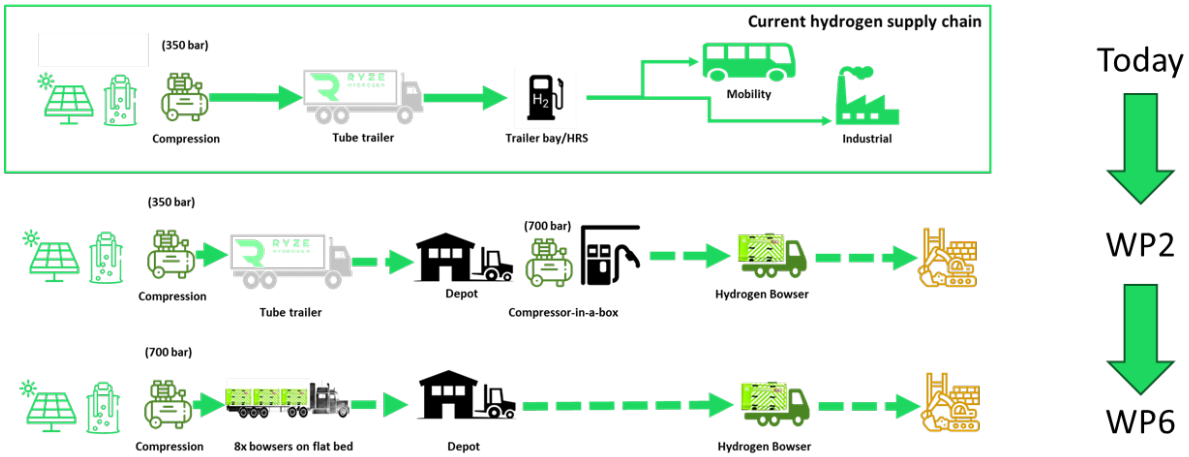


Figure 7 - Overview of hydrogen supply chains developed under H2-to-Site

The supply chain equipment developed on the H2-to-Site project can be used to either extend the existing supply chain, or provide a completely new approach for hydrogen delivery. CIAB enables the existing supply chain to compress hydrogen on site to 700 bar to fill a Mobile Refueller, and subsequently supply to high-pressure NRMM. This approach may be suited to large scale, long-term construction site projects.

Alternatively, the supply chain developed by the H2-to-Site project consortium for high-pressure NRMM equipment compresses hydrogen to 700 bar at a central hydrogen production site and subsequently stores the hydrogen in a Mobile Refueller. This Mobile Refueller is then delivered via flatbed trailer to the construction site and used to refuel NRMM. This same supply chain can be adapted for low-pressure mobile generators, compressing hydrogen to either 350 bar or 700 bar at a central hydrogen production site into MGS systems. The filled MGS are then transported via a flatbed trailer to the construction site. This method of supply offers significant flexibility, enabling several smaller sites to be supplied using the same delivery and supply assets through a “milkround”-style approach.

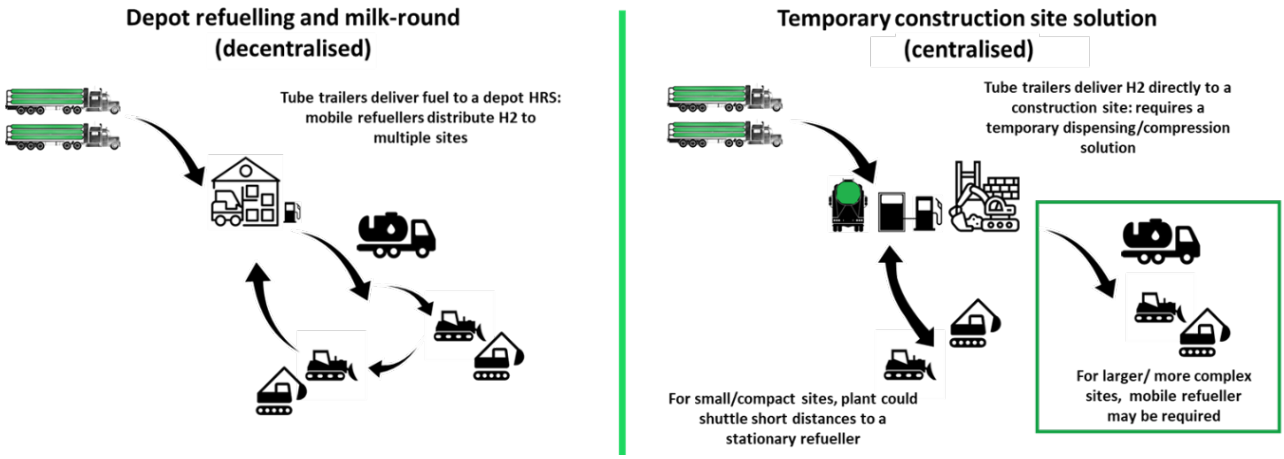


Figure 8 - Summary of potential supply chain operation using H2-to-Site equipment

4.2 WP2: Mobile Refueller

4.2.1 Key design considerations and challenges

Design and method of delivery

Initially, a traditional tube-trailer style mobile refueller with on-board compression was considered: this was discarded early on, for several reasons.

- Cost: the compression/booster takes up space, reducing the capacity of the asset. This results in a higher cost to the customer: delivery costs remain the same, while the volume of delivered hydrogen is reduced.
- Flexibility: a tube trailer style supply chain results in a single quantity of hydrogen being delivered to a single customer for a fixed delivery cost. A milkround-style approach is only feasible if pre-arranged refuelling times are agreed upon: severely impacting upon the customer experience. A modular solution reduces the cost to the customer by spreading the delivery cost across multiple assets, and separation refuelling schedules from any dependence on delivery times gives customers full flexibility.
- Scalability: a repeatable solution that does not require a drivetrain is simpler to manufacture, and significantly more scalable. Supply chains also scale more effectively: if demand is clustered within a region, multiple customers can be serviced with a single driver and delivery.
- Based on the above points, a modular, more flexible approach was designed: where Mobile Refuellers can be moved using several different methods, and can be dropped off at sites.

Flow and temperature control

Under ideal conditions, a gas that is compressed very quickly will approximate to an adiabatic process, where no heat is exchanged with the environment: this leads to an increase in the temperature of the gas, as per the below equation:

$$T_2 = T_1(\frac{P_2}{P_1})^{\frac{y-1}{y}}$$

where y is the heat capacity ratio, T is temperature, and P is pressure.

Hydrogen is a highly compressible gas, meaning its volume significantly decreases under pressure. When hydrogen is pumped into a tank at a much higher pressure than the starting pressure inside the tank, the gas compresses rapidly. While hydrogen does not behave as an ideal gas, and the process is not adiabatic, the speed of compression approximates to the above relationship: illustrating the challenges with temperature development.

Once the gas is heated, the rate at which heat can be dissipated is dependent upon several factors: including the surface area of the tank, thermal conductivity of the tank material, and ambient temperature. High ambient temperatures reduce the heat transfer rate, as the temperature gradient between the heated gas and environment is decreased.

The main challenge is that these two factors combined can result in the temperature of the gas exceeding the safe operating limits of the tank: risking structural integrity. This is exacerbated for refuelling procedures where the vehicle tank is drained: in the below examples, a half-empty tank (150 bar) is compared with filling an empty (20 bar) tank.

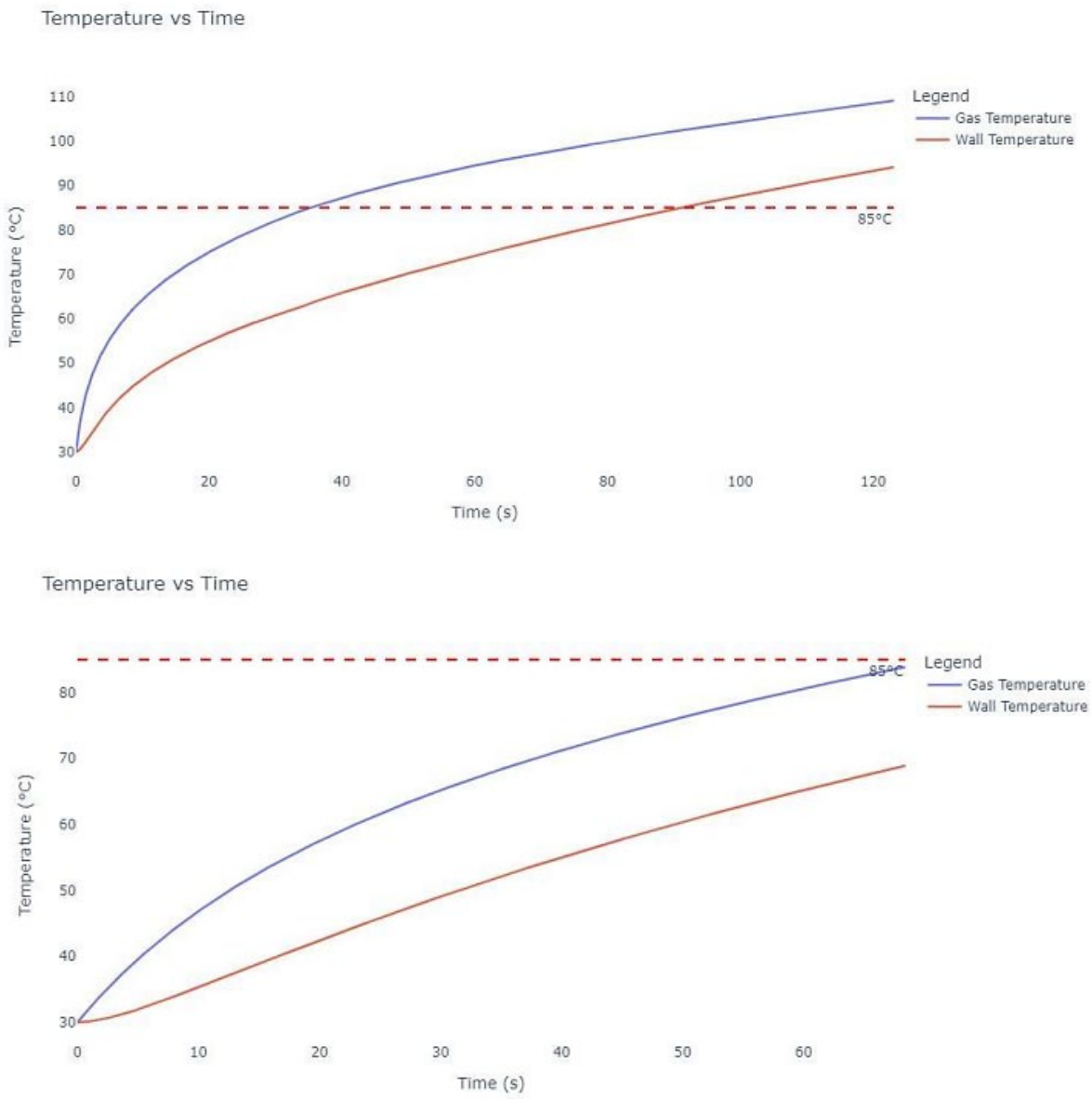


Figure 9 - Tank temperature modelling for refuelling from a starting pressure of 20 bar (top), and 150 bar (bottom)

Refuelling standards and regulatory compliance

Current refuelling standards, such as SAE J2601-5, assume active precooling down to -40°C fuel delivery temperatures, in order to mitigate the heating issues discussed previously: this is not feasible on mobile cascade systems due to the power and infrastructure requirements.

The protocol assumes SAE J2799 communications for full functionality, which are not implemented on current construction machinery.

Refuelling protocols are also written in such a way that they group Type III and Type IV gas cylinders together: this slows down refuelling unnecessarily on Type III systems.

Some standards, such as ISO 19880-1, permit the use of manufacturer-approved refuelling protocols: this allows HYKIT to implement safe but rapid refuelling tailored to the vehicle configuration, without the need for active cooling.

Permits and regulations

Early on, the need for TPED and ADR approval was quickly identified. All TPE used in the UK must bear a Rho mark: a conformity mark that proves that the equipment has been conformity assessed under ADR regulations. This is required for any use of the TPE: regardless of whether a commercial activity is taking place.

The aim of the refueller is to be as temporary as possible, maximising safety while requiring minimal site setup: despite this, Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) assessments are currently required for every site receiving hydrogen.

4.3 WP3: Fuel cell generator

4.3.1 Key design considerations, challenges, and learnings

Initial development of fuel cell in a box (FCIAB) focussed on early scoping, ensuring that component lead times were possible, initial testing of key components, and determining remaining costs and timelines for certification. The project resulted in high-level designs and the successful procurement of the key components necessary to begin the manufacture and testing of FCIAB.

Two significant challenges were identified during the next phase of the project. Firstly, the fuel cell type intended to be used in the first FCIAB models was designed and optimised for use in a vehicle. Although some of the shortcomings could be mitigated by reducing power output, prolonged and sustained use of the fuel cell showed performance challenges. In addition, heating of the fuel cell under high loads remained an issue.

Secondly, certification was identified to be a major barrier to development. The certification process for a generator model is different than Type approval for a vehicle or TPED. Any changes to core components require re-certification, at significant cost to the project.

Given the greater-than-required optimisation challenges faced, and the prohibitive cost of certification, the decision was made to stop WP3 development of equipment. The learnings and early outcomes of this project will be shared with HYKIT, a new OEM entity formed within the group of companies, who will have the necessary resource and expertise to undertake the full R&D program required to make FCIAB a reality.

Market Entry Barriers

- High certification and sales costs for the EU market: These costs are driven by the fact that certification is non-transferable if core components change, requiring recertification for even minor updates, thereby adding to both time and financial burdens.
- Increased labour demand on Wrightbus (WB) Engineering without specialised expertise: As generators are not Wrightbus's core business, a lengthy development program would require the establishment of a dedicated team to ensure project success.

Electrical design and cooling

A key specification of the unit depends upon the cooling of the fuel cell: operation must take place within fuel cell tolerances to avoid degradation, and heating of the hydrogen gas within the fuel cell must be minimised.

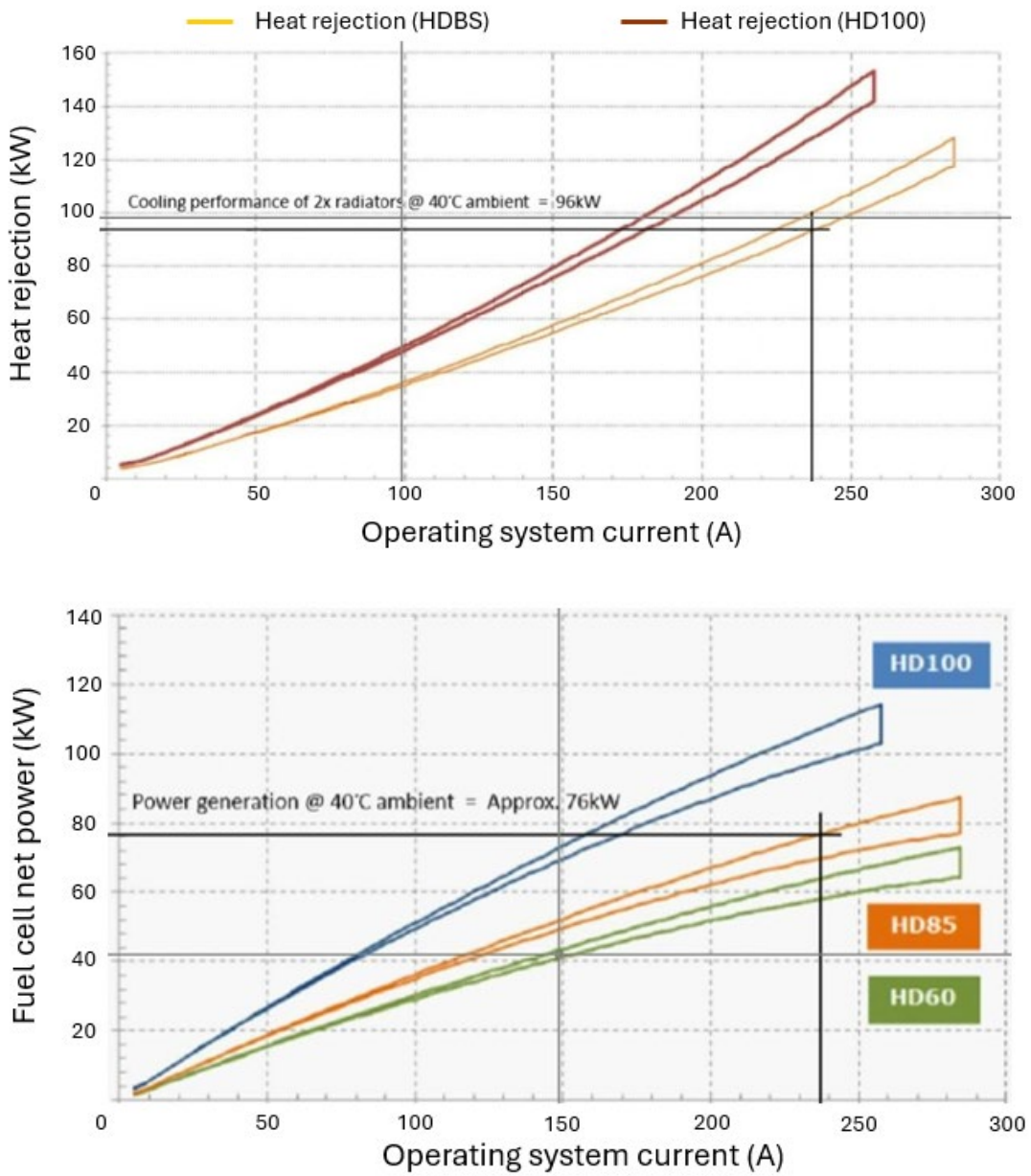


Figure 10 - Heat rejection analysis for proposed generator design

Heat rejection analysis was conducted for the fuel cell, assuming two radiators within the system, as shown above. This setup indicated that there would be a risk of the fuel cell overheating if power requirements exceeded 60kW (HD60) power output, while a third radiator would provide cooling suitable up to 85kW (HD85) power output. A third radiator (HDBS) would add an additional DC-DC system and three more fans: significantly increasing the development costs of the prototype unit.

In order to determine the amount of cooling and ancillary equipment required for the system, power load profiles were sourced from Maximator for the X-tower unit, which will be used in the WP5 CIAB. These load profiles indicated that a maximum power output of ~54kW would be required for compression up to 635 bar as would be

required for future Mobile Refueller units: indicating that the fuel cell power can be limited to safe levels of operation from a cooling perspective.

Further technical challenges

Continuous operation of the fuel cell for an extended period (~3-5 hours, as required for SSP filling) requires balance of plant that ensure stable and synchronised power output. Unstable power output poses several risks, including:

- Slower filling times
- Non-uniform filling times, which could introduce gas expansion and flow-rate effects
- Tripping of safety systems on the CIAB, should power output drop below certain levels

Synchronisation of several units requires additional battery storage and ancillary systems, which introduces further optimisation and BOP challenges. Although the load profile could be limited for CIAB, limiting power output significantly reduces the number of alternative applications that the unit could be used for. Certification processes pose significant challenges and risks for the development cycle (more detail in following sections).

Certification challenges

Certification remains a critical factor for market entry with significant costs and time requirements. Homologation, the process of certifying that a product meets regulatory standards for a specific market or application, is essential for the generator to ensure compliance with safety, environmental, and operational requirements.

This is particularly important as the generator will be deployed in diverse use cases, including construction sites and hydrogen refuelling. The costs are further compounded because certification is non-transferable if core components change, necessitating recertification for any design or component modifications.

Key Risks:

- Certification processes are non-transferable when core components are altered.
- Time required to certify and prove reliability is estimated at 8 months.
- Durability testing depends on hydrogen availability and costs.

A change request was therefore submitted, to use part of the remaining WP3 budget to support the leasing of a fuel cell generator to allow for the full range of testing to

continue as planned. The market was engaged for a fuel cell generator of appropriate size for the CIAB power output, available on relatively short notice. Two generators were selected for testing based on this procurement exercise: an Elemental Energy H2IPO 100, and the Inocel Gen-Z 200.

A comparison of the specifications of the generators can be found in the table below.

Table 2 - Specification comparison of Elemental Energy and Inocel generator solution

	Elemental Energy	**Inocel**
Rated power (EOL)	60 kW	160 kW
Peak power (EOL)	100 kW	200 kW
Battery pack	185kWh Lithium-ion	67kWh Lithium-ion

4.4 WP4: Tube trailer

4.4.1 Key design considerations and challenges

Ryze operates a fleet of Multiple Element Gas Containers (MEGCs) as part of its standard operations, and standardisation is crucial for operational flexibility. The aim of this work package was to update the existing P&ID to incorporate several new upgrades that would improve usability and functionality for site applications.

Many construction sites are unlikely to have the space required for the long-term storage of a 40-foot tube trailer: as a result, the expectation was that the tube trailer would only be used on the largest sites, or for satellite filling stations for the Mobile Refuellers.

4.4.2 Technical development

- Pneumatic valves: MEGCs contain a series of hydrogen storage cylinders connected with a combination of valves and pipework (multiple elements). The pre-existing chassis design used on previous trailer procurements required manual interaction with individual section valves to commence any filling/dispensing processes. To minimise the need for user interaction, the project decided on a re-designed solution to incorporate pneumatic valves across the MEGC, paired with a user interface to improve accessibility and mitigate errors.
- Material/chassis selection: Various cylinder types are available for use in trailers. Type II cylinders use a metallic liner with a composite hoop wrapping

to provide strength and weight savings over a Type I cylinder, which is made entirely of metal. Type III cylinders reduce the inner metallic liner further, and use the outer wrapping as the pressure bearing material, while Type IV cylinders (the lightest available on the market) use a composite inner liner and carbon fibre/polymer wrapping. With reduced weight comes increased cost and complexity of manufacture.

- Certification requirements: MEGC-style tube trailers must meet a series of regulatory requirements, including the following:
    - Directive 2010/35/UE: Transportable pressure equipment directive (TPED)
    - EN 13807:2017: Transportable gas cylinders - Battery vehicles and multiple-element gas containers (MEGCs) - Design, manufacture, identification and testing
    - EN 13480-3:2017: Metallic industrial piping. Design and calculation
    - ADR 2021: European Agreement concerning the International Carriage of Dangerous Goods by Road
    - Type approval and certificates of conformity should be sourced before use.

Commissioning

Tube trailers must be commissioned before being put into service: the commissioning process requires safe preparation, testing under controlled conditions, and validation in order to achieve TPE certification. The process steps are detailed below:

- Pre-commissioning: commissioning can only commence once type approval certificates and certificates of conformity have been received, and once a suitable site is identified.
- Preparation and checks: a series of checks and preparations must be undertaken prior to filling, including but not limited to earthing, determination of separation distances, standard trailer checks (e.g. visible damage, connections free from dirt and debris).
- Conditioning: the cylinders within the MEGC must be temperature conditioned, using heaters not exceeding design temperature limits (typically 65°C). Temperatures are measured at several points to ensure even heating. Conditioning begins when the coolest cylinder reaches 35°C on the surface, and must be maintained for 24 hours.
- Nitrogen vent: once conditioning is complete, a nitrogen flush to 30 bar pressure is required to ensure that the trailer is free from moisture and air.

- Hydrogen fills: hydrogen is added to the system at a controlled flow rate, following a standardised filling procedure. Several fills are required in order to achieve acceptable purity of hydrogen within the trailer.
- Leak tests: pressure hold tests and leak spray tests are finally conducted to ensure that the vessels are maintaining pressure.

All commissioning proceeded according to plan, with no issues reported and the trailers fully validated before being used to transport hydrogen from HYGEN's Tyseley site to the test quarry.



Figure 11 - Commissioning setup for the tube trailers

4.5 WP5: Compressor-in-a-box (CIAB)

4.5.1 Key design considerations

The WP5 team, consisting of Ryze Power, iGAS, and later with external support from HYKIT, defined the operational needs and design intent for a containerised, semi-mobile compressor suitable for refuelling Mobile Refuelling equipment. A functional design specification was developed over several workshops, outlining the following design requirements for market engagement:

- Performance: Fill hydrogen from 20–30 bar up to 635 bar (possibly 700 bar). Minimum throughput ~25 kg/h, able to fill 6 SSPs (50 kg usable each) in 12 hours.
- Operation: 24-hour operation, unmanned capability, 60 kVA max power, high reliability, minimal maintenance.

- Integration: Compatible with different TPE sizes (75–300 kg H_2), dual parallel fills, telemetry, and remote diagnostics.
- Design envelope: 20-ft ISO container, road-transportable, designed for CE/UKCA compliance, construction-site resilience, and operation for –20 to +65°C.
- Electrical and control system design: integrated PLC with HMI, safety interlocks, alarms, and remote telemetry consistent with unmanned operation.
- Safety & controls: HMI-based monitoring, automatic fill cut-offs using SSP pressure/temperature data, full earthing and venting strategies, defined fault handling.

4.5.2 Technical development

FEED study

The Front-End Engineering Design (FEED) study, led by iGAS, established the engineering and design framework for CIAB. The scope of work covered project management, process engineering, design development, and the preparation of formal technical deliverables forming the foundation of the later design and build phases.

Key activities included:

- Process and Design Development: Preparation of process flow diagrams (P&IDs), the Functional Design Specification (FDS), and initial layout and equipment identification for a mobile compressor system capable of filling multiple hydrogen buffer vessels (SSPs) from either tube trailers or electrolysers.
- Safety and Regulatory Basis: Alignment of the design with UK and EU pressure systems, machinery, and ATEX directives, alongside the preparation for later HAZOP and SIL reviews.
- Documentation and Deliverables: Creation of a Design Register, Design Quality Plan, and structured document control to ISO 9001:2015. Deliverables included engineering specifications, datasheets for major components, and CE marking compliance evidence for pressure and electrical systems.
- Client Engagement: Scoping and design review meetings with Ryze to confirm flow, pressure, and fill requirements; mechanical and electrical interfaces; and site parameters for mobile deployment.
- Project Management and Verification: Establishment of change management procedures, verification processes, and design validation checkpoints to ensure traceability and alignment with future build, FAT, and SAT phases.

Compressor selection

A total of seven compressor manufacturers were approached via an RFQ process, to determine whether a suitable compressor was available on the market within the timeframes of the project. Of the seven manufacturers approached, only two provided a product meeting all the above design and performance specifications. The limiting factor was either the maximum outlet pressure of semi-mobile options on the market, or the need for static installation. A booster compressor was not considered, due to the need to operate from both tube trailer supply (30-350 bar) and electrolyser supply (<30 bar).

The shortlisted suppliers had different strengths that were both valuable to the project:

- Maximator offered a superior flow rate when paired with a tube trailer, and was a defined product with potential for lead times to reduce.
- Hydrosys offered a superior flow rate when paired with an electrolyser, shorter lead times, and the option of producing a more bespoke product.
- The detailed specifications of each compressor solution are described in the table below.

Table 3 - Specification comparison of Maximator and Hydrosys compressor solution

	Unit	**Maximator**	**Hydrosys**
Type		Diaphragm	Piston
Inlet Pressure Minimum	barg	20	20
Inlet Pressure Maximum	barg	50	35
Inlet Temperature Minimum	°C	-10	-20
Inlet Temperature Maximum	°C	40	46
Outlet Pressure Maximum	barg	700	700
Flow rate at 30 bar inlet	kg/h	16.5	25.2
Flow rate at 50 bar inlet	kg/h	36	25.3
Containerised	Yes/No	Yes	Yes
Size LxWXH	cm	560x300x260	850x260x270

Power	kW	41	85
Lead time	Months	10 to 12	6 to 8
Number of Stages	#	3	4

After further technical evaluation and supplier engagement, the consortium confirmed Maximator as the preferred supplier. An agreement was reached between Ryze, iGAS, and Maximator on the final design that met all requirements and was compatible with the overall supply chain design. Ryze and iGAS maintained regular dialogue with Maximator throughout this period, issuing a formal letter of support to secure a manufacturing slot and reduce potential delivery delays.

Manufacturing delay

In mid-October, upon Maximator receiving the major piston parts, a roundness defect on one of the pistons was discovered. This required the part to be fully re-manufactured, with an initial delay estimate of 9 weeks. As a specific and bespoke component, a replacement was not readily available, and no possible mitigations were identified in the project risk review.

The initial view was that this delay could be mitigated by iGAS receiving two of the three stages of the compressor, to reduce this delay to 2-3 weeks: enabling FAT in week 48, and delivery to the quarry in mid-February 2025 as roughly intended.

However, the timing of the delays and proximity to Christmas holidays, resulted in a 5-week delay in total: this meant that CIAB testing could not proceed within original project timelines, resulting in an extension.

Factory Acceptance Testing (FAT) and Commissioning

Formal Factory Acceptance Tests (FATs) for the Compressor-in-a-Box (CIAB) were conducted at Maximator GmbH's Hydrogen Competence Centre in December 2024, attended by representatives from Ryze, iGAS, HYCAP, HYKIT, M-Tech and Maximator UK.

The purpose of the FAT was to validate performance, safety and control functionality of the integrated X-Tower compression system prior to shipment for installation within the CIAB container at M-Tech's facility.

The FAT programme included:

- System inspection – mechanical and electrical walkthrough of the Gas-Filling-System (GFS) container, verification of roof-mounted vent and control-panel integration.

- Compressor module configuration review – confirmation of Maximator's revised three-stage design (X-15 / X-30 / X-45) replacing the earlier X-05 / X-15 / X-45 arrangement.
- Performance and endurance testing – staged operation using hydrogen from 100 – 260 bar inlet to up to 700 bar outlet, recording pressure, flow and temperature.
- Leak integrity and E-Stop tests – validation of containment, interlocks and emergency shutdown response.
- Operator training and Siemens v2.0 control interface familiarisation.

Testing confirmed the revised 15 / 30 / 45-stage configuration achieved the target outlet pressures (to 700 bar) and superior thermal performance compared with earlier concepts. Flow rates of ~23 kg h^{-1} at 83 bar inlet and ~27 kg h^{-1} at 190 bar inlet were observed, matching or exceeding design predictions, with outlet temperatures remaining below 31 °C.

FAT results

During the two-hour endurance test a high hydrogen alarm (25 % LEL) was repeatedly triggered. Investigation determined this was caused by a pressure-relief valve (PRV) lift on Stage 1, linked to manual ramp-up of the compressor exceeding programmed control rates. Although no loss of containment occurred, the event resulted in test interruption and classification as a critical issue requiring root-cause analysis and component inspection.

The PRV was subsequently removed for bench-testing, with findings confirming that rapid manual start-up had temporarily exceeded the inter-stage pressure limit. Corrective actions included replacing the PRV, updating the control logic to enforce automated start-up sequencing, and re-running endurance validation.

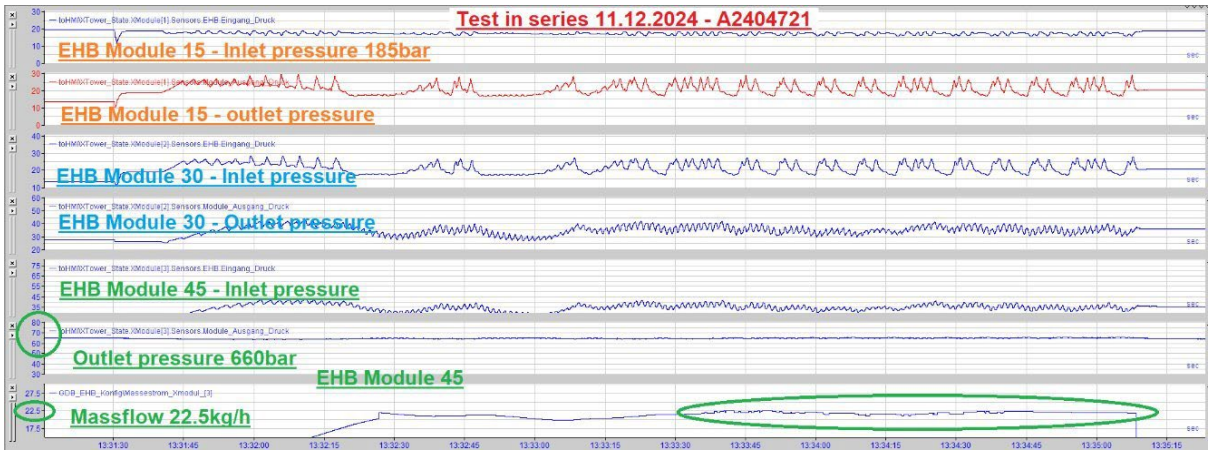


Figure 12 - Sample initial FAT results for CIAB

Follow-up FAT

A second FAT was scheduled to repeat the endurance and leak-integrity testing

under controlled PLC start-up conditions, confirm correct PRV operation, and verify all safety interlocks within the Safety PLC trip chain. This secondary FAT ensured the compressor met full acceptance criteria before release for shipment and integration.

4.6 WP6: Mobile supply chain equipment

4.6.1 Key design considerations and challenges

As with the Mobile Refueller, cost, flexibility, and scalability were the focus of the design of the supply chain. Work package 6 focussed on increasing the mobility of the refuelling assets. Early design studies considered a large, conventional mobile hydrogen refueller, but this concept was discounted due to complexity, weight, and limited on-site flexibility. A larger version of the existing Mobile Refueller was also explored, though this offered only incremental benefit over the established design.

Following several design iterations, the project team selected a variant of the existing Mobile Refueller platform, largely retaining the frame, footprint, and packaging. This approach offers advantages in terms of standardisation, modularity, and economies of scale, while maintaining compatibility with pre-existing safety and control systems.

The smaller, standardised footprint also enhances operational flexibility: each unit can be lifted, positioned, or redeployed using readily available site equipment, enabling rapid setup even on constrained sites. To complement this, a bespoke 40-ft flatbed and Moffett configuration was developed and commissioned in partnership with Montracon, capable of transporting up to six Mobile Refuellers simultaneously. Each unit can be lifted on and off the flatbed using the Moffett, allowing fast turnaround and minimal handling time.

This combined system introduces a “milk-round” style delivery model, enabling a scalable, high-throughput supply chain for hydrogen distribution. It combines the mobility and flexibility of SSPs with the storage and cascade refuelling capability of larger refuelling systems, representing a step change in the practical deployment of hydrogen for temporary or distributed demand sites.

4.6.2 Technical development

Delays and re-scope

The most significant challenge encountered during this phase was the procurement of Type IV composite cylinders, which form the core pressure storage component of both the Mobile Refueller and Mobile Gas Storage (MGS) systems. At present, Type IV cylinders are produced by only a small number of global OEMs, and the sector has faced sustained disruption arising from supply chain bottlenecks, testing and

certification delays, and international tariff uncertainty. The extent of this supply chain uncertainty only became apparent late in the project development cycle.

Given that the Mobile Refueller and MGS designs are first-of-a-kind (FOAK) and utilise a bespoke cylinder configuration, it was not feasible to substitute alternative suppliers without introducing major re-engineering, re-certification requirements, and extended delivery times. As a result, the project experienced delays while working closely with the cylinder OEM to identify viable solutions.

Over several months, Ryze and its engineering partners engaged directly with the OEM to explore mitigation strategies, including the use of available stock to accelerate prototype build and the reallocation of limited certified inventory. Parallel discussions were undertaken to secure an alternative Mobile Gas Storage solution using compatible cylinder types.

Ultimately, a replacement system resembling a 10ft MEGC, using the same Type IV cylinders in a different, standard packaging, was sourced in order to meet project timelines: the difference in specification is shown below. Refuelling and dispensing results using this system were consistent with expectations for the MGS, validating the concept. Nonetheless, the MGS remains the preferred long-term solution, due to its interoperability within the designed supply chain, and a capacity calculated to provide the best cost-per-kg delivered for an average construction site.

Table 4 - Comparison between intended MGS design and project replacement

	Unit	**HYKIT MGS**	**Replacement**
Pressure	Bar	380	380
Capacity	Kg H_2	69	217
Volume	Litre	2,680	8,400
Number of cylinders	#	8	24

4.7 WP8: Case studies

In parallel with equipment development, Ryze worked with three major delivery partners (Sizewell C, Skanska, and Mace Dragados) to work through how hydrogen NRMM and associated supply chains could be integrated into construction environments, through a series of desk-based case studies.

The case studies presented three distinct deployment scenarios:

- A nuclear powerplant construction site: similar to the Phase 1a demonstrations, focussing particularly on health and safety considerations.
- A large remote earthworks project for Skanska: utilising a wide range of equipment, similar to the demonstration during Phase 2.
- A complex urban excavation at HS2 Euston with Mace Dragados: determining the art of the possible when faced with space constraints, urban environments, and complex route planning considerations.

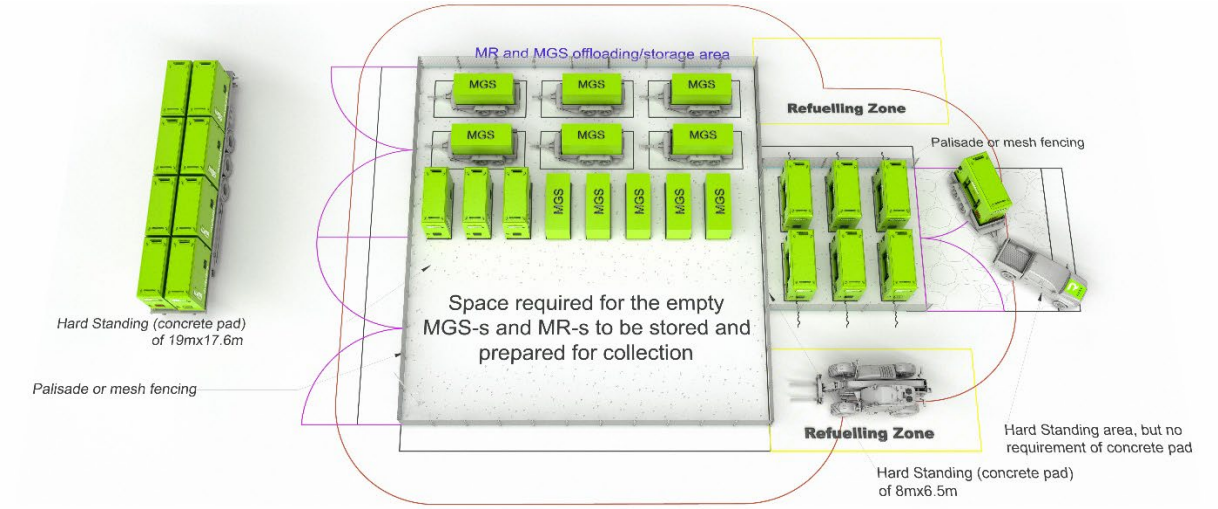


Figure 13 - Example of refuelling area developed as part of Skanska case study

For each case study, the Ryze engineering team determined the necessary refuelling pathways, equipment layouts, logistics operations, and safety considerations. The solutions and designs were shared and refined at a series of workshops, to elucidate any challenges or requirements for the site, and to discuss any further considerations relating to the operation of hydrogen refuelling at construction sites.

These sessions indicated that, supported by the project demonstrations, hydrogen NRMM can be safely refuelled at 350 bar using mobile assets, and that both low-pressure (generator) and high-pressure (NRMM) applications can be supported using scalable, modular supply chains. The work also identified specific site-level considerations, such as traffic flow, hardstanding availability, site access, and operator training, which influence how hydrogen logistics must be tailored for different construction environments.

The case studies show that the equipment, procedures, and supply chains developed through H2-to-Site could be deployed at real sites today. They also highlight the wider enablers needed for sector-wide adoption, facilitated by the following agreed enabling actions:

- **Standardised refuelling protocols:** Hydrogen in construction is an emerging field and currently hydrogen refuelling standards are primarily focused on static, road mobility applications. Specific standards for heavy-duty NRMM are not yet available. A coordinated effort between government, industry, and standards bodies is needed to develop a dedicated standard for hydrogen refuelling for construction use cases. This will be critical to scaling hydrogen deployment and allow efficient refuelling and compatibility across multiple sites and suppliers.
- **Training and workforce development:** A safe and efficient hydrogen transition will depend on a readily deployable, trained workforce. Construction sites often work with contractors, who will benefit from a trained workforce that can be rapidly deployed. A nationally approved set of training modules, supported by government and emergency services, and working with industry, should be established focused on safety, operations, and emergency procedures, and not place undue burden on construction site operators.
- **Insurance safety standards and templates:** To support understanding among insurers of emerging hydrogen technologies, safety standards and educational materials should be developed. These resources could act as reference templates, helping to simplify and accelerate the approval process for future projects by reducing the need for extensive and repetitive site-specific risk documentation. By creating the knowledge base and standardising the risk assessments, the procedures for future deployment will be streamlined and promote insurer confidence of the novel hydrogen technologies.

5 Demonstration study

5.1 Project plan

5.1.1 Initial testing plan

The original test plan for the H2-to-Site project was for all equipment to be received sequentially on site between August 2024 and February 2025, based on planned equipment development timelines, starting with the Mobile Refueller. Each piece of equipment would then be tested and validated separately, before being integrated into the wider supply chain to prove the modular concept.

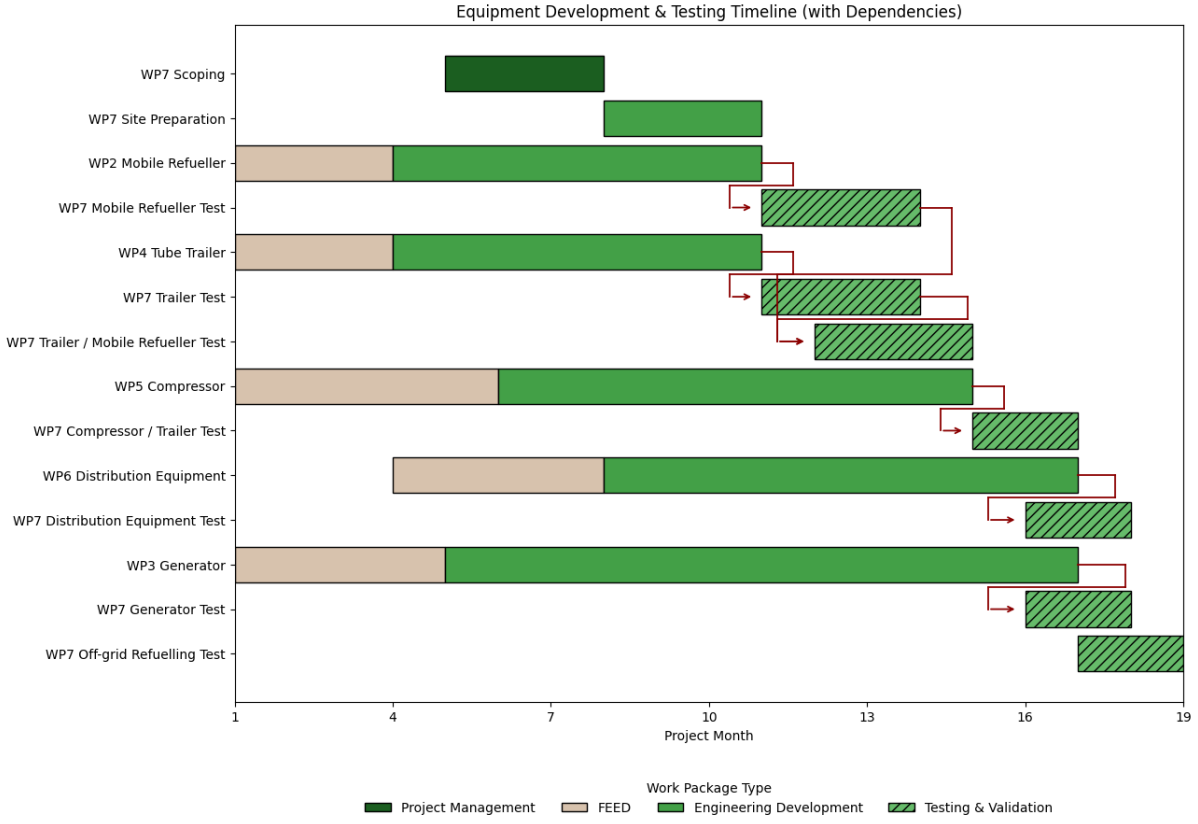


Figure 14 – Initial project development and testing plan at project start

5.1.2 Finalised testing plan

Changing development timelines resulted in a significant departure from the intended testing schedule. The Mobile Refueller (WP2) and tube trailers (WP4) were developed and commissioned ahead of schedule: as the test site already had facilities for the receipt and dispensing of hydrogen, initial testing and validation of the Mobile Refeuller and tube trailers was accelerated.

On the other hand, the development of the ancillary pieces of equipment was delayed or changed for various reasons (Design considerations, technical development, and challenges). Most notably, the roundness error discovered late in the compressor manufacturing process, and supply chain issues relating to the procurement of the necessary components for WP6, led to a series of delays to the associated testing sub-packages. This resulted in two distinct test phases, taking place in Q2 2024 and Q2-3 2025.

However, the accelerated Phase 1 test schedule led to an opportunity to extend testing beyond the original programme: the success of Phase 1, and achievement of ADR approval for the Mobile Refueller, an opportunity arose to test the equipment at live construction sites where hydrogen NRMMs were used to deliver work previously undertaken by diesel NRMMs. Between September 2024 and February 2025, hydrogen was supplied to twelve construction sites on UK roads using ADR-approved supply chains, proving the viability of the following equipment on a range of live construction sites:

- Hydrogen combustion generator/generator, using a tube trailer to supply hydrogen.
- Hydrogen telehandler, using Mobile Refueller for hydrogen dispensing.
- Hydrogen backhoe, using Mobile Refueller for hydrogen dispensing.

This allowed for an extended series of real-world demonstrations, over a total period of 6 months, between Phases 1 and 2 of testing under controlled conditions at the test quarry. The final test programme is shown below.

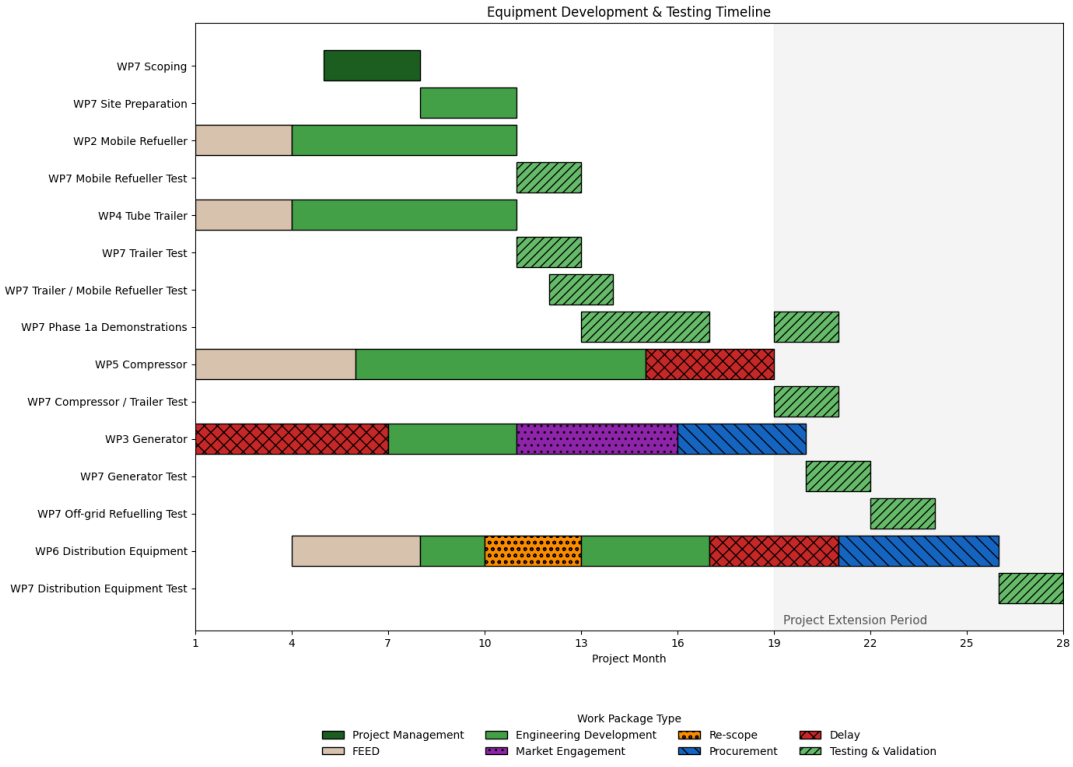


Figure 15 - Finalised testing plan (Phase 1 – blue dates, Phase 2 = yellow dates, green periods = test periods)

		Week commencing					
Number	NRMM tested	09-Sep-24	16-Sep-24	23-Sep-24	30-Sep-24	07-Oct-24	14-Oct-24
1	Genset						
2	Genset						
3	Loadall						
4	Genset						
5	Loadall and backhoe						
6	Backhoe						
7	Genset						
8	Loadall						
9	Genset						
10	Backhoe						
11	Backhoe						
12	Genset						

		Week commencing						
Number	NRMM tested	21-Oct-24	28-Oct-24	04-Nov-24	11-Nov-24	18-Nov-24		24-Feb-25
1	Genset							
2	Genset							
3	Loadall							
4	Genset							
5	Loadall and backhoe							
6	Backhoe							
7	Genset							
8	Loadall							
9	Genset							
10	Backhoe							
11	Backhoe							
12	Genset							

Figure 16 - Timeline of external site trials conducted as part of the extension to Phase 1

5.2 Methodology

5.2.1 Roles and responsibilities

To ensure efficient and coordinated delivery of the H2-to-Site project, the consortium developed a RACI (Responsible, Accountable, Consulted, Informed) matrix, led by Ryze Power. This framework was used to clearly define roles and responsibilities across all project phases: development, testing, and commissioning.

Given the multi-partner nature of the project, involving equipment manufacturers, infrastructure specialists, and construction operators, the RACI matrix played a crucial role in aligning expectations and minimising operational delays. The full matrix is presented in the figure below, illustrating how responsibilities were distributed across the consortium partners for all major project development and testing activities.

Ryze Power Project Delivery Resource Assignment Matrix

Project Name: Red Diesel Replacement Competition - H2 to Site

R - Responsible A - Accountable C - Consulted I - Informed

NAME / Deliverables	Project control (Budget, Schedule)	WP2: Refueller development (Design)	WP2: Refueller development (Items PO)	WP2: Refueller development (Manufacture)	WP2: Refueller development (Commissioning)	WP3: Fuel cell generator testing	WP4: Tube trailer development (P&ID)	WP4: Tube trailer development (Manifold)	WP4: Tube trailer development (Certification)	WP4: Tube trailer development (Commissioning)	WP5: Compressor Development (FEED)	WP5: Compressor Development (Manufacturing)	WP5: Compressor Development (Commissioning)	WP6: MGS/Flatbed Development (Design)	WP6: MGS/Flatbed Development (Manufacturing)	WP6: MGS/Flatbed Development (Certification)	WP6: MGS/Flatbed Development (Commissioning)	WP7: Quarry Demonstration (Scoping)	WP7 - Hydrogen delivery	WP7: Quarry Demonstration (Safety)	WP7: Quarry Demonstration (Testing)	WP7: Quarry Demonstration (Data collection)
Ryze Power Project Engineering (PN)	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	C	C	A	A	A
Ryze Power Project Engineering (DS)	C	I	I	I	I	I	I	I	I	I	C	C	C	I	I	I	I	R	C	R	R	R
Ryze Power Project Engineering (JA)	C	C	C	C	C	R	R	R	R	R	C	C	C	R	R	R	R	I	I	I	I	I
Ryze Power Project Manager (LR)	R	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	A	C	C	C	C
Ryze Power Operations (CP)	I																	C	R	C	A	C
Ryze Power Commercial Support (CL)	C	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	C	I	I	I	I
Ryze Power Commercial Support	I	I	I	I	I									I	I	I	I	I	I	I	I	C
Ryze Power Accounts	A		I			I		I	I	I	I	I	I				I	I			I	
Ryze Power Subcontractors					R	R	R	R	R	R			R				R					
HyKit engineering	I	R	R	R	R									R	R	R	R	C		A	C	A
Engineering	I	I	I	I	R									R	R	R	R	C		A	C	A
Testing Personnel	I																	R		R	R	R
iGAS	I										R	R	R					C		C		

R Responsible - who performs the task

A Accountable - who signs off

C Consulted - who provides expert judgement

I Informed - who is kept informed

Figure 17 - H2-to-Site Project Testing Delivery RACI Matrix

5.2.2 Site setup

The Ryze team, in collaboration with quarry staff, completed a comprehensive site setup process including risk assessments, site analysis, and training. Quarry, already equipped for hydrogen NRMM testing ahead of the H2-to-Site project, allowed for a quicker and more efficient setup compared to establishing a new site, eliminating the need to repeat the safety studies outlined in the previous section.

At this stage, the following key areas were reviewed to ensure project readiness and alignment between teams:

- Project Handover Documentation
- Change Management System
- Detailed Design Engineering and Safety Studies
- Risk Register, including risk identified in similar past projects
- Project Execution Plan
- Project Organisational Chart and Staffing Plan
- Delegations of Authority
- Overall Project Schedule
- Project Execution Organisation, Staffing & Deployment Status

The test site already had the following provisions for hydrogen refuelling in place:

- Static Maximator compressor capable of high-pressure hydrogen refuelling: allowing tests to commence in the event of delays to CIAB
- Hard-standing area
- Established exclusion zone and safety barriers
- Trailer bays equipped with pipework and pressure let-down systems
- Due to the site's existing infrastructure, some standard project checks, such as gas and utility contracts and permitting, were not required.

5.3 Minimum safety requirements

The H2-to-Site project consortium conducted the demonstration trials in full accordance with international best practices, including ISO 19880-1 (hydrogen refuelling station safety), IEC 61508/61511 (functional safety of control systems), and guidelines from EIGA and the BCGA, such as CP33 (storage and use of hydrogen) and CP41 (hydrogen vehicle refuelling stations). As part of this approach, the implementation of the hydrogen refuelling/dispensing facility was supported by a suite of structured safety studies. These studies ensure that both the inherent

process risks and site-specific hazards are systematically identified, assessed, and effectively mitigated. The primary studies conducted include:

- **Hazard Identification (HAZID)**: A site-wide HAZID is recommended to evaluate external threats and environmental risks affecting the hydrogen refuelling areas, such as proximity to traffic routes, third-party utilities, or flammable materials. This includes human factors, loss of containment, and natural hazards (e.g. flooding and lightning).
- **Generic Risk Analysis (GRA)**: The GRA assesses the full spectrum of potential accident scenarios associated with hydrogen use, including leaks, ignition, deflagration, and overpressure. This quantitative or semi-quantitative analysis determines the frequency and severity of credible events and is used to define the Elements of Importance for Safety, such as gas detection systems, safety shutoff valves, and emergency venting provisions.
- **Dangerous Substances and Explosive Atmospheres Regulations 2002** (**DSEAR)**: A DSEAR assessment identifies and evaluates the risks associated with the use, storage, and generation of dangerous substances: such as gases, vapours, mists, and combustible dusts, which could potentially ignite or explode. The assessment ensures that appropriate measures are taken to eliminate or control these risks through zoning, equipment selection, signage, training, and emergency planning.

  Key points of the DSEAR Regulation are:

  - Required by UK law for workplaces handling flammable or explosive materials
  - Identifies hazardous zones (eg. Zone 0, 1, 2 for gases)
  - Evaluates ignition sources and implements control measures
  - Ensures compliance with ATEX equipment standards
  - Includes employee training and emergency preparedness
- **Hazard and Operability Study (HAZOP) & Safety Integrity Level (SIL) Assessment** A HAZOP study systematically reviews process deviations and potential failures in the hydrogen system, identifying hazards related to pressure, flow, temperature, and control logic. Where automated safety systems (e.g. emergency shutdown or gas detection) are used to mitigate risks, a SIL assessment is carried out to determine the required reliability of these functions based on consequence severity and event likelihood.
- **Interface HAZOP**: An interface HAZOP examines the interactions between the hydrogen installation and third-party systems, such as utilities, data interfaces, site security, and emergency response mechanisms. This ensures that risks are not transferred across organisational or system boundaries.
- **Quantitative Risk Assessment (QRA), if applicable**: For installations that breach inventory levels defined within L111 (Guidance on COMAH 2015), a QRA is required by the Competent Authority in addition to other statutory obligations. This involves modelling event consequences (e.g., thermal radiation, overpressure, and the

dispersion of hydrogen plumes) and comparing societal and individual risks to accepted thresholds.

- **Emergency Response and Evacuation Study**: Based on identified scenarios, a study of evacuation routes, muster points, and first responder access is conducted in accordance with Ryze processes and HSE guidance document HSG191 (Emergency planning for major accident hazards). This includes simulation of gas cloud behaviour and blast radius predictions to inform safety distance zoning.

5.3.1 Phase 1 - Initial quarry testing

As the test quarry has a pre-installed static compressor on-site, the project could commence with initial testing of the Mobile Refueller and Tube Trailers ahead of commissioning of other equipment. Following commissioning of the Tube Trailers, the trailers were filled at Tyseley Energy Park in Birmingham and driven by road to the test quarry. On-site facilities included a hard standing area, pipework, and suitable safety distances and precautions.



Figure 18 - Clockwise from top left: trailer bay setup, on-site compression, close-up of refuelling nozzle in use, close-up of Mobile Refueller dispensing point

Several training sessions were held, initially with the core Ryze RDR team, and three separate Standard Operating Procedures were created through initial validation sessions: for filling of

the Mobile Refueller, Transportation of the Mobile Refueller over short distances, and filling of NRMM using the Mobile Refueller. The Mobile Refueller was filled using the on-site compression, with a maximum fill of up to 500 bar possible. Each fill was preceded by a series of pre-filling checks, as defined by the agreed upon Standard Operating Procedure. Data was primarily collected for high pressure refills of NRMM on-site, up to 350 bar. Strict filling protocols were followed to ensure control of temperature and pressure differentials. The development Mobile Refueller required an ATEX zone of 2m during fills, according to regulations and based on the existing design.

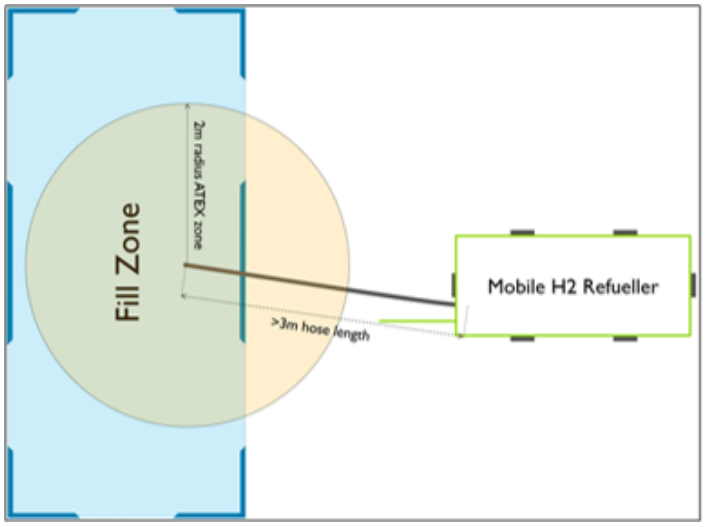


Figure 19 - Diagram of filling layout, including ATEX zone during filling

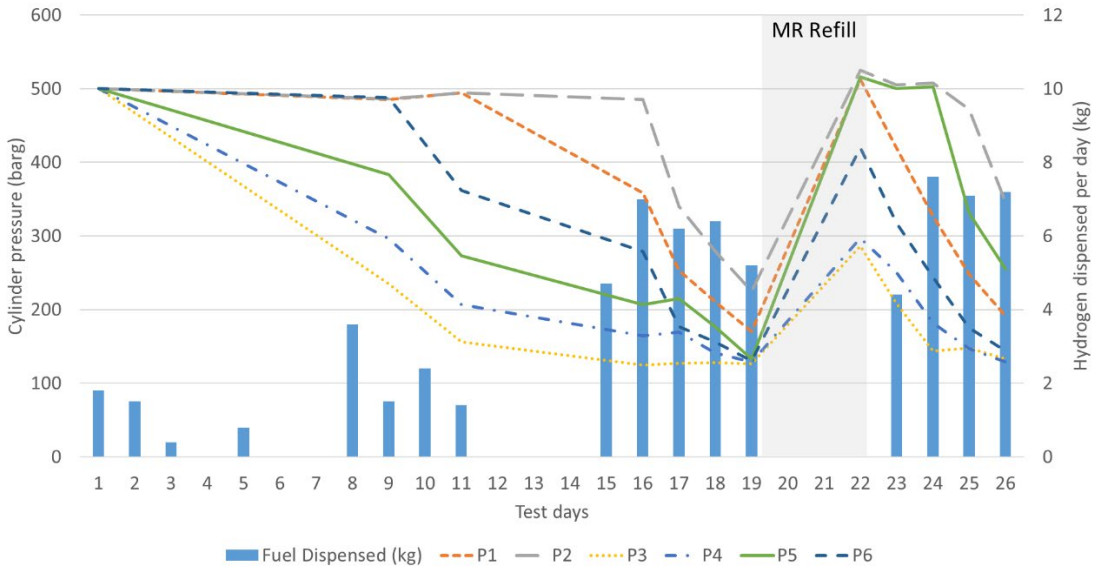


Figure 20 - Sample of Mobile Refueller validation results

Figure 20 shows a sample of test results over an extended period of testing: the pressure within each cylinder is shown individually, illustrating the principle of cascade refuelling. Slight variations in pressure are visible in cylinders when unused: this was determined to be caused

by differences in ambient conditions, and no leakage was observed when unused. Dispensing tests were ramped up in intensity over time, up to a maximum individual fill of 9kg.

Quarry testing continued uninterrupted across a 7-week period, with a 97% average availability across the three Mobile Refuellers. Approximately 1.5 tonnes of hydrogen was used during this first phase of testing, across trailer and Mobile Refueller usage: equivalent to approximately 8.6 tonnes of carbon saved at the point of use relative to an average diesel/biodiesel blend[12].

5.4 Phase 1a

The Mobile Refueller combined with the ADR-approved Trailer (MRT) and towed by a 4x4 pickup truck, has been extensively tested across British roads to validate its operational suitability for hydrogen delivery to remote quarry sites. An example of the MRT configuration is shown in the figure below.



Figure 21 - Mobile Refueller Trailer (MRT) towed by a 4x4 pickup

As part of the approved project change request, the trial scope was expanded beyond the controlled quarry environment to include active deployments at external customer sites. This extension enabled hydrogen equipment to operate under genuine working conditions, demonstrating practical performance, logistics, and refuelling procedures across multiple real-world applications. The Mobile Refuellers were filled both at the original test quarry (Phase 1 location) using the project's Tube Trailers as the source of supply, and, for the first time, directly at the HYGEN Tyseley electrolyser and hydrogen refuelling station.

The Mobile Refuellers were deployed on after achieving ADR approval, travelling a combined total of over 3,000 miles on UK roads without encountering major operational issues. This extensive road testing has successfully demonstrated the practical feasibility and reliability of mobile hydrogen distribution. Over the course of the trial, the Mobile Refuellers were refuelled a further 20 times and completed 50+ hydrogen dispensing operations to hydrogen NRMM at quarry locations.

[12] Gov.uk - Greenhouse gas reporting: conversion factors 2025

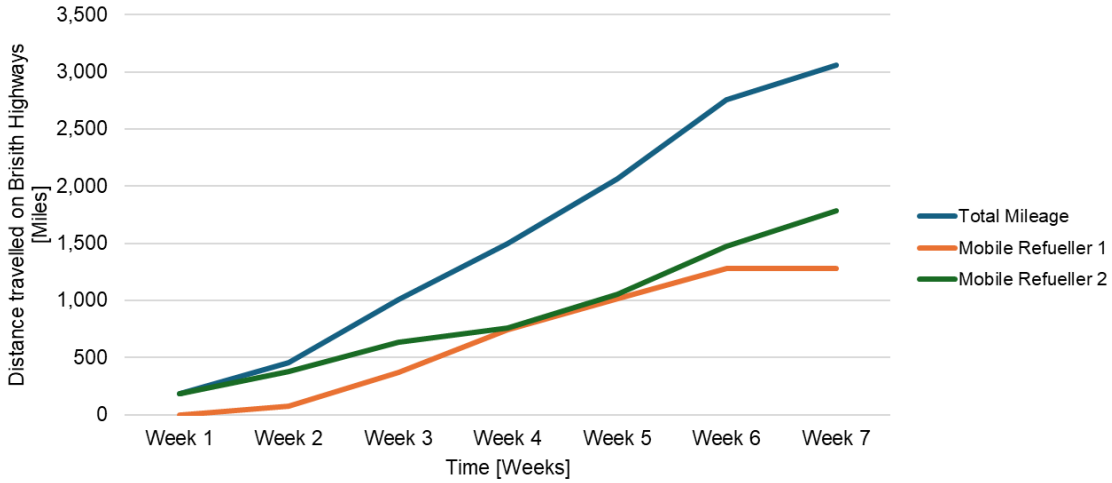


Figure 22 - Distance travelled by Mobile Refuellers on British Highways

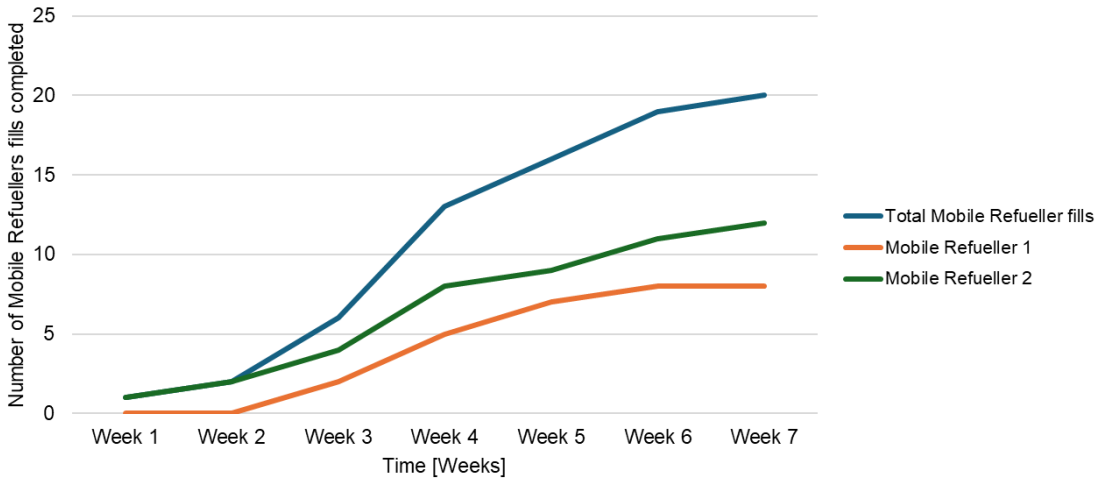


Figure 23 - Number of Mobile Refueller fills completed

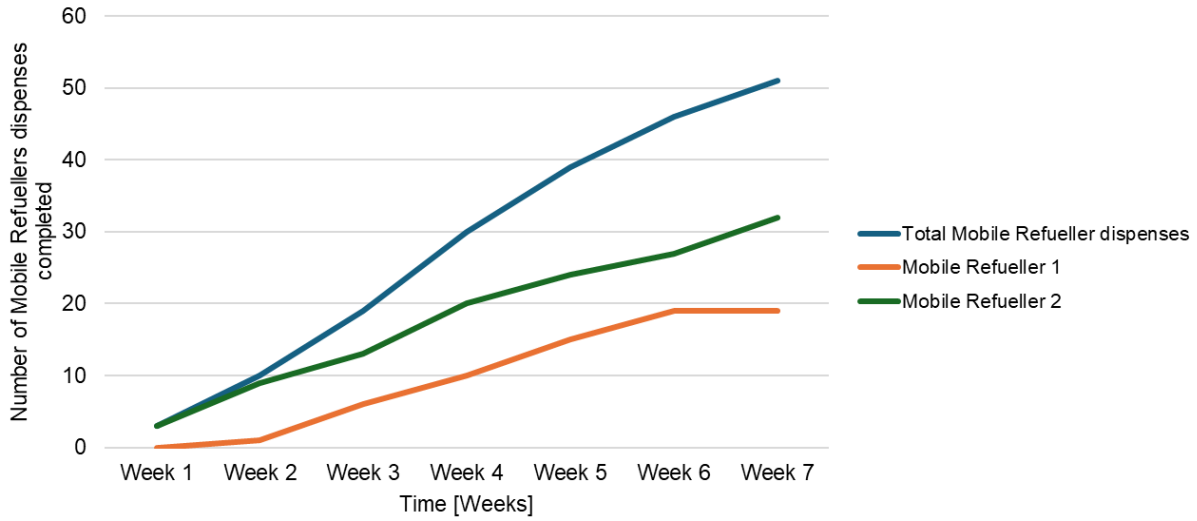


Figure 24 - Number of Mobile Refueller dispenses completed

The Mobile Refuellers were used to refuel hydrogen powered NRMM, consisting of a telehandler and a backhoe loader. The telehandler has been successfully fuelled by a Mobile Refueller at external testing sites 27 times, and the backhoe 20 times, as summarised in the table below. These refuelling operations were conducted at various external sites ranging from housebuilding sites to wastewater treatment plants.

Table 5 – Summary of Phase 1a refuelling results and performance

NRMM	Number of Fills	Fuel level at start [%]	Avg. pressure start [bar]	Filling Time [min]	Avg. pressure end [bar]	Fuel level at end [%]
Telehandler	27	28%	96 bar	12-14	350 bar	100%
Backhoe loader	20	37%	126 bar	20-24	350 bar	100%

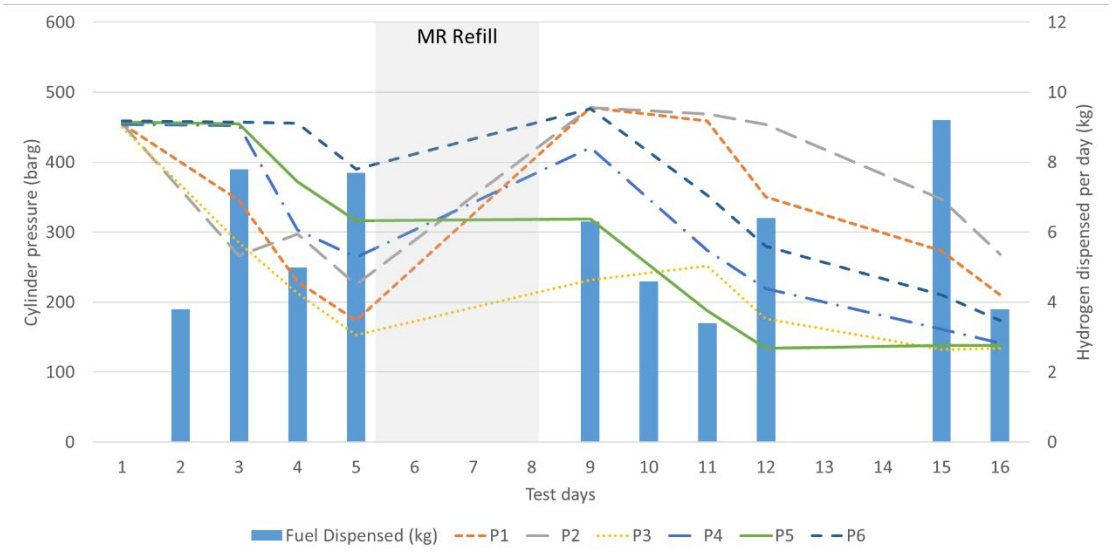


Figure 25 - Sample test data from a Phase 1a refuelling demonstration

As with Phase 1 testing, and as illustrated in Figure 25 the Mobile Refueller performed similarly in terms of refuelling performance and pressure readings. No difference was noted in terms of pressure, storage, or filling capability between controlled quarry trials and live operations with longer road distances covered.

Figure 25 highlights a challenge that was observed during refills of the Mobile Refueller: when filling at the Tyseley compressor, performance issues were noted in filling the Mobile Refueller that were not found when filling Tube Trailers or other vehicles at the refuelling station.

In addition to the technical and operational learnings of operating these supply chains under real conditions, a comprehensive suite of documentation was developed as part of this project phase, including HAZIDs, risk assessments, standard operating procedures, and training documents. These outputs now provide a replicable framework for safe and efficient mobile hydrogen deployment across future customer sites.

5.5 Phase 2

Phase 2 consisted of the development, commissioning, and testing of the Mobile Refuelling equipment, CIAB, and hydrogen-powered generators. These were tested at the quarry test site as depicted in . In this phase, the CIAB was developed, commissioned, and tested to refuel the Mobile Refuellers. Additionally, a set of hydrogen-powered generators were leased to support an off-grid demonstration of CIAB, using hydrogen for both power and refuelling, with the aim of proving the full combination of modular equipment for large site refuelling.

An updated site layout was designed for the testing programme: two possible layouts were deemed possible within the space constraints of the testing area, with the final location selected based on ease of access for lifting larger equipment into place (e.g. CIAB).

5.5.1 Mobile refuelling equipment

A series of commissioning and validation activities were undertaken to demonstrate the safe, compliant, and operational performance of the mobile refuelling equipment developed under the H2-to-Site project. This testing campaign focused on the integrated flatbed–Moffett system, the handling and deployment of the Mobile Refueller units, and the first-use commissioning of the 10-foot storage trailers.

40-ft Flatbed Commissioning and ADR Approval

Prior to entering operation, the flatbed underwent full commissioning and ADR approval to ensure compliance with dangerous goods transport regulations. Testing included verification of all locking mechanisms, tie-down points, and load-bearing components. Multiple loading cycles were performed to confirm system integrity under dynamic conditions. In addition to the trailer, the Moffett was also mounted onto the back of the flatbed, undergoing a series of checks to ensure safe and secure operation.



Figure 26 - Initial validation of lifting and locking mechanisms, using a Mobile Refueller test frame

The approval process validated that the trailer configuration, when carrying hydrogen refuelling assets, met all regulatory and safety criteria for public-road operation.

Moffett Validation Testing

To ensure compatibility with the Mobile Refueller, a structured validation programme was conducted for the rear-mounted Moffett forklift. Testing was staged to build confidence and eliminate risk:

- Initial lifting tests using an empty test frame to validate fork geometry, lift capacity, centre-of-gravity behaviour, and operator visibility.
- Loading onto the truck, demonstrating the Moffett's ability to place equipment safely and accurately onto the flatbed within defined tolerances.
- Full-scale validation with a complete Mobile Refueller, proving stable movement, controlled manoeuvrability, and safe handling of the unit under various lifting and travel conditions.

These tests confirmed that the Moffett could reliably handle the full mass and dimensions of the Mobile Refueller without imposing undue stress on the equipment or compromising safety.

10ft trailers – commissioning and validation

Finally, the 10-ft hydrogen storage trailers were commissioned and tested to confirm readiness for Phase 2 operations. Testing activities included:

- Pressure and leak checks of the storage system,
- Validation of fill-line connections and interface points,
- Controlled first fills, following a similar programme to the tube trailer commissioning

The commissioning fills confirmed that the trailers were capable of receiving and storing hydrogen to their rated pressures, and that the trailer-mounted valve, vent, and instrumentation systems operated as designed.

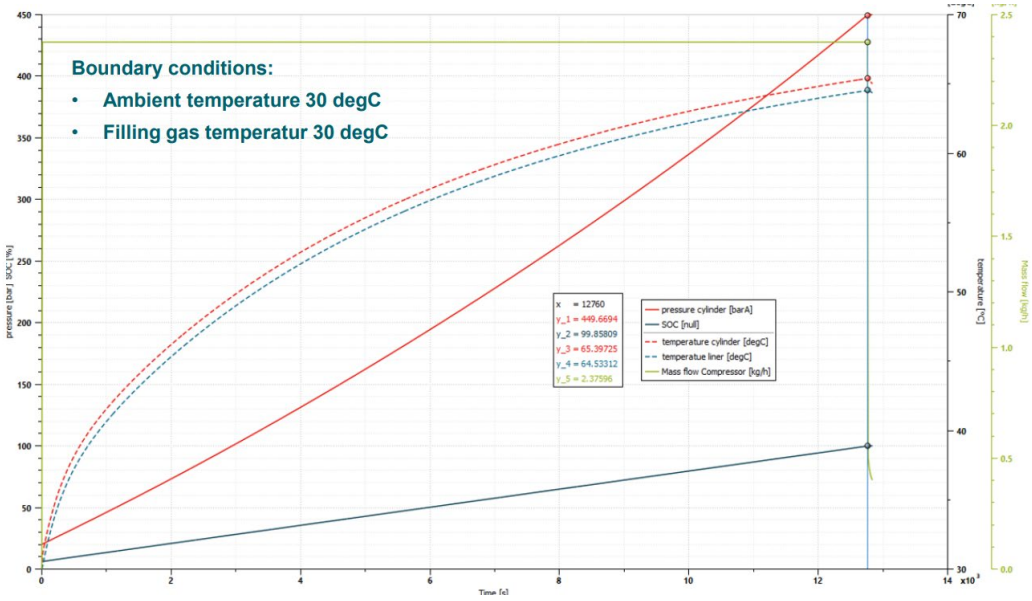


Figure 27 – Commissioning data for 10ft MEGCs

5.5.2 CIAB testing

The CIAB was tested in collaboration with Maximator to verify its performance, safety, and reliability. Three initial performance tests were conducted, each compressing hydrogen to a final pressure of 700 barg from varying inlet pressures:

- 100 barg inlet to 700 barg outlet
- 180 barg inlet to 700 barg outlet
- 260 barg inlet to 700 barg outlet

All three performance tests were successfully completed. The compressor demonstrated stable operation and consistent flow delivery across the tested pressure ranges.Following this, an endurance test of two hours was conducted. Hydrogen was compressed in three stages from 190 barg to 620 barg, with the following parameters:

Table 6 - The pressures and temperatures for the various compression stages

Parameter	Stage 1	Stage 2	Stage 3
Inlet Pressure [barg]	190	210	430
Outlet Pressure [barg]	210	430	620
Inlet Temperature [°C]	10.3	11.3	13.0
Outlet Temperature [°C]	11.5	25.8	13.0

During this test, a temperature increase was observed, which is not expected under normal operating conditions. Additionally, a hydrogen spike was detected by the vent system sensor, indicating a leak. This was most likely caused by an unintentional Pressure Safety Valve (PSV) lift in Stage 1 compression. The PSV, rated at 300 barg, should not have activated, as the outlet pressure at that stage reached only at peak 210 barg. As a corrective measure, the PSV was replaced.

A second two-hour endurance test was then conducted, compressing hydrogen from 180 to 690 barg through intermediate pressures of 240 and 400 barg, at a constant flowrate of 22 kg/h. This test showed no abnormal temperature rise and no hydrogen leakage. Power consumption during both endurance runs was measured at 35.6 kWh.

The Gas Flow System (GFS) functioned as intended. In a separate test compressing hydrogen from 185 barg to 667 barg, a stable mass flowrate of 19-20 kg/h was maintained during this test.

During testing, two design improvements were recommended by Maximator and implemented to improve safety of operations:

- Installation of a stainless-steel door on the right side of the CIAB container.
- Addition of an extra bracket opposite the chimney vent to support a second vent stack.

5.5.3 Off-grid hydrogen refuelling station

Finally, once the individual components of the supply chain were validated with sufficient confidence, the refuelling site was set up for the off-grid refuelling test. The tube trailer was connected to both the generator and CIAB using a manifold: pressure was regulated into the generators, while through CIAB the increased pressure of the tube trailer was used to reduce power and compression requirements for a more efficient fill. The test setup is shown Figure 28.



Figure 28 - Off-grid refuelling test setup, with HYKIT Mobile Refueller (front), generator (front middle), CIAB (obscured, middle: vent stack visible), and tube trailer (background)

The generators were operated in manual mode with energy output directed to a resistive load bank, allowing accurate measurement of hydrogen fuel consumption at different power outputs. The power outputs represent power into the compressor, up to a maximum of 60kWe: the maximum load of CIAB.

The Elemental Energy H2IPO was tested at 25%, 50%, 75%, and 100% load, corresponding to 15, 30, 45, and 60 kWe, respectively. The gas consumption for various loads is shown in Figure 29. As the unit approaches its maximum rated power, small efficiency losses are observed, leading to increased hydrogen gas consumption. A small disparity between the measured mass gas consumption and fuel cell reported data was also observed. This disparity can have multiple causes, including sensor calibration differences, purge losses, or system boil-off, but it remains small enough to be considered operationally insignificant.

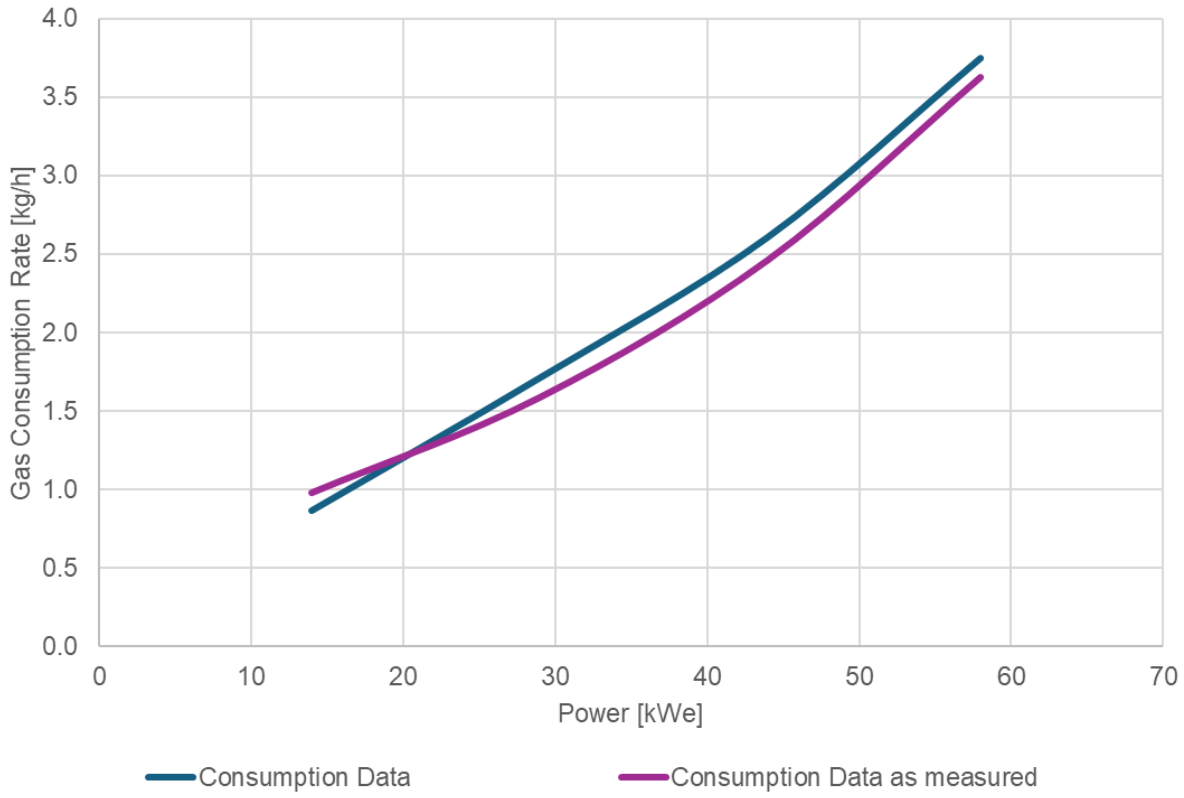


Figure 29 - Comparison of Elemental Energy generator gas consumption and the actual measured gas consumption

The Inocel generator was tested at a load varying from 14 to 101 kWe. A similar trend was observed for the Inocel fuel cell generator, although the difference between the generator data and the measured data was smaller and more consistent here, as can be seen in the figure below.

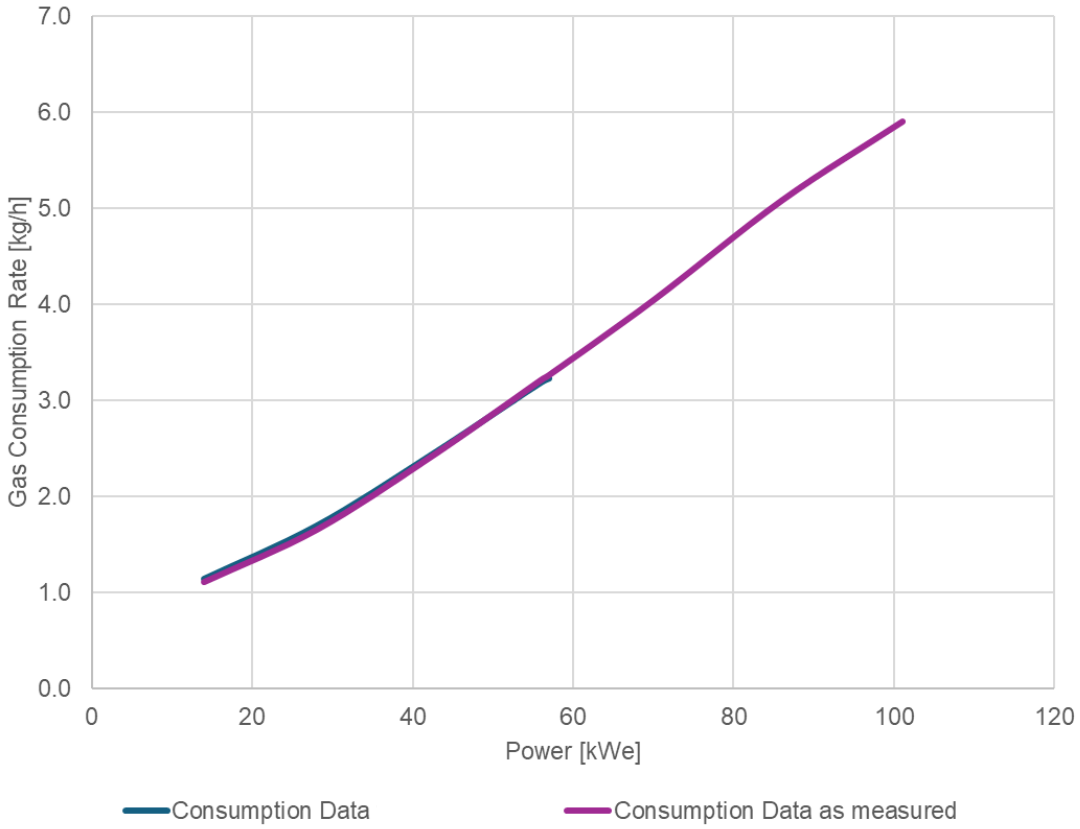


Figure 30 - Comparison of Inocel generator gas consumption and the actual measured gas consumption

These measured values were used to determine the efficiencies of the respective generator during refuelling, as can be seen in the figure below. Both units showed higher efficiency at lower loads, with efficiency decreasing as output increased. The Inocel unit demonstrated relatively consistent performance for loads above 40 kWe, maintaining a fuel consumption of approximately 57 grams of hydrogen per kWh and a respective efficiency of 58%, whereas the Elemental Energy generator displayed more variation across the load range.

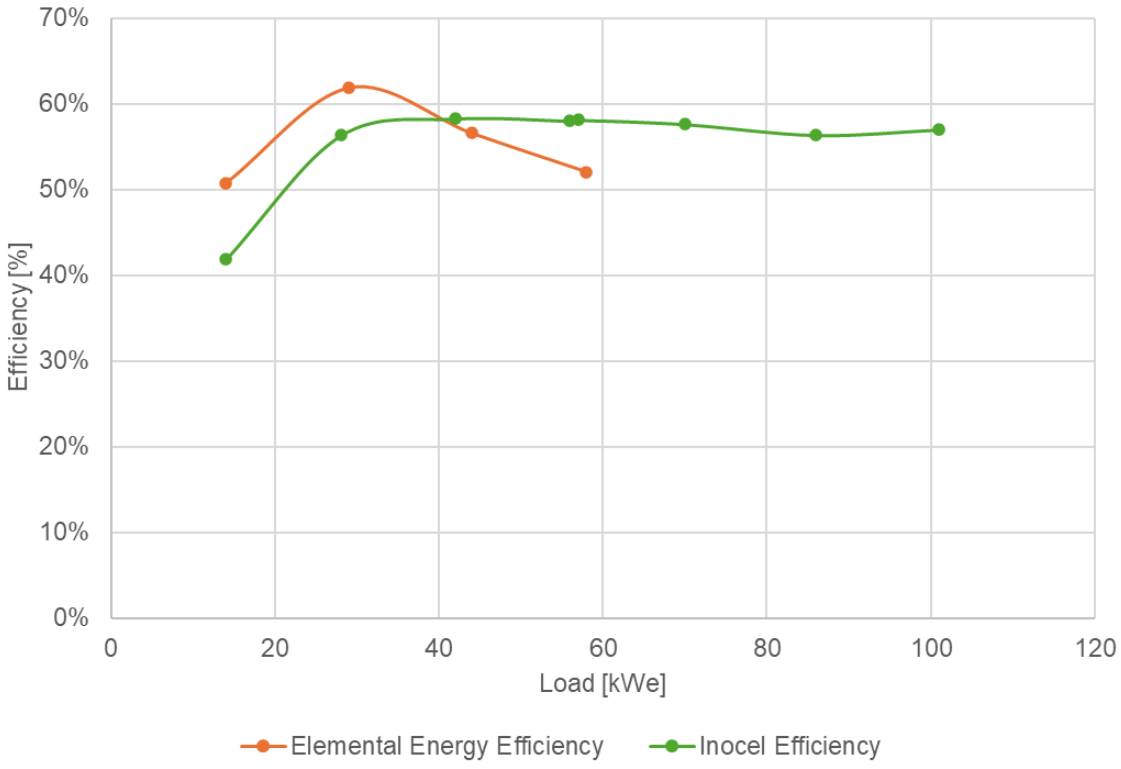


Figure 31 - Efficiency comparison between the Elemental Energy and Inocel generator

Power measurements were recorded for CIAB during fills, displaying expected performance with both generators, with the capability of filling Mobile Refuellers without requiring a grid connection or power outlet for the compressor.

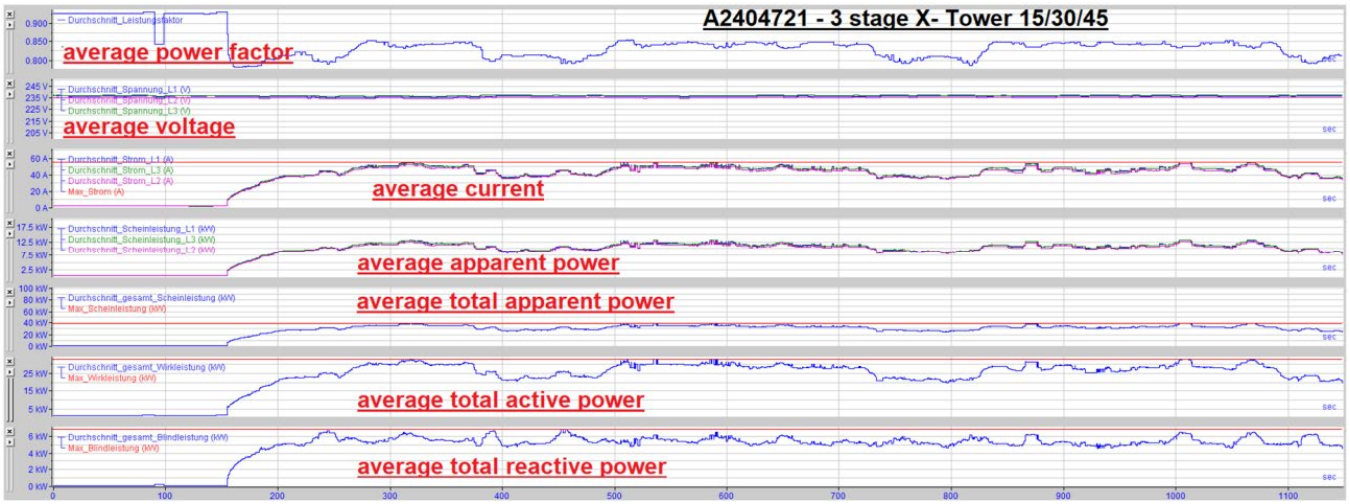


Figure 32 - Compressor performance outputs

6 Conclusion

The H2-to-Site project has conclusively demonstrated that hydrogen-powered non-road mobile machinery can be safely, reliably, and commercially operated in real construction environments. Through a comprehensive programme of controlled demonstrations, supply-chain operation, and detailed feasibility case studies with leading contractors, the project has proven the full end-to-end model required to decarbonise construction using hydrogen.

The practical demonstrations carried out during the project validated every major component of the supply chain: mobile refuellers, modular gas storage, the flatbed–Moffett logistics system, and the containerised compressor. Over 3,000 miles of road operation, dozens of refuelling events, and multiple hydrogen NRMM types were tested under real working conditions, delivering a robust evidence base for safe operation, effective refuelling, and construction-ready performance. These trials also established clear operating procedures, safety frameworks, and regulatory insights that will support future deployments.

The case studies undertaken with Sizewell C, Skanska, and Mace Dragados further demonstrated that hydrogen can be integrated into a diverse range of construction environments. The case studies validated the technical feasibility, identified site-specific considerations, and confirmed that hydrogen supply chains can be designed to meet their operational needs.

In conclusion, H2-to-Site project has established the equipment, operational knowledge, safety protocols and market pathways needed to move from isolated demonstrations to early commercial rollout. With continued collaboration between industry and government, in particular on standards, training and insurance, the project provides a clear pathway for accelerating hydrogen adoption and unlocking significant emissions reductions across the construction sector.

6.1 Summary of project achievements and metrics

The project achieved several milestones during development, validation, and demonstration, resulting in novel equipment and supply chains being tested and proven.

- Development, validation, and demonstration of Mobile Refueller refuelling into 350 bar backhoes and telehandlers
    - 500 bar cascade refuelling system proven under controlled conditions at test quarry: 100+ fills conducted over 6-week initial testing period
    - ADR approval gained for MRT system

- 50+ refuels of hydrogen-powered NRMM across 12 live commercial construction sites under controlled conditions: including assessments, setup, documentation, and training for each site

Metric	Performance
Refuelling times	12-14 minutes (backhoe) 20-24 minutes (telehandler)
NOx emissions	0.01-0.06 g/kWh (vs Tier 4 limit of 0.40)
Total H2 use across project	7,600 kg
Estimated project GHG savings	59 tonnes CO2e

- Commissioning and validation of tube trailer, including fills at Tyesley Energy Park, transport on UK roads, and use of pneumatic valve operation to support filling at scale
- Commissioning and validation of 10ft trailers
- Development, commissioning, and validation of CIAB, including:
  - Filling of Mobile Refuellers up to 500 bar pressure using on-site power
  - First-of-a-kind demonstration of off-site refuelling using hydrogen for both power and compression

Table 7 - Summary of TRL progress for equipment developed under the RDR programme

Equipment	TRL – Project start	TRL – Project end
Mobile Refueller	TRL 5	TRL 8
Tube trailer	TRL 9	TRL 9
CIAB	TRL 6	TRL 7
Flatbed/Moffett	TRL 7	TRL 8
MGS	TRL 5	TRL 6

Table 8 - Summary of supply chain development as a result of the RDR programme

Supply chain	CRL – Project start	CRL – Project end
Single Mobile Refueller	CRL 3	CRL 8

Bulk Mobile Refueller (flatbed)	CRL 3	CRL 6
Off-grid refuelling station	CRL 3	CRL 6

6.1.1 Job creation

The project has supported the creation and early development of HYKIT, a UK-based hydrogen storage and infrastructure developer, founded during the project's development phase. HYKIT has already secured £15 million in seed funding, established a 44,000 ft manufacturing facility in Bicester, and created more than 20 direct jobs, with a similar number supported across its UK supply chain.

Ryze can further directly attribute a further three new full-time employees (FTE) to the company: a Project Engineer, a Field Engineer, and a Business Analyst. Ryze has experienced significant growth during the project, with a 20x increase in revenue and a 2=35% increase in FTEs through the period.

6.1.2 New partnerships

The H2-to-Site project has led to several new business relationships. The most notable is the incorporation of HYKIT, and the close partnership formed between Ryze and HYKIT in developing and commercialising hydrogen supply chains for construction.

In addition, Ryze and Inocel have partnered on several opportunities following the H2-to-Site project, with Ryze supplying hydrogen to Inocel fuel cell generators across several events.

6.1.3 Commercialisation plan

The H2-to-Site project has demonstrated a new, technically viable, and commercially scalable hydrogen supply chain for the UK. HYKIT have already taken steps to improve upon and commercialise the Mobile Refueller concept, increasing the storage capacity and working pressure to 635 bar: supporting more efficient logistics and reduced refuelling times.

Ryze will continue to build on the Phase 1a demonstrations, incorporating HYKIT's equipment (including Mobile Refuellers and MGS systems) into its commercial hydrogen distribution model. Ryze has supported a further 8 follow-on demonstrations beyond the H2-to-Site project, including the first supply of hydrogen to National Highways' Lower Thames Crossing project, filling a JCB 540-180H Loadall at Gallagher Group's Hermitage Quarry, and a JCB backhoe loader at Skanska's site in Gravesend. Ryze is developing commercial relationships with a wide range of rental companies and site operators, sharing learnings from the H2-to-Site project and developing opportunities in anticipation of HAR hydrogen offtake from Bradford Low Carbon Hydrogen.

To support the rollout of hydrogen construction equipment, HYKIT will continue to build up and commercialise the equipment demonstrated on this project. A key element of HYKIT's longer-term commercialisation plan is to strengthen UK manufacturing capability across the hydrogen equipment supply chain. HYKIT already relies on multiple domestic vendors and is exploring the establishment of UK Type IV cylinder manufacturing, which would reduce reliance on imports, cut lead times, and support the creation of additional skilled jobs.

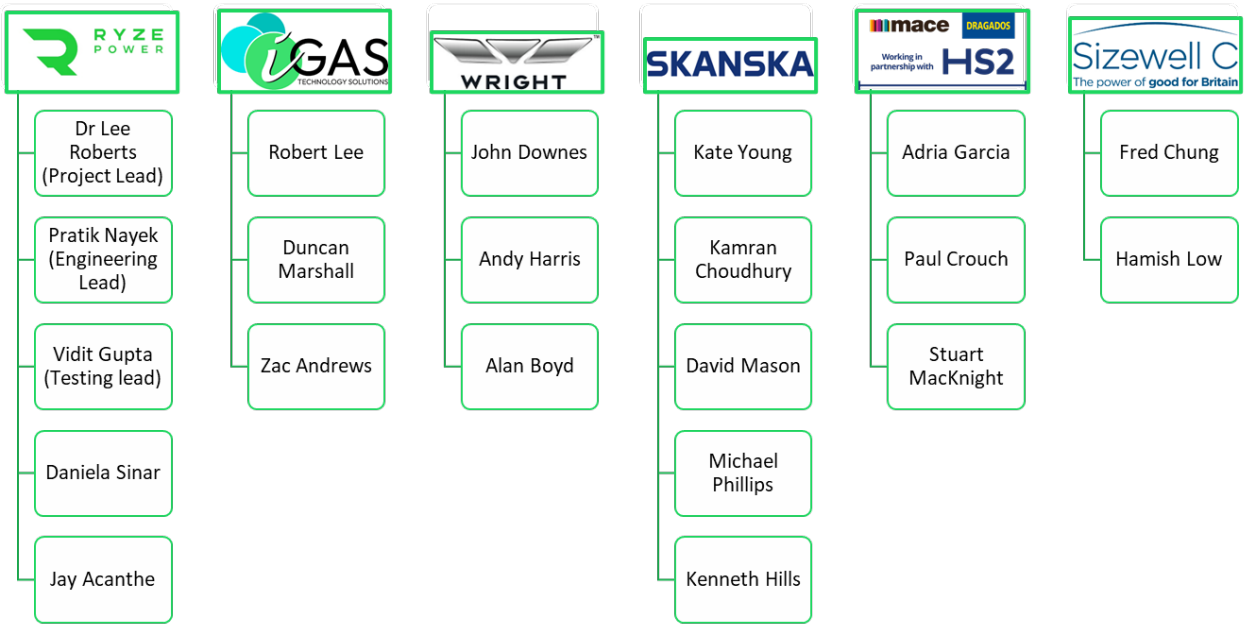
Together, Ryze and HYKIT provide a credible, near-term route to market for hydrogen in the construction sector. Ryze will deploy and operate the supply chains proven in this project, ensuring that construction customers can access safe, reliable, sustainable, and cost-effective 350 bar hydrogen refuelling. HYKIT will manufacture the equipment required to scale this approach nationally and, over time, internationally.

Table 9 - Summary of commercialisation plan

	2023-2025	2025-2027	2025-2030	2030+
	1. Demonstration phase (H2-to-Site)	2. Early commercial deployment	3. Manufacturing scale-up	4. Full market adoption
Objectives	• Development of supply chain • Techno-economic modelling • Controlled trials at test quarry • Demonstrations at work construction sites	• Expansion of construction site trials • Operation of "Drop-and-collect" model of deployment • Multi-site "milkround" approach adopted	• Commercialisation of HYKIT asset manufacturing • Development of UK supply chain vendors • First export opportunities	• Mobile Refuellers for distributed and small/medium sites • CIAB/tube trailer supply chain as hub for larger projects/high demand regions • Integration with low-carbon hydrogen hubs and HAR production sites
Outcomes	• Safety cases, SOPs, and training materials developed • Validation of supply chains and operations • Proofs of concept	• First long-term deployments • First commercial clusters around large projects • Demand aggregation in identified target regions	• Reduced unit cost • Greater supply chain resilience • Product expansion	• Nationwide hydrogen refuelling network for construction supply

Appendix A: Key consortium members

Main consortium:



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