



HyDeploy Project

Project Close Down Report

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1.0 Project Background

The HyDeploy project seeks to address a key issue for UK customers: how to reduce the carbon they emit from heating their homes. The UK has a world class gas grid delivering heat conveniently and safely to over 83% of homes. Emissions can be reduced by lowering the carbon content of gas through blending with hydrogen. This delivers carbon savings, without customers requiring disruptive and expensive changes in their homes. It also provides the platform for deeper carbon savings by enabling wider adoption of hydrogen across the energy system.

The HyDeploy project was delivered by a consortium of partners, consisting of: Cadent; Northern Gas Networks; Progressive Energy; Health and Safety Executive – Science Division; Keele University and ITM Power. Alongside the core consortium were a number of key subcontractors, such as Dave Lander Consulting, Kiwa Gastec, Otto Simon, Orbital Gas and Thyson Technology.

Since the inception of the HyDeploy project in 2017 much greater focus on hydrogen deployment has taken place. Driven by political developments such as the Net Zero target set in 2019 and the more recent 10 Point Plan and Energy White Paper, building on foundational reports such as the Net Zero report by the Committee on Climate Change. Hydrogen deployment is now recognised as a central technological pillar of the UK's decarbonisation strategy, with blending identified as the early enabler of the hydrogen journey. Both the 10 Point Plan and Energy White Paper specifically identify the need to unlock hydrogen blending by 2023. HyDeploy (including HyDeploy2) is the only major technical programme within the UK driving the deployment of hydrogen blends within the gas distribution system, therefore the successful outcome of the broader HyDeploy programme is now crucial to facilitating the delivery of HMG hydrogen policy objectives.

The phased approach taken by the project secured the necessary evidence base to support the first UK application to blend hydrogen in a live gas network, alongside the design and installation of a hydrogen grid entry unit and electrolyser. The project culminated in the first live operation of hydrogen containing gas in the UK since the conversion from towns gas was completed in 1976.

The key regulatory hurdle that had to be addressed to enable the trial was the 0.1 mol% hydrogen limit imposed by the Gas Safety (Management) Regulations (GS(M)R). The HSE has the power to grant exemptions to stipulations within GS(M)R if a safety case application can be made that evidences that the proposed changes do not prejudice the health and safety of those impacted by the change. HyDeploy successfully made this case to the HSE, which resulted in the granting of the first hydrogen exemption to GS(M)R.

A successful installation process was then undertaken, followed by the trial itself. Robust evidence was gathered across both the distribution network and end users to demonstrate the safe use of hydrogen blends within existing infrastructure. This ground breaking project has demonstrated the principle that safe hydrogen blend deployment is possible and technically achievable using a private gas network. This provides the foundation to expand this to the public gas network and then wider roll out. The HyDeploy project is the transitional project turning hydrogen from a concept to reality for the UK energy system.

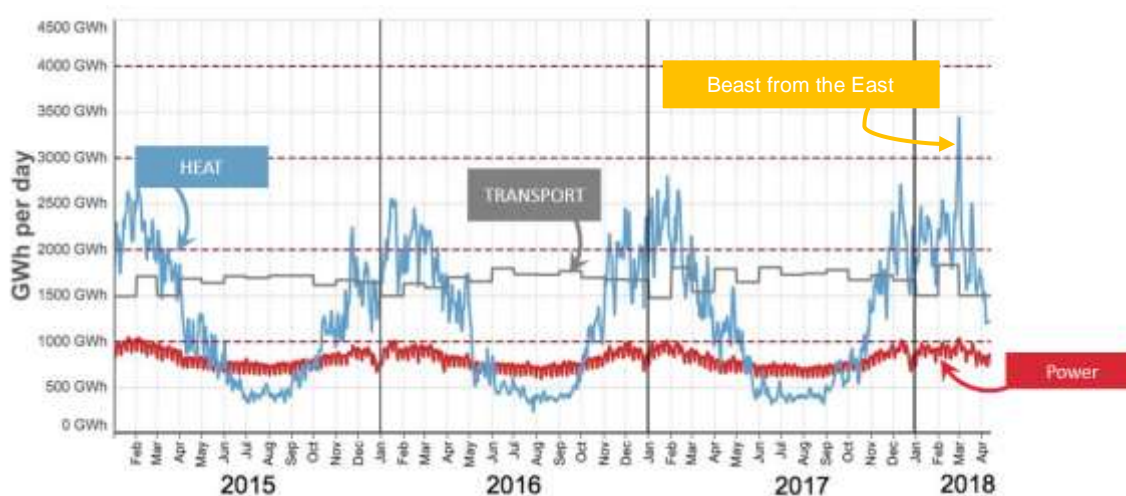
2.0 Executive Summary

2.1 Scope and Objectives

According to HMG emissions data (BEIS, 2021) in 2019 domestic combustion produced 66.5 MtCO₂, sharing first place with passenger vehicles (67.0 MtCO₂) as the largest sources of UK emissions. The need to decarbonise heating supplies has become ever more urgent over recent years, with policy focus shifting from an electrification-focused decarbonisation mindset to a more holistic system-thinking strategy.

HyDeploy commenced in 2017 when the UK's decarbonisation strategy was to achieve an 80% reduction relative to 1990 by 2050. In June 2019 UK parliament passed into law its 2050 Net Zero target, becoming the first developed nation in the world to do so. This growth in environmental ambition brought into sharp focus the need to tackle the resultant emissions of all elements of the UK economy. Domestic heating, industrial and heavy transport have always been deemed to be the 'hard to reach' elements of the national emissions profile. This is because of the user requirements within each of these energy demands. For domestic heating, the variation in demand, both seasonally and diurnally, combined with consumer expectations of on-demand heating result in a challenging functional specification for any supply chain to maintain secure and reliable supplies throughout the year. This variation in demand is demonstrated in Figure 1.

Figure 1: Daily energy demands



Across the UK 23 million homes as well as businesses are heated with natural gas, from a network extending over 280,000 km – the equivalent of circumnavigating the world seven times. The reason for this dominance is due to the inherent advantages of gaseous energy as a source of heating. Gaseous energy sources can be combusted to produce high temperature heating on demand which leads to a lower infrastructure footprint needed to distribute the resulting heat, as well as being able to heat properties rapidly on demand. Most importantly gaseous energy sources can be readily compressed and stored within the supply network itself to allow instantaneous demand management without compromising supply security or network stability. Given the vital nature of heating to consumer's quality of life and health, supply security is of paramount importance. The source of such gaseous energy has been

natural gas since the conversion from towns gas was completed in 1976. In 2018 gas supplies were 99.5% natural gas, with the remainder consisting of biomethane, predominantly from anaerobic digestion. To achieve the target of Net Zero by 2050 all of the natural gas directly supplied to consumers will need to be replaced with a low carbon alternative.

The objective of this first HyDeploy programme was to demonstrate that a blend of hydrogen, up to 20 mol%, could be safely distributed and used within the current gas network. The blending of hydrogen within existing natural gas supplies is a pragmatic and achievable first step along the pathway of full conversion to 100% hydrogen. Historically hydrogen deployment has been restricted by the 'chicken and egg' of hydrogen supply being contingent upon hydrogen appliance availability and vice versa. The successful deployment of electric vehicles was able to access an established supply market of low carbon electricity, and therefore no simultaneous co-deployment of supply and demand technologies was required to facilitate electric vehicle adoption. The blending of hydrogen up to 20 mol% is designed to be non-disruptive to existing consumers, meaning no change to current appliances is required to receive the hydrogen blend. This strategy therefore learns valuable lessons from the decarbonisation of passenger vehicles to remove the need for co-deployment of independent technologies. Blending enables a supply chain of hydrogen production to be established without being dependent upon the simultaneous deployment of hydrogen appliances - breaking the historical 'chicken and egg' constraint.

Supplying a blend of hydrogen to all UK homes currently heated with natural gas will result in 29 TWh pa of low carbon heat, which is the equivalent to removing 2.5 million cars from the road without causing any disruption to consumers. For context, the annual generation of biomethane in the UK in 2018 was 3.5 TWh. Therefore, the blending of hydrogen is a no-regrets opportunity to both establish a meaningful hydrogen supply chain facilitating deeper adoption of hydrogen, and simultaneously generate material carbon savings without consumer disruption.

The importance of hydrogen blending at the start of the HyDeploy programme was not well understood. The inertia of hydrogen blending has progressively increased over the course of the project to the point where it is now a central element of HMG hydrogen objectives. In the recently announced 10 Point Plan, the blending of hydrogen up to 20 mol% by 2023 is the second hydrogen objective, alongside 5 GW of production capacity by 2030. The blending objective is reiterated within the recently released Energy White Paper. HyDeploy (including HyDeploy2) is only technical programme in the UK unlocking hydrogen blending in the gas distribution network, therefore the successful outcome of the broader programme has become central to HMG hydrogen objectives. This is testament of the industry leading progress HyDeploy has made in progressing the deployment of hydrogen within the UK gas network.

The primary regulatory constraint restricting hydrogen blending within the UK gas grid is the Gas Safety (Management) Regulations (GS(M)R), 1996. Schedule 3 of GS(M)R restricts the hydrogen content of natural gas to 0.1 mol%. GS(M)R is a secondary legislative instrument that falls under the Health and Safety at Work Act, 1974. Therefore, the Health and Safety Executive (HSE) are the governing regulator of the legislation. Section 11 of GS(M)R allows for Exemptions to be granted by the HSE, such Exemptions can be granted if a demonstration can be made that the requested change '*does not prejudice the health and safety of those affected*'. A demonstration is therefore required that a 20 mol% hydrogen blend is as safe as natural gas. The purpose of the HyDeploy project was to provide this demonstration to enable

a live gas network to operate with a hydrogen blend over a time-bounded trial. Therefore, the objectives of the project were to:

1. Provide the necessary evidence base to demonstrate that, for the purposes of the proposed trial, a 20 mol% blend of hydrogen was as safe as natural gas.
2. Safely conduct a trial at Keele University (Keele) and provide a hydrogen blend to live consumers.

Both of the key objectives of the HyDeploy project were achieved. The Keele trial was the first live gas network to utilise hydrogen above the specified regulatory limit within the UK and the first gas network to utilise hydrogen since the conversion from towns gas was completed in 1976.

2.2 Project Outcomes

The project has successfully demonstrated that it is possible to achieve an Exemption to the hydrogen limit within GS(M)R Schedule 3 and that live gas networks are capable of safely operating with a hydrogen blend. The key project outcomes of the HyDeploy project have been:

1. The establishment of a sufficiently robust evidence base and QRA to justify the first ever hydrogen blend trial within the UK.
2. Generating the technical and procedural precedents for evidence generation and review by the HSE, which have informed subsequent safety case submissions through HyDeploy2 and the wider hydrogen safety case industry.
3. Successfully manage an intensive engagement and review process with the HSE, where 142 individual questions were raised against the safety case evidence base and successfully responded to.
4. The design, fabrication, installation and operation of the UK's first hydrogen grid entry unit.
5. The process integration of novel hydrogen production and blending technologies to create the first hydrogen delivery system based on electrolytic generation into a live gas grid.
6. The safe delivery of the UK's first hydrogen blend trial to 100 homes and over 30 university/commercial buildings, where no loss time injuries were recorded across the trial duration. The trial delivered over 42,000 scm of hydrogen and abated over 27 tCO₂.
7. The establishment of a long-term appliance evidence base through collaboration with the four major boiler manufacturers in the UK.
8. Evidencing of the operational suitability of hydrogen blends with domestic appliances as well as larger commercial appliances including catering equipment and boilers up to 600 kW.
9. Evidencing of the operational suitability of hydrogen blends with medium and low-pressure distribution systems as it relates to key performance metrics such as: pressure control; rhinology and uniform gas compositions.
10. Promotion of supply chain innovation through facilitating development trials of gas detection and analysis technologies.
11. Establishment of a robust social science evidence base to understand real world attitude of consumers using hydrogen blends.

HyDeploy has been a very successful project that has delivered on its objectives and enabled the UK to take the first practical steps of demonstrating the safety and operational feasibility of hydrogen blends.

2.3 Successful Delivery Reward Criteria

All Successful Delivery Reward Criteria (SDRCs) were delivered to the satisfaction of Ofgem. The project extended beyond the original timeline, primarily due to an operational hiatus that had to be imposed due to the COVID-19 national lockdown, impacting contractor resource availability and site access. However, the project extension was within the 12 months beyond which a material change would be required to be sanctioned. The submission timings of any affected SDRCs were agreed with Ofgem and all SDRCs were submitted in line with the agreed timings.

Table 1: SDRCs Successfully Delivered to Ofgem

SDRC	Title	Target Date	Delivered
9.1	Communications Plan	24.11.2017	✓
9.2	Laboratory Appliance Tests	30.03.2018	✓
9.3	Onsite Survey Programme	25.05.2018	✓
9.4	Exemption & QRA	29.06.2018	✓
9.5	Exemption Approval	31.08.2018	✓
9.6	Gateway to Phase 2	31.08.2018	✓
9.7	Hydrogen System Installation	26.04.2019	✓
9.8	Completion of Field Trial	28.02.2020	✓
9.9	Public Network Trial Definition	31.03.2020	✓
9.10	Dissemination & Close Out Report	31.03.2020	✓

The programme has been able to deliver truly world leading innovation within the hydrogen landscape and achieve more than originally committed to, through the harnessing of a dedicated project team as well as key third party collaborations.

2.4 Learning

The HyDeploy project has made significant progress in the technical and regulatory requirements to enable the introduction of a hydrogen blend within the UK gas distribution network.

All project partners have benefited from their involvement in the project, where valuable learning has been captured from the delivery of the programme. At a project-level, the main learning outcomes are:

1. It is possible to provide a robust demonstration of the parity of safety between natural gas and natural gas containing a hydrogen blend up to 20 mol%, undertaken in the context of the trial network.
2. The necessary level of evidence to sufficiently demonstrate such risk parity should not be underestimated. More time than originally anticipated was required to support the completion of the safety case stage (Phase 1) to both, generate the necessary level of evidence, and fully respond to all HSE questions.
3. The largest areas of potential engineering risk are in the interface between independent systems. All mechanical, electrical and instrumentational interfaces require focus to ensure a seamless delivery of an overall solution is achieved.
4. Gas demands on the low-pressure network are far more variable than expected. No historical monitoring data exists on flow variability at the low-pressure network depth, therefore HyDeploy has generated the first real world evidence base of actual flow patterns at this network depth. Such information will be beneficial to the future design of blending units and supports the broadly accepted view that blending should take place at the highest-pressure tier practically possible.
5. Network operations and appliances are capable of accepting a hydrogen blend without operational constraints or issues.
6. There was no formal reporting of any disruption or perceived change in their use of gas. This experiential evidence is in line with the technical evidence that appliance safety and performance is not adversely affected by the introduction of a hydrogen blend.
7. Electrolytic hydrogen generation requires operational optimization to ensure operating modes generate reliability and consistently across expected demand ranges.

The key learning of the HyDeploy programme is that the safe blending of hydrogen within live gas networks is possible. Before HyDeploy the introduction of hydrogen within the gas network was an ambition. Following HyDeploy the introduction of hydrogen within the gas network has been demonstrated to be feasible and achievable. This is a critical learning as it provides confidence within the gas industry and with wider stakeholders that hydrogen offers a viable pathway to decarbonise the nations gas supplies.

3.0 Project Description and Outcomes

3.1 Phase 1: Evidence Gathering and Customer Engagement

The Phase 1 scientific programme provided the technical foundation of the evidence presented to the HSE in support of the Exemption application. The evidence base generated spanned; appliances; gas characteristics; gas detection; and materials/assets. An outline of the key results within each area follows.

3.1.1 Appliances

The laboratory appliance testing had two overarching objectives:

1. Understand the performance implications of introducing a hydrogen blend, across a wide range of appliances
2. Understand the limit of operability for a select number of appliances with regards to hydrogen content within the fuel

The first workstream consisted of selecting a broad range of domestic gas appliances, including gas cookers, fires and boilers. Each appliance was fed with 13 test gases at a constant test pressure, each designed to promote a different response or flame characteristic. The test gases consisted of both reference gas mixtures (G20/G21/G23/G222) and hydrogen additions, the highest concentration being G20 (methane) with 28.4 mol% hydrogen – which is the maximum concentration of hydrogen that can be blended into pure methane before the lower normal Wobbe limit specified within GS(M)R is reached (47.2 MJ/m³).

Each appliance was fitted with instrumentation to provide accurate characterisation of the combustion effects. Thermocouples were installed on critical components along with pressure measurement and flue gas analysis to ensure all of the appliance areas of interest were monitored.

The gas fire testing assessed the performance of the appliances. A number of fires were tested, representative of the fires present on the Keele network. All fires tested were capable of operating on all of the test gases. Thermocouple readings indicated no risk of overheating of components. Even when operating on a blend, the fires retained the characteristic flame colour, albeit marginally more subdued. As hydrogen increases flame stability due to the higher flame speed, testing was conducted on oxygen deficiency sensors (ODS) which cut off fuel supply when the flame receded from a thermocouple due to lack of oxygen. All of the fires on the Keele site fitted with ODS devices were verified to cut off below the 200 ppm limit, although the programme identified the need for further work to establish the more general case. Further testing of ODSs was conducted as part of HyDeploy2, where analysis of the test data concluded no increase in gas fire risk as a consequence of introducing a hydrogen blend.

The gas cooker results demonstrated that all critical component temperatures remained within acceptable limits when hydrogen was introduced. Variation in thermocouple readings was observed as a result of changing the fuel composition, but at no point did the variation in temperature results indicate overheating of components or potential degradation. Pressure indication within the oven always remained within the necessary performance safety specifications. Figures 2 shows the resulting flame appearance of pure methane (left hand side) compared to methane with 28.4 mol% hydrogen (right hand side). The difference is marginal, which is indicative of the wider gas cooker results.

Figure 2: Cooker hob flames (LHS – Methane, RHS – 28.4 vol% Hydrogen)



The gas boiler testing focused on flue gas analysis alongside internal temperature measurements and flame ionization currents. The flame characteristics for each test gas, including up to 28.4 mol% hydrogen, were stable with complete combustion being achieved. As expected, the carbon dioxide readings reduced by up to 0.5 mol% with the addition of hydrogen.

The critical temperature readings assessed components including the burner plate and the heat exchanger. Much like the gas cooker, some variation was observed but not at a level affecting degradation or causing performance issues. As expected, the flame ionisation current reduced with the addition of hydrogen. The level of reduction did not compromise the protective safety function of the device. For the minority of appliances which use flame ionisation current to control the fuel/air ratio, there was an observed difference in control behaviour but not affecting safety performance.

Following the baseline operational testing to determine expected performance of appliances during the trial, limit testing was conducted to understand the operational limits of a sample of appliances. This testing involved varying the composition of the fuel by increasing the hydrogen content until operational issues arose.

The principal effect that hydrogen promotes for gas appliances is an increase in flame speed, which could lead to flame out as a result of the flame travelling at a higher velocity than the flue/air mixture (lightback). The limit of operability for the appliances tested was far beyond the operating limits of up to 20 mol%. For the selection of appliances tested, flame out due to lightback began at 80 mol% however some appliances only flamed out at 100 mol% hydrogen.

Overall, the laboratory testing indicated that across the range of domestic appliances tested, they were capable of operating safely on hydrogen concentrations up to 28.4 mol%. It should be noted that all gas appliances sold in the UK are certified with reference gas G222 which contains 23 mol% hydrogen.

A team of local gas fitters undertook field testing of installations and appliances across the network enabled by the communications programme. Over 130 properties and buildings were tested, including more than 230 individual appliances. These ranged from domestic units to commercial catering equipment and large boilers up to 600 kW. The purpose of these tests was (a) to establish and ensure the fundamental integrity of the appliances and installations on natural gas, and (b) to evaluate whether the findings in the laboratory were replicated in

the field using bottled gas blends connected at the gas meter. Overall, the installations and equipment on the Keele site were found to be well maintained, although some of the private properties required remedial work or replacement to bring them up to standard on natural gas.

All pipework was pressure tested with natural gas and all appliances performance tested with natural gas. The pipework and appliance testing was then repeated with bottled gas containing 28.4 vol% hydrogen. All leak tight pipework and safe appliances with natural gas were also leak tight and safe with a hydrogen blend – without any exceptions. Performance in the field on blends fully replicated the findings in the laboratory, in all cases performing just as safely on the blend as on natural gas.

3.1.2 Gas Characteristics

The gas characteristics of natural gas containing up to 20 mol% hydrogen, in comparison to natural gas, was an important area of understanding to underpin the quantitative risk assessment and support appropriate supplementary guidance for operational procedures to be developed, where needed.

The focus of the gas characteristics workstream was to understand the pertinent safety related characteristics of the gas relative to natural gas, this included:

1. Dispersion characteristics in the event of a leak
2. Flammability characteristics
3. Combustion characteristics in the event of ignition

The dispersion characteristics of natural gas containing up to 20 mol% hydrogen were found to be comparable with natural gas. As laminar flow is a function of the viscosity of the fluid, the relative leak rate of a 20 mol% hydrogen blend was found to be equivalent to natural gas – due to the blend having a viscosity that is 99% of methane's. Turbulent flow is a function of the density of the fluid. Therefore, given that the density of the blend is 85% relative to methane, it was determined that a turbulent leak containing 20 mol% hydrogen could be up to 10 vol% greater by volume. However, given the lower enthalpy of combustion of hydrogen relative to natural gas, the potential energy release rate was in fact lower for all leaks.

Hydrogen and methane are extremely miscible; therefore, separation of the gases was assessed as not being realistic in the context of the trial. For example, an isothermal column would need to be on the order of 100s of metres for sufficient gravitation potential to separate the two gases from each other by even 0.1 mol%. This is consistent with international assessments.

The flammability limits of hydrogen are known to be wider than natural gas, therefore understanding the resultant implications of blending up to 20 mol% was of interest. The limit of most interest is the Lower Flammability Limit (LFL) as this defines the point at which a mixture of released fuel and air becomes a hazard. The variability of the LFL resulting from the spectrum of natural gas compositions leads to an imprecise conclusion. The effect of mixing methane with hydrogen at 20 mol% resulted in a reduction in the LFL limit from 5 vol% to 4.75 vol%. This magnitude of change is comparable to the baseline variability of natural gas data. However, a conservative position was adopted to recommend a reduction in the LFL limit from 5 vol% to 4.75 vol%.

Because hydrogen has a lower density than natural gas, the buoyancy of a blend is greater than the buoyancy of natural gas. In an open environment this would aid dispersion from a potential leak, however within an enclosed environment such as a room there would be little expected difference between the two gases – this assessment was experimentally confirmed in HyDeploy2.

The flame speed of hydrogen is known to be greater than the flame speed of natural gas. Therefore a 20 mol% hydrogen blend exhibits slightly different combustion characteristics compared to natural gas. Relevant research on a 20 mol% hydrogen mixture which is applicable to real world situations is limited, therefore a conservative assessment was carried out. On this basis, it was determined that the overpressure profile of blended gas resulted in higher peak overpressures relative to natural gas. Further work was conducted under HyDeploy2 to experimentally determine the actual relative differences, which were found to not be of undue concern. The greatest potential risk of a gas' overpressure characteristic is the propensity to self-detonate. It was determined that, much like natural gas, blended natural gas containing up to 20 mol% does not express the characteristic of self-detonation.

An important characteristic of any gas is its gas group. The gas group rating of a gas defines the specifications of any electrical equipment that could be exposed to it, as described by the Atmospheric Explosion (ATEX) rating of the electrical equipment. Both natural gas and natural gas containing up to 20 mol% hydrogen are deemed as IIA gases. Therefore, any current electrical equipment suitability rated for natural gas exposure is also sufficient for exposure to blended gas containing up to 20 mol% hydrogen.

The results of the gas characteristics workstream were aggregated to support the Quantitative Risk Assessment and provided a framework for supplementary guidance to be generated for the operational procedures. This ensured any 'hydrogen effect' was properly accounted for within the relevant operational procedures to maintain the same level of operational integrity historically experienced by the Keele network.

3.1.3 Materials and Assets

The interaction of hydrogen with materials is an important area which must be understood when evaluating hydrogen injection. The initial stage in this workstream was to undertake a comprehensive asset register of the Keele University gas network to evaluate the spectrum of materials for laboratory testing. The Keele University network consisted of both medium and low pressure pipework with; 4,381 meters of medium density polyethylene (MDPE) across both pressure tiers and 100 meters of medium pressure steel pipework, all services to users were either MDPE or steel. Once all of the relevant materials on the Keele network were understood a process of three separate testing regimes was undertaken:

1. Assess hydrogen uptake into powder and rod samples up to 75°C and up to 9 weeks of soaking
2. Soak specimens in a chamber for up to 6 weeks followed by mechanical testing
3. Assess any implications for electrofusion jointing and pipeline 'squeeze-off' techniques.

The powder and rod samples refer to the physical state in which the material specimens were prepared for testing. Preparation into these states provides a high surface area for hydrogen

absorption and therefore promotes uptake. The soaking times were agreed following an in-depth literature review.

The soaking chamber is shown in Figure 3.

Figure 3: Materials soaking chamber



The importance of the three testing regimes was to understand, not only any material effects but also implications for operational procedures.

The powder and rod sampling to measure hydrogen absorption concluded that for around half the materials tested no meaningful hydrogen take up was observed for either the powder or rod samples. Any absorption was found to be irreversible and informed the selection of materials to undergo soaking followed by tensile testing.

The soaking of samples, as pictured in Figure 3, was undertaken at 1.5 barg in conditions of pure methane, pure hydrogen and reference gas G222 (containing 23 mol% hydrogen). The soaking time was up to 6 weeks, followed by testing of mechanical properties. The tensile testing measured:

1. Total elongation at failure
2. Modulus of elasticity
3. Ultimate tensile strength
4. Proof strength

The results of the tensile testing for the suite of materials tested showed no noticeable effects on the tensile properties of materials on the network, resulting from exposure to the hydrogen blends at the operational pressures. Alongside assessments of identified specific components, these results provided the confidence that no incremental reduction in Keele network integrity would be experienced due to the introduction of a hydrogen blend at 20 mol%.

Electrofusion and squeeze-off testing are relevant for operations associated with Polyethylene (PE) pipelines. Figure 4 shows the process of squeezing off a PE pipe, a procedure used to isolate pipeline sections.

Figure 4: Squeeze off demonstration



The piping samples were soaked in pure hydrogen for 6 weeks and then squeezed-off, followed by hydrostatic testing 1 and 6 weeks after. The pipework passed both hydrostatic tests, indicating that exposure to hydrogen did not compromise the pipelines integrity to be isolated and sequentially returned to service.

During the trial further materials work was undertaken via soaking sample specimens in the actual blended gas over the course of the trial. The purpose of the additional testing was to establish whether steady state effects have been achieved and to build a more detailed picture of expected long term effects in real world conditions.

It was concluded that for the purposes of the trial on the Keele network, no incremental degradation of materials was expected due to exposure to blended natural gas containing up to 20 mol% hydrogen.

3.1.4 Gas Detection

Accurate gas detection is a fundamental requirement for the safe operation of a gas distribution network. An experimental programme was therefore undertaken to test commonly used gas detectors, including domestic detectors, at hydrogen blends of varying concentrations and map the output responses of the instruments.

The full suite of output measurements was recorded, inclusive of flammable gas readings from the ppm range to vol% range through to CO measurements. All commonly used instruments on both the Cadent and NGN networks were tested, a selection is shown in Figure 5.

Figure 5: Gas detectors (A = fixed, B = survey)



A testing enclosure was constructed with inlet connections of methane and hydrogen, this allowed for any desired atmospheric composition to be generated and multiple instruments to be tested with an identical environment.

There was a broad pattern of results from the detectors indicating that the presence of hydrogen does have an effect on detectors currently used on the network. For flammable gas measurements, which generally rely on a thermal conductivity-based sensor, readings would be over sensitive. This doesn't present a safety concern as the effect is conservative, however issues concerning nuisance alarms and operator confidence in the instruments are import concerns. For the purpose of the trial at Keele a linearly affected instrument was chosen and the appropriate calibration calculated to ensure the output measurement would be robust to any blend up to 20 mol% hydrogen. The manufacturer calibrated the detectors to the desired level to certify the detectors were fit for purpose.

The carbon monoxide sensor used in common detection instrumentation is an electrochemical cell which oxides the carbon monoxide and measures the rate of hydrogen ion production. When hydrogen encounters the sensor, it breaks down and produces further hydrogen ions, therefore providing a second signal – this is interpreted as carbon monoxide and results in an output measurement. Much like flammable gas instrumentation, the laboratory testing indicated that the presence of hydrogen generated conservative readings. However, this could result in response procedures being invoked, so the potential risk was therefore nuisance and operator confidence in the detector readings.

Following a review of available detectors on the market, a technical selection process was conducted to identify appropriate instrumentation which would not result in nuisance alarms. A detector was identified that contains a carbon monoxide hydrogen-compensated sensor which provides the necessary level of compensation to not produce nuisance alarms due to a blend of up to 20 mol% hydrogen. The detector also had the appropriate ATEX rating and portability requirements.

The identified carbon monoxide detector was used in conjunction with the appropriately calibrated flammable gas detector for the purposes of the trial, this strategy was reviewed and agreed as part of the Exemption process. The two detectors in combination provided the necessary level of measurement accuracy to allow all current action levels to be maintained.

A dedicated training package of familiarisation was developed for all operatives and contractors associated with the operation of the Keele network. Through the training material, operative's competency to use the detection instrumentation was tested prior to the trial commencing.

Following the successful identification of available detectors and the development of the associated training, a process of industrial engagement with manufacturers was undertaken. This process sought to engage with gas detection instrumentation manufacturers to provide a framework of collaboration and facilitate the development of a single detector capable of being deployed on both a natural gas network and blended network containing up to 20 mol% hydrogen. This engagement was successful and led to the develop of a prototype detector by one of the major gas detection manufacturers, which subsequently underwent field testing.

3.1.5 Quantitative Risk Assessment

To allow a discrete comparison of risk between natural gas and a hydrogen blend to be computed, a Quantitative Risk Assessment (QRA) was developed. The QRA enabled the causal relationships to be understood between public risk and the characteristics of a gas conveyed within a gas network, both in relation to the network itself and downstream usage within buildings.

Risk was defined as the risk to life due to exposure to carbon monoxide (CO) or as a consequence of fires/explosions. A fault tree was developed using 'AND', 'OR' and 'NOT' logic gates to enable the detailed relationships underpinning gas usage risk to be developed. The fault tree was developed to the necessary level of detail to allow identification of the gas-specific basic events that must combine with environmental, mitigative and human behavior basic events to trigger the chain of risk causality.

Risk due to CO exposure relates to a combination of; high CO in the appliance flue gas; poor fluing or ventilation; and CO build up not prevented by a person. All three of these events are required to create the conditions necessary for CO exposure to represent a risk to life. It is this combination of three independent events that yields the relatively low risk of CO poisoning within domestic settings due to natural gas usage. As CO risk relates to poor appliance behaviour, this leg of the QRA was subcategorized by appliance type within a domestic setting. This allowed any appliance-specific considerations to be taken account such as safety devices that are unique to certain appliances. The CO leg of the fault tree was subcategorized into; central heating boilers; space heaters; cooker hobs; cooker grills; and cooker ovens.

The basic fault tree structure for each of these appliance legs was identical, however segregation allowed appliance-specific inputs to be evaluated; for example, appliances operations per year. Of the independent events necessary for any potential fatality to occur, the only one which relates to the quality of gas supplied is the 'high CO in the appliance flue gas', as this relates to the dynamics of combustion. The dominant cause of high CO within an appliance's flue gas is due to appliance malfunction. For the purpose of the trial free servicing was undertaken prior to and during the trial to minimise the chances of malfunctioning appliances being present on the network during the trial.

Risks due to fire and explosions ('F/E') were categorized into the following: appliance lightback; explosion due to release from the appliance; explosion within a confined space;

external explosion. Once again, a series of independent events are necessary for such scenarios to be realised. These events are; flammable gas is released; the gas accumulates to a flammable concentration; an ignition source of sufficient magnitude is present; and a person does not prevent the explosion.

The fault trees for the four sub-branches of the F/E leg of the QRA were unique in their structure due to each scenario being a unique chain of events that could lead to an F/E event occurring. The gas quality specific basic events were however common to all, as they related to the fundamental gas characteristics and are therefore independent of the specific chain of physical events. The one exception to this related to the risk of gas quality leading to lightback within appliances – which was experimentally found to remain unchanged following the introduction of a 20% blend. The necessary gas characteristic investigations that required exploration therefore related to the impact of a hydrogen blend with respect to:

1. The propensity and magnitude of leakage
2. The accumulation behaviour of leaking gas
3. The ignition characteristics of a flammable cloud
4. The resultant impact of ignition upon building structures

Analytical investigations were undertaken to understand any differences in the above four considerations between a hydrogen blend and natural gas.

The structure of the QRA was developed to be regionally agnostic. This allowed both model validation to be undertaken as well as the development of geographically specific models based on input specification. Following the development of the QRA structure, three scenarios were developed to enable validation and a rigorous comparison of risk to be undertaken of the specific region under consideration, namely, Keele University. The three scenarios developed are summarised in Table 2.

Table 2: QRA scenarios

QRA Scenario	Region	Fuel
1	Great Britain (GB)	Natural Gas
2	Keele University	Natural Gas
3	Keele University	Hydrogen Blend

The first scenario was developed to enable validation of the model using public data from independent and credible sources. This allowed the relevant inputs to be specified for the outturn results of the model to be compared to public data sources. Following validation of the logic structure a regionally specific QRA was developed (scenario 2), based on specific inputs relating to the Keele University network. This allowed the baseline regional risk related to natural gas to be understood as a datum for comparison. The final scenario (scenario 3) was a modification to scenario 2 where the gas quality-specific inputs were modified to reflect a hydrogen blend. Comparison of the QRA results between scenario 2 and 3 allowed a direct risk comparison between the hydrogen blend and natural gas to be undertaken for the Keele University network being considered.

3.1.6 Customer Engagement

Extensive customer engagement was undertaken throughout Phase 1 for three purposes:

1. Personal engagement with the residents due to receive the blend to provide information and assurances and allow consumers to ask questions to gain clarity on the project and its intent
2. Create a channel to collect information related to the gas appliances and installations due to receive the blend
3. Provide the basis to gain a wider understanding of customer perceptions of hydrogen

Approval was secured from an Ethical Approval Committee at Keele University for the project, prior to engagement with any participants in the programme. The customer engagement was primarily undertaken through site liaisons who personally engaged with the residents through door-knocking exercises. This enabled a bilateral relationship with the residents to be established to ensure they were being brought 'along the journey' of the project. Alongside door-knocking, written engagement was also undertaken through letters and leaflets, as well as a social media campaign to leverage as many engagement channels as possible. Contact with customers and stakeholders was a priority throughout the project.

Figure 6: Typical material shared with onsite customers



Figure 7: Customer engagement




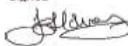
3.1.7 Metering and Billing

Extensive engagement with Ofgem and Keele University enabled a project-specific gas billing mechanism to be utilised for the trial. The principles of which were to assume gas qualities in the favour of the consumer throughout the trial and to ensure no consumer paid for the hydrogen received through the blend supplied. The system was implemented effectively throughout the trial and administered in accordance with the agreed structure with Ofgem. The process implemented for the trial was a pragmatic solution in favour of the residents, the long-term implications of the energy transition with respect to energy billing are being investigated by separate projects such as the Future Billing Methodology (FBM) project.

3.1.8 GS(M)R Exemption

Throughout the development of the evidence base, the project team engaged closely with the HSE Officers responsible for this programme. The Exemption application was submitted on 25th June 2018. This was followed by a process of detailed challenge and review with over 140 clarification questions which were addressed by the project team. A final determination was made on 1st November 2018, granting an Exemption to operate the trial at 20 mol% blend on the Keele network. This was an extremely constructive process, with the regulator making a determination on a complex application in around four months. On the basis of the Exemption the project Steering committee sanctioned progression to the next project stage on 1st November 2018.

Figure 8: Exemption certificate

 <p style="text-align: center;">The Health and Safety at Work etc. Act 1974 The Gas Safety (Management) Regulations 1996 Certificate of Exemption No.1 of 2018</p> <ol style="list-style-type: none"> The Health & Safety Executive ("The Executive"), in accordance with the power conferred on it by Regulation 11(1) of the Gas Safety (Management) Regulations 1996 (SI1996/551) ("The Regulations"), and being satisfied of the matters referred to in Regulation 11(2), grants the following exemption. Keele University, whose registered office is: Keele University, Keele, Staffordshire ST5 5BG, is exempt from the requirement imposed by Regulation 8(1) of the Regulations in so far as it relates to the requirements in Part 1 of Schedule 3 of the Regulations that the hydrogen content is $\leq 0.1\%$ (molar); This exemption only applies in relation to the conveyance of natural gas (methane) in the G3 element of the Keele University gas distribution network, as described in the safety case prepared by Keele University dated 23rd August 2018. This exemption allows natural gas with a Hydrogen content of less than or equal to 20% (molar) to be conveyed in the G3 network described above. <p>This exemption is granted subject to the following conditions:</p> <ol style="list-style-type: none"> Gas conveyed in the network described above should comply with all other requirements and prohibitions imposed by regulation 8(1) of the Regulations. Keele University will notify The Executive of the date when gas containing hydrogen content above 0.1% (molar) first enters the G3 network. Keele University will notify The Executive upon completion of the trial. 	<p>5. This certificate shall come into force on 1st November 2018 and shall remain in force until such time it is revoked by the Executive by a certificate in writing.</p> <p>Signed </p> <p>Mr Jonathan Holvey HSE Head of Operations</p> <p>A person duly authorised by the Executive to act in that behalf.</p> <p>Date: 1st November 2018</p>
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3.2 Phase 2: Installation of Compound and Network Equipment

3.2.1 Compound Integration

A 20 x 20 m compound was built at Keele University to house both the Grid Entry Unit and electrolyser, along with all associated equipment. The complete compound is shown in Figure 9.

Figure 9: Integrated compound



The construction work was overseen by Otto Simon Ltd (OSL) on behalf of Cadent. Alongside the hydrogen generation and blending equipment, supply and return pipework was installed to redirect the Keele University campus natural gas supply into the compound, and then return the hydrogen blended gas to the network for distribution to the end users.

3.2.2 Electrolyser

A 0.5 MWe electrolyser supplied by ITM Power was designed and installed in the HyDeploy compound at Keele University. This included a power supply unit (PSU) as well as a 5 m³ buffer tank operating at 20 barg to enable sufficient ullage to allow regeneration of the driers. The hydrogen was drawn directly from the buffer tank for blending, with the electrolyser refilling the storage within a defined pressure envelope.

Figure 10: Installed electrolyser system



3.2.3 Grid Entry Unit

In order to safely blend hydrogen into the network, a hydrogen grid entry unit was required. Whilst the equipment had some similarities to a biomethane grid entry unit, the requirement to reliably blend hydrogen at set levels was novel. Thyson Technology Ltd was selected as equipment provider and undertook final design and fabrication based on the specification and design developed during the Exemption process. The equipment completed fabrication and was initially Factory Assessment Tested (FAT) using inert gases at their facility. This was followed by a second FAT phase at NGN's Low Thornley site. This allowed full blending to be assessed with the product flared, unlike at Keele University. The unit performed well within the parameters that could be tested remotely from a live network and was accepted for delivery to Keele.

The GEU was the first hydrogen grid entry unit designed in the UK and therefore a clear example of where the HyDeploy project has stimulated innovation within the gas industry to

facilitate the development of critical future technologies.

Figure 11: GEU internals



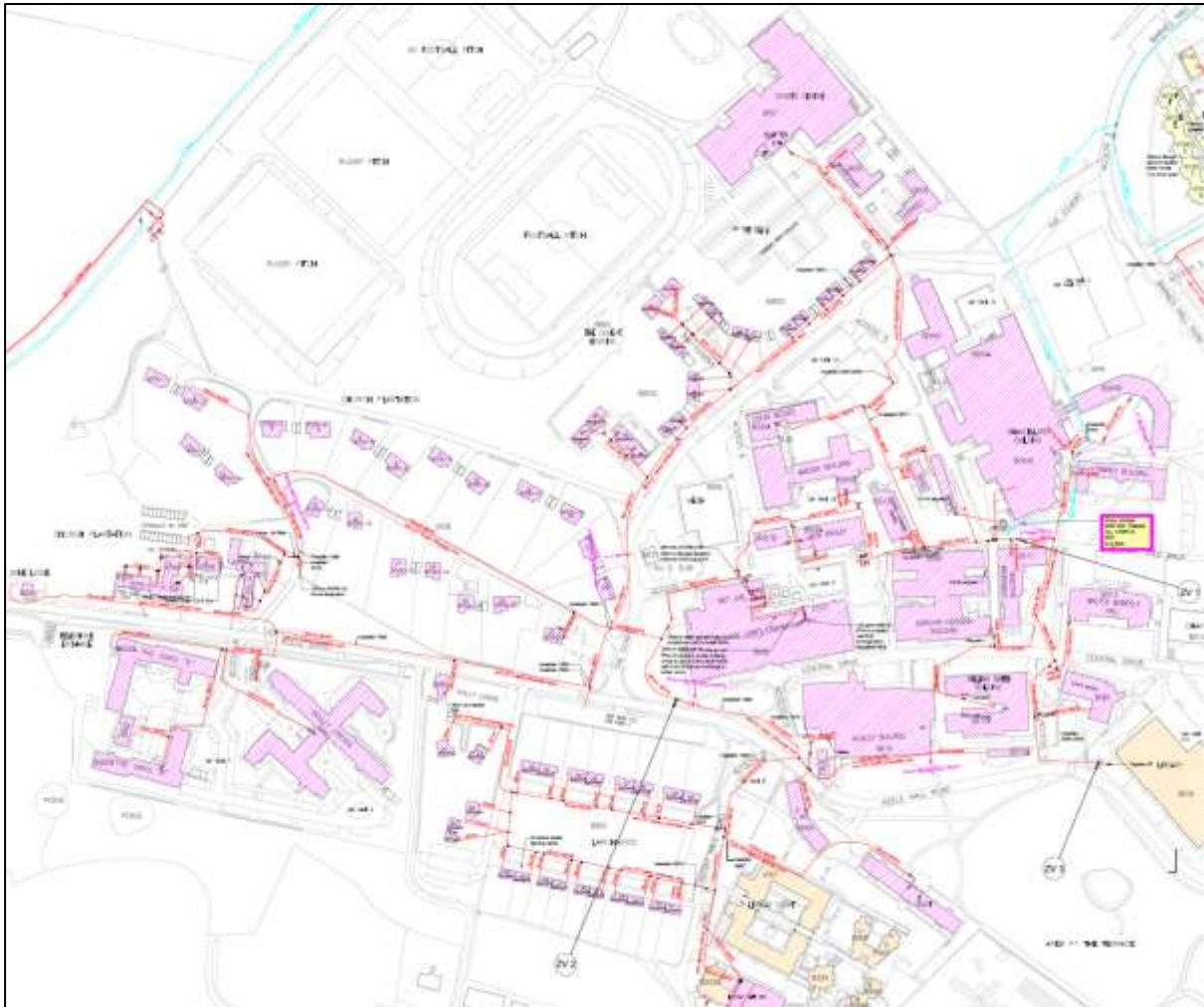
The GEU comprised of gas analytical instrumentation and controls to allow the stipulated blend level to be achieved whilst remaining within all other gas quality limits stipulated by GS(M)R and to any process limitations.

3.2.4 Network Monitoring

Network monitoring equipment was installed across the blended network to provide an overall evaluation of the operation of the network and collect critical confirmatory data to test the expectations of how the network would operate when transporting a hydrogen blend. Six stations were installed across the network to provide a representative understanding of the network operation. Each station contained a live pressure logger to observe pressure profiles, a rhinology test point to confirm odour intensity, and a gas sampling point to allow manual sample extraction for compositional testing at the Chemistry laboratories on campus.

A map of the Keele University campus and network that received the hydrogen blend is provided in Figure 12.

Figure 12: Keele Network



To support the network monitoring a gas chromatograph was installed at the extremity of the network to provide a continuous stream of compositional data to be obtained and allow comparison with the samples taken from the sample points as well as the compositional instrumentation within the GEU. These facilities are shown in Figure 13.

Figure 13: Gas sample point (left) and Network GC (right)



3.2.5 Boiler Research Facility

The project had strong support from the major boiler manufacturers who maintained their appliance warranties for the duration of the trial at Keele. However, they were keen to collect data to support the long-term operation of their equipment in preparation for hydrogen blend roll out. One of the larger boiler houses at Keele was adjacent to both the blended hydrogen network as well as one of the other natural gas networks which had no hydrogen injected into it. This provided the opportunity to install a bank of boilers, with two from each of the manufacturers, one operating on the blend and the other on natural gas. An intensive operational regime was defined, with some boilers operating continuously at maximum load, some at minimum load and others cycling between the two.

Figure 14: Boiler research facility



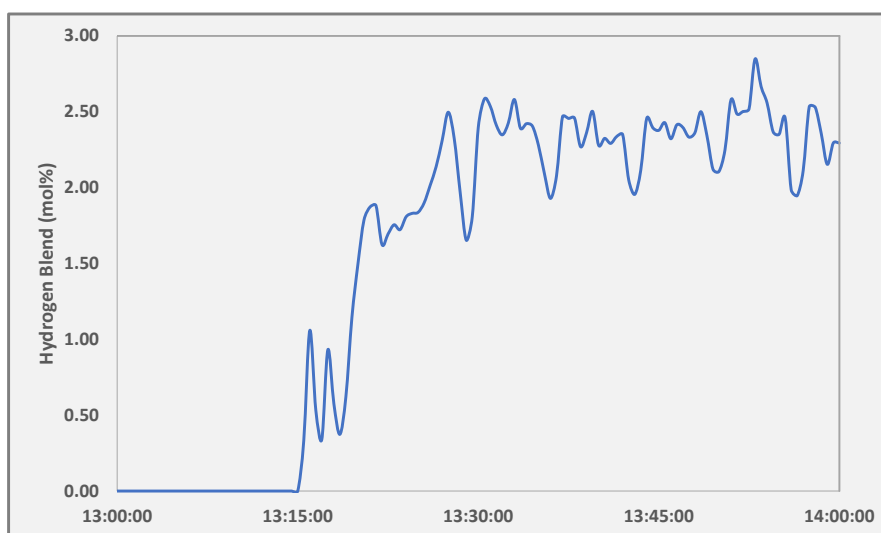
All boilers operated well throughout the trial, consuming fuel volumes equivalent of up to 18 years of normal domestic operations. The boilers were returned to the manufacturers at the end of the trial for performance testing and component integrity analysis.

3.3 Phase 3: Hydrogen Blend Trial

3.3.1 Sanctioning Blending and Injection

On October 30th 2019 at 1:15 pm the HyDeploy gas network at Keele University became the first to transport a hydrogen containing gas within the UK in over 40 years. This was a watershed moment in the story of decarbonisation with the UK. Demonstrating the ability to safely transport and use hydrogen blends lies at the core of the HyDeploy project. This historic moment is graphically captured in the figure below.

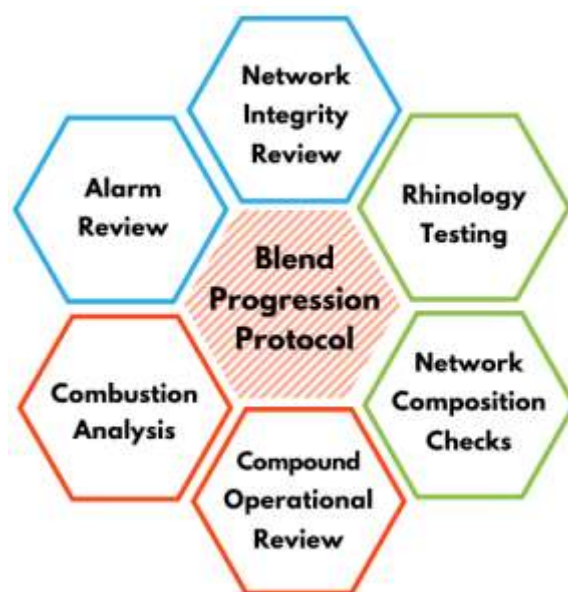
Figure 15: Initial blend on the 30th October 2019



The initial injection of the hydrogen blend was set to a few percent mol%. Given the requirement to not flare gas on this site, the first processing of the hydrogen blend during commissioning had to take place with the resulting gas being supplied to the downstream network. Therefore, from the first generation and processing of the hydrogen, the trial was live. This meant that a cautious approach was appropriate to allow the subsequent equipment integration, commissioning and control tuning to take place with a comfortable operational margin below the Exemption limit of 20 mol%.

Following the completion of the equipment commissioning, an agreed blend progression protocol was implemented to safely manage increasing the blend level in a methodical and robust manner. The basis of the evidence presented in support of the Exemption application was that, no detrimental effects were expected across both network and appliance operations due to the introduction of the blend. The purpose of the blend progression protocol was to prove this across the full range of blend levels. The terms of the granted Exemption did not specify this approach as being required to prove the safety of a blend, however the project took the decision that a controlled and methodical process was the best way to safely manage operations in this first-of-a-kind demonstration of a hydrogen blend. The necessary stage gates within the blend progression protocol are outlined in Figure 16 below.

Figure 16: Blend progression protocol



Following each stage of progression, the imposed maximum blend level restriction was lifted, from the initial 2 mol% through to all restrictions be lifted within the exemption limit i.e., 20 mol%. With each sanctioning of a subsequent blend level, the operational requirements of the compound equipment changed, with more hydrogen at greater blend percentages required to be blended with natural gas. This meant that the control tuning within the equipment was necessary, with troubleshooting and optimisation exercises required at each stage to ensure the best possible performance was being delivered by this first-of-a-kind technology. This process of operational troubleshooting and optimisation led to the blend progression process taking somewhat longer than originally anticipated, with the final stage of all restrictions being lifted within the 20 mol% exemption limit taking place in February 2020. Following this process blending was to be conducted within process limits, without any artificial constraints, and safe in the knowledge that the performance and safety of both the downstream network and appliances was demonstrated and documented.

The purpose of the HyDeploy project was to demonstrate the safe transportation and use of hydrogen blends within a live network. Therefore, extensive networking monitoring was undertaken throughout the trial to collect evidence on network and appliance operations.

3.3.2 Compound Operations and Gas Demands

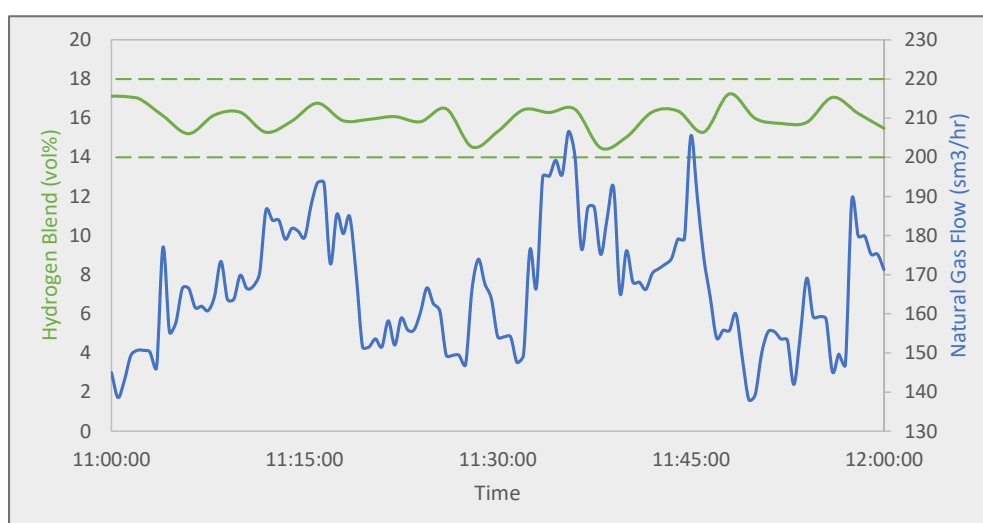
The hydrogen production and blending equipment consisted of a 0.5 MWe Proton Exchange Membrane (PEM) electrolyser supplied by ITM Power and grid entry unit (GEU) supplied by Thyson Technology Ltd. The GEU was the first hydrogen-natural gas blending unit ever designed and constructed in the UK and the Keele University trial was the first time an electrolyser has been integrated with a gas network within the UK. Therefore, the trial offered many learning opportunities to understand how best to operate the combined generation and blending process.

The operational learning captured, particularly concerning hydrogen supply, from the Keele trial was leveraged to inform the operational strategy of the subsequent trial at Winlaton, Gateshead being developed through HyDeploy2 and due to commence in Summer 2021.

Through a methodical identification and troubleshooting process being delivered by a dedicated team of project personnel and technology specialists any operational constraints were able to be identified and worked through to enable the continuation of blending following any necessary remedial actions being undertaken.

HyDeploy has provided the first insight into gas demand profiles at this level of granularity within the gas network. This is a key technical output of the project, as prior to commencing the trial there have been no studies or measurements taken to detail gas demand profiles at this depth of the gas network. The gas demand profile, particularly its variability, was a key operational consideration when managing the blend level. This is because the purpose of the GEU was to maintain a set flow ratio between the downstream natural gas demand and the hydrogen, to maintain a constant blend set point. Therefore, a greater degree of natural gas flow variability produces a more onerous operating environment as constant adjustments are required to maintain the hydrogen blend set point. The natural gas flow variability was discovered to be much more variable than anticipated, which resulted in extended operational control tuning and increasing the margin of control applied to the blend set point to always ensure the integrity of the blend limit, as stipulated by the Exemption. The figure below provides a typical example of this flow variability and the resulting blend percentage achieved during the same period. A time period of one hour has been selected so the full extent of the flow variability can be observed.

Figure 17: Natural gas demand profile and blend percentage



It can be seen that very rapid natural gas flow changes, both increasing and decreasing, were commonplace with eight rapid changes occurring within the hour profile shown in Figure 15. It is also worth noting that the natural gas flow data shown is data taken every 30 seconds, which was the limit of granularity of the data acquisition system. Therefore, the real-world flow variability that was being controlled against was even greater than displayed in the above graph.

The natural gas flowrates varied significantly across the trial, as would be expected with both diurnal and seasonal demand patterns. Typical seasonal gas demand patterns were also affected by the implications Covid-19 restrictions. Table 3 demonstrated this seasonal variability.

Table 3: Natural gas demand seasonal variability

Month	Minimum hourly NG demand (scmh)	Maximum hourly NG demand (scmh)
Jan-20	42	327
Apr-20	34	217
Jul-20	14	64
Oct-20	30	230
Jan-21	55	299

The blend rate was controlled by firstly assessing the maximum percentage of hydrogen that could be blended based on the desired set point and incoming natural gas quality (Wobbe number). A flow rate measurement on the incoming natural gas was then used to calculate the necessary hydrogen flow rate to achieve the given blend level. Two layers of verification were then applied to confirm the blend rate; the first being a check of the flow ratios between the hydrogen and natural gas using independent instruments, and the second being a physical measurement of the hydrogen percentage via an analyser. A 'volume loop' was installed to provide the necessary control loop timing to allow the analyser to measure and output a figure, which was on the order of 9 seconds. Following the two-stage validation process, the blended gas was directed out of the GEU and into the supply line for the downstream network.

3.3.3 Trial End

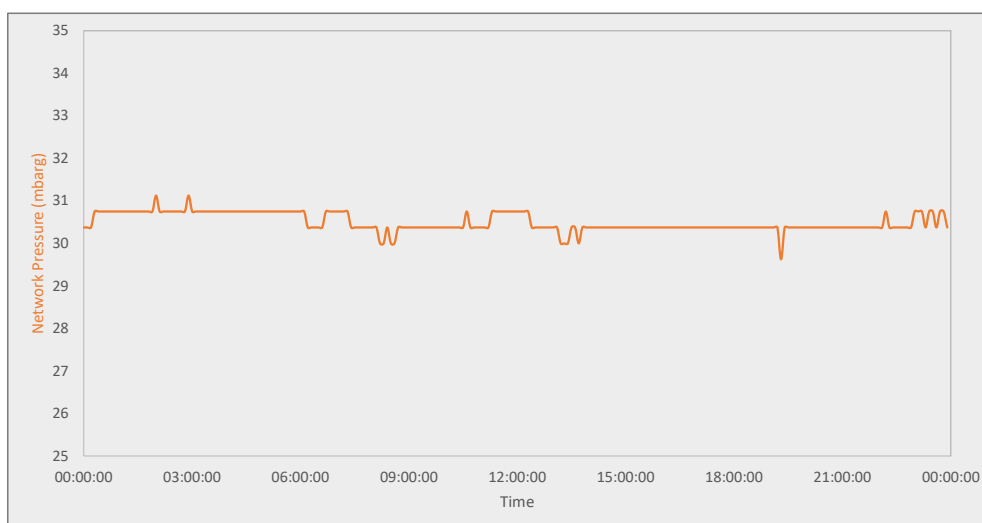
The trial successfully delivered on its objective of demonstrating the technical and operational feasibility of distributing and using hydrogen blends. Over the course of the trial 42,000 scm of hydrogen was delivered to the Keele University network, which abated over 27 tonnes of CO₂.

A controlled and safe process was undertaken to cease blending operations. The electrolyser was turned off on the 5th March 2021 with the necessary valve movements made on the 8th March 2021 to isolate the compound and revert the Keele University network back to natural gas. A subsequent process of decommissioning all network installations was undertaken, which reverted the network back to its pre-trial state. Physical isolations were also made between the compound supply/return pipework and the natural gas supply to the Keele University network.

3.3.4 Network Pressures

To monitor network pressures six pressure loggers were installed across the network. The locations were selected in such a way as to provide a comprehensive understanding of the network pressures during blending operations. As the hydrogen blend remained within the Gas Safety (Management) Regulations (GS(M)R) Wobbe limits, no pressure control issues were expected. Over the course of the trial this expectation was confirmed, as adequate pressure control was maintained throughout the trial. A 24-hour example of network pressures during the trial is given in Figure 18.

Figure 18: Typical network pressures



3.3.5 Network Gas Composition

Gas composition across the network was a key network monitoring objective. The six sample points installed contained facilities to retrieve gas samples from the network for laboratory analysis by Keele University's School of Chemical and Physical Sciences. This sampling allowed a network-wide understanding of the gas composition to be understood and evaluated. Alongside the six sample points a permanent Gas Chromatograph was installed on the network to continuously monitor the composition of the gas at the extremity of the network.

It was expected prior to the trial that no difference in composition would be experienced over the network. The rounds of manual network sampling undertaken at each blend level, as well as the continuous monitoring of the composition at the extremity of the network, demonstrated this.

Across all network sampling results the difference between the measured hydrogen concentration and the known concentrations from the GEU and network GCs was within the error of the measurements. This provides strong confirmatory evidence that network gas composition did not vary over the network.

3.3.6 Network Surveys

A comprehensive survey regime was implemented through the trial to document the integrity of the network, to allow comparison with historical trends. The survey regime consisted of regular above ground leakage surveys of the network, using the approved gas detectors and procedures developed during Phase 1. Alongside the above ground surveys were integrity checks of the governor and any repair techniques utilised. Across all of the survey activities no increase in failures or faults was identified through the trial, relative to historical trends. This provided sound evidence of the suitability of existing network assets to be repurposed without disruption for the transportation of hydrogen blends.

3.3.7 Gas Detector Trial

Following extensive pre-trial research and analysis a gas detection solution was identified to administer network procedures and maintain the current action levels that relate to emergency response. This solution was agreed with the HSE and utilised two existing detectors that were available from manufacturers. The market was engaged to develop a single detector solution that would automatically re-calibrate itself based on the hydrogen content of the gas sample being analysed. A prototype detector was developed by manufacturer Bascom Turner and was tested via the G23 process of equipment acceptance that the GDNs use. Over the course of the Keele trial field testing as well as laboratory analysis was undertaken to evaluate the accuracy of the instrument and its operational readiness. This is a strong example of where the HyDeploy project identified a need to facilitate the transition to a blended gas network and then engaged the market to enable solutions to be developed and adopted.

3.3.8 Rhinology

Rhinology analysis allows GDNs to confirm natural gas contains the appropriate odor intensity to allow public reporting of potential leaks. Ensuring the odor intensity of the gas does not reduce below the perceivable limit when hydrogen is blended is critical to ensuring the integrity of the public reporting system. The supplied hydrogen wasn't odourised prior to injection and the odourant dosing rate of the upstream natural gas supply wasn't increased.

The sample points shown in Figure 13 were designed to accommodate rhinology testing. Preceding each blend level increase during the blend progression schedule confirmatory results were required on the odor intensity to confirm the gas' smell retained its characteristic intensity. Two positive rounds of testing on all six sample points were required to allow the blend level to be increased. Across all blend levels and testing rounds, all six sample points were found to be 'satisfactory' by Cadent engineers. This conformed with pre-trial expectations that no perceivable effect would be experienced due to the blending of the hydrogen into the gas supplies.

3.3.9 Materials

The analysis of materials to evaluate their suitability for exposure to a hydrogen blend was a core technical focus of the HyDeploy programme. In aid of furthering the evidence base generated through the programme a series of material samples ('coupons') were installed within a bespoke piece of pipe within the hydrogen grid entry unit. These samples were exposed to the real-world blend over the course of the trial. At the end of the trial the samples were removed from the GEU for mechanical testing using the same methodologies as the mechanical testing undertaken in support of the safety case development.

3.3.10 Appliance Monitoring Results

Appliance surveys were committed to being undertaken within the Safety Case submission to the HSE in support of the Exemption. The appliance surveys took the form of annual Gas Safe checks for the domestic homes, both private and university-owned, as well as regular monitoring of a select number of commercial appliances.

The appliance surveys recorded combustion performance data as well as carrying out operational soundness checks. The information collected over the duration of the trial

demonstrated that appliances operated as expected and maintained sound combustion performance. No increase in failure rates were observed relative to business-as-usual repairs and remedial action. This evidence is in line with the pre-trial laboratory results and provides strong confirmatory evidence that appliances, both domestic and commercial, are suited to operate as required on a hydrogen blend.

3.3.11 Boiler House Research Facility

The boiler research facility operated without issue over the full length of the trial. The maximum firing boilers consumed the equivalent quantity of gas that would be expected to be consumed in 18 normal years of operation, therefore the test conditions provided a robust basis of assessment to determine any potential long-term implications.

The boilers were extensively instrumented by the manufacturers and installed at Keele under a bespoke control system. They ran through an accelerated testing regime and were then provided back to the manufacturers at the end of the trial for assessment. The manufacturers are unaware which boiler was operating on which gas. In the same facility two gas hobs were also set up in order to demonstrate to visitors the comparison between blend and natural gas operation. An example boiler internals is shown below, alongside the full installation.

Figure 19: Boiler internals

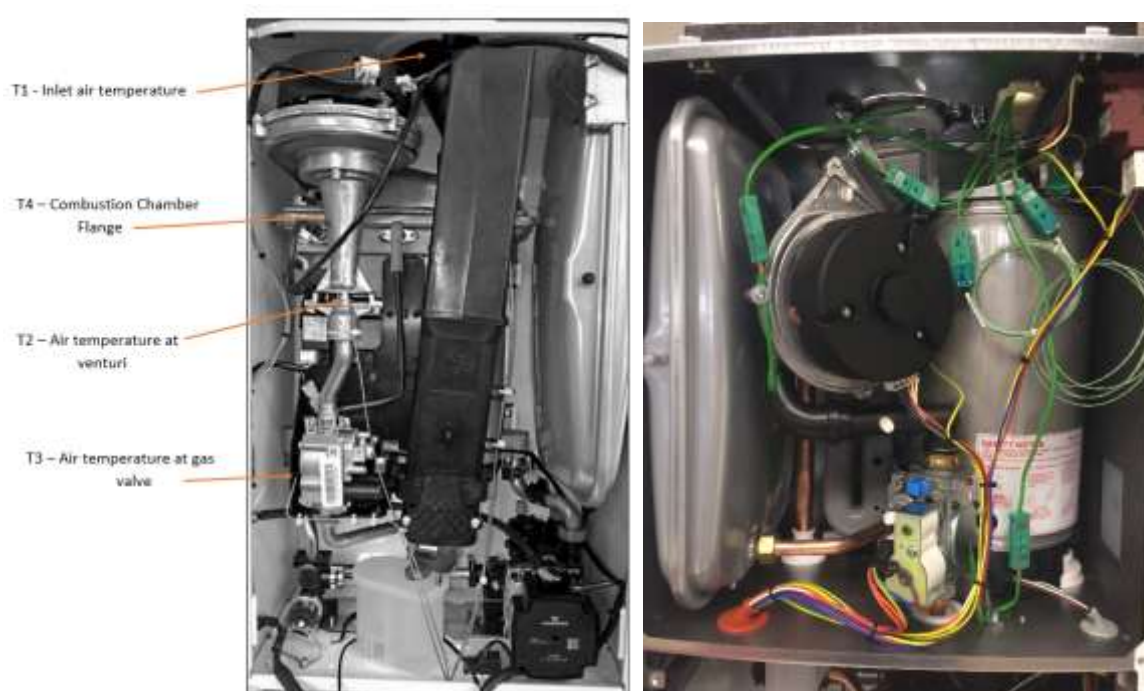


Figure 20: Full boiler installation



Throughout the course of the year flue gas analysis readings were taken on both sets of boilers and analysis undertaken. This research was peer reviewed by all four boiler manufacturers as well as two major suppliers of gas detection equipment to the UK market. The peer review team established that current flue gas analysers are suitable for use with a hydrogen blend. This research has been made publicly available via IGEM and has resulted in a joint Gas Safe technical bulletin (TB) being issued with the Heating & Hot Water Industry Council (HHIC) summarising the findings. The technical bulletin was TB 157, published in May 2020, and provides the needed assurance of equipment continuity for the downstream industry.

3.3.12 Gas Sensor Trial

The pathway to Net Zero will necessitate compositional changes to the gas currently supplied to consumers, with the introduction of hydrogen and biomethane. Therefore, the need to understand gas compositions at a regional and local level, either directly at the point of use to optimise combustion or to inform a net zero compliant energy billing regime, will be fundamental to enabling the gas network to support the pursuit of achieving Net Zero.

The current reference technology utilised for these purposes is a gas chromatograph (GC) such as the one shown in Figure 13. A GC is well established technology with known operational performance and accuracy, which is why it has been the reference the technology for many decades. However, it is likely devices will be needed that provide compositional analysis which do not require a mains power connection (so can be installed remotely) and do not have the cost or maintenance requirements of a GC. Separate from HyDeploy, such developments were underway by the Dutch research organisation TNO, supported by Orbital Gas. HyDeploy offered up the blended gas network for them to install and field trial an innovative analyser capable of measuring the composition of blended natural gas. Figure 18 shows the installation, which consists of three sensor probes installed at the boiler research facility outlined previously.

Figure 21: Gas sensor probes



At the end of the trial the sensors were removed for further laboratory testing, with an ambition for the next generation of the probe to be field tested in the follow-on trial at Winlaton under HyDeploy2. This is another example how demonstration trials can provide important resources and facilities for the private sector to bring forward and test solutions to unlock the wider market, beyond the core purpose of the programme.

3.3.13 Customer Engagement & Social Science

Consumers lie at the heart of the HyDeploy project. The basis of blending hydrogen into the gas network is that it unlocks material quantities of decarbonisation, provides a foundation for deeper carbon savings through hydrogen deployment and achieves these without disrupting consumers. To formally analyse the experience of residents taking part in the trial, along with their views and feelings of consuming blended gas, a social science programme of research was undertaken by Keele University. This consisted of pre-trial interviews to baseline the resident's views and expectations, and interviews towards the end of the trial to understand the impact of being a part of a live trial and see if any change in attitudes towards hydrogen blends has resulted from participation in the trial.

The residents demonstrated an overall positive enthusiasm to being a part of the first hydrogen blended trial and took pride in being at the vanguard of hydrogen deployment. A degree of understandable anxiety was initially present due to the first-of-a-kind nature of the trial. However, this anxiety decreased over time as understanding about the process increased and reassurances were received. The results of the social science study will be published to inform the wider industry and policy makers concerning deployment strategies for hydrogen.

Figure 22: Resident engagement



Strong communication links were established pre-trial to ensure a bilateral relationship with the residents was created for the project to provide information and assurances, and to provide an opportunity for the residents to engage with the project. These links were maintained throughout the trial to enable continued dialogue with the residents. An unforeseen complexity that had to be accommodated was the impacts of Covid-19. A proactive project decision was made to maintain the links of communication throughout the trial, but not actively physically engage in line with general site guidance and so the residents did not feel under any pressure to physically engage with project personnel.

A dedicated in-person resident's event was planned during the trial, but ultimately had to be online. These challenges were embraced by the project team and dealt with appropriately to still ensure communication lines remained open with the residents throughout the trial. To that end, no formal issues or complaints were received from the residents throughout the trial, with generally positive support for *'being able to make a difference without having to do anything'*.

3.4 Policy Engagement

The project maintained regular contact with Ofgem, BEIS, standard setting bodies and wider stakeholders to ensure the learning from HyDeploy is leveraged within policy development. Such engagement has been through bilateral meetings, working groups and membership of advisory groups such as the Ministerial Hydrogen Advisory Council and Gas Blending Group. This engagement has allowed policy makers to be kept abreast of the latest progress from the HyDeploy programme in clearing barriers for the adoption of hydrogen blends.

4.0 Performance

4.1 Overall Performance

The project sought to prove the technical and regulatory viability of providing a hydrogen blend to a live gas network. This has clearly been demonstrated, as described in Sections 3.1 and 3.3.

The technical evidence base generated to support the safety case application to the HSE, in pursuit of an Exemption to the 0.1 mol% hydrogen limit within Schedule 3 of GS(M)R, was successful in:

1. Identifying the key technical contributors of risk as a consequence of the conveyance and use of natural gas.
2. Developing and validating a risk model to understand the relationship between gas quality characteristics, physical phenomena and mitigations.
3. Developing a robust comparative analysis of the impacts of a hydrogen blend relative to natural gas for the key technical contributors.
4. Generating a rigorous comparative safety analysis to demonstrate the risk parity of a hydrogen blend compared to natural gas.
5. Managing the ongoing engagement process with the HSE throughout the evidence creation stages and the resulting safety case submission to allow the evidence base to be appropriately reviewed and ultimately accepted by the HSE, as the basis of an Exemption.

Through in-depth monitoring of both the network and appliance operations through the trial, as described in Section 3.3, the project provided meaningful initial evidence that the existing infrastructure is capable of receiving a hydrogen blend from both a distribution and utilisation perspective. The combination of rhinology testing, network pressure analysis and compositional monitoring has provided confidence that the medium-pressure and low-pressure tiers of the distribution network are not detrimentally affected by the presence of a hydrogen blend. Regular monitoring of critical safety and performance metrics of downstream appliances, as well as monitoring of alarms and leaks, has also shown that no adverse operational impacts should be expected following the introduction of a hydrogen blend.

By establishing the technical and safety evidence to demonstrate the feasibility of providing a hydrogen blend for distribution and utilisation, the project has significantly increased the potential for deployment of hydrogen blends within the gas distribution network. This meaningful progression has demonstrated the viability of hydrogen in playing a critical role in achieving the UK Government's environmental ambitions of Net Zero by 2050 and has shown a pathway to develop a Net Zero compliance gas distribution network.

4.2 Progress Against Bid Plan

The progress of the project against the outlined plan within the bid is set out in the following table:

Table 4: Progress against bid plan

Programme Element	Progress
1. Site communications and stakeholder engagement	An extensive communications and engagement plan was developed, submitted to Ofgem and was approved under the relevant University governance process. Communications material was produced, including the project website with necessary booking processes and systems. A dedicated customer liaison officer facilitated a successful programme. Excellent customer participation was secured during the house-to-house testing phase, with positive feedback. During the second and third phases of the programme, the impact on customers was much less significant, although engagement continued. Subsequent rounds of Gas safe checks were undertaken in 2019 and 2020 alongside agreeing the billing regime for the trial with OFGEM in 2019. In parallel, the Keele University undertook independent research into customer perceptions of low carbon energy and the trial itself. This engagement continued into the trial phase. With the Covid impacts, online events were arranged with residents, other members of the Keele community and local and national stakeholders. A series of final engagement activities took place at the end of the programme to disseminate the findings from the project.
2. Pre-Exemption activities to develop the Exemption / safety case	This was the most extensive element of the programme during the first phase of the project, as it provided the detailed evidence base for the Exemption. This work drew on the national and international evidence base available, as well as detailed experimental and test work undertaken as part of the project. This was completed and the Exemption granted in November 2018. This provided the basis for the equipment to be fabricated and installed in the second phase and operated in the third phase.
3. Specification and design of hydrogen production and mixing units	During the first phase of the project a detailed functional specification was developed, an extensive tender process undertaken to select a supplier for the GEU and detailed design work undertaken. In parallel a basis of design and FEED was undertaken for the electrolyser, followed by detailed design. This information formed an important part of this first Exemption submission, demonstrating that blending could be delivered, and the foundation for the second phase of the project.
4. Write safety case and apply for GS(M)R Exemption	The full Exemption was developed and submitted on the 25 th June 2018. This was followed by a period of robust interrogation including over 140 clarification questions, to

Programme Element	Progress
	ensure that the evidence was fully understood. An Exemption to blend hydrogen at 20 mol% for the trial on Keele's network was granted on 1 st November 2018.
5. Regulatory and billing arrangements	<p>Billing. A billing regime was developed and agreed with Ofgem for the trial. Based on the billing management system used by the University, the practical details were developed to implement the approach. This was a conservative regime, ensuring that no customers were adversely affected during the trial.</p> <p>Electrolyser ownership. This proved to be a greater regulatory challenge than had been originally anticipated. Given the small scale of the operation there had been an expectation that it would be possible to secure a suitable derogation to allow the GDN to own the equipment. An alternative ownership solution had to be implemented. This was successfully delivered through some changes with the arrangements with ITM, in order to transition to the third (operational) phase of the programme.</p>
6. Predevelopment installation activities	The Basis of Design (BoD) for the equipment and modifications to the network was developed as part of the Exemption submission. Some early work on the network and services was undertaken where they could be integrated into wider university schedules.
7. Secure project gateway clearances	Internal project gateway clearances were achieved. The key criterion was granting of the Exemption from the HSE. The other requirements were: securing of the necessary planning permission; and the formal agreement by the University Executive Committee. The process was carefully managed to enable Steering Committee sanction the day after the Exemption was granted to expedite project progress, and the consumers were informed the next day.
8. Installation of hydrogen injection equipment	<p>A detailed execution plan was developed for the hydrogen production and injection equipment. Final detailed design work was undertaken, orders placed and the equipment fabricated. An extensive programme of acceptance testing was undertaken. The GEU was initially tested at the fabrication works, followed by a second phase of 'Factory Acceptance Testing' at NGN's Low Thornley site where the blended product could be flared. A similar programme was undertaken for the electrolyser fabrication and factory testing at ITM's works.</p> <p>In parallel site works were undertaken, including provision of utilities and connections, and the compound itself. During</p>

Programme Element	Progress
	<p>summer 2019 and early autumn, the individual equipment items were transported and installed onsite.</p> <p>All the necessary documentation and assessments were undertaken, including the G17 process to ensure that the equipment was designed, fabricated and installed appropriately. The HSE attended the site to review the final installation.</p>
9. Installation of network monitoring equipment	<p>Network monitoring, including sample points, were strategically located around the trial network to enable compositional, pressure and rhinology data. These provided confirmation of network gas flows and enable validation of network models. These were all safely installed, alongside a network Gas Chromatograph.</p> <p>A dedicated appliance test facility was established. The four major boiler manufacturers each provided two fully instrumented boilers which were installed in a strategically located university boiler house such that they could be operated on natural gas and a hydrogen blend respectively. Based on duty cycles selected by the manufacturers to represent accelerated life time tests, they were being operated and monitored during the entire trial phase. Following the trial these were stripped down and a 'blind' assessed undertaken by the manufacturers without knowing which of their units was operated on a blend. This will provide ground breaking evidence of blend operation to support long term deployment.</p>
10. Pre-injection processes	<p>The processes were agreed as part of the Exemption and detailed operational plans were developed. Pre-trial tests of pipework and appliances were undertaken to ensure that the Gas Safe position maintained, and that a clear reference was developed against which the trial phase could be benchmarked.</p> <p>The gas detection solution agreed as part of the Exemption was implemented, with equipment procured and installed at the university security building, such that FCOs attending site had appropriate access to equipment ready to use.</p> <p>A training programme was developed and delivered for all operatives and other network stakeholders in the delivery of the trial phase. This ensured that the revised procedures for the trial, including changes to gas detection were fully implemented. A local Gas Safe bulletin was developed with the support of the appliance manufacturers to ensure gas safe engineers operating in the region were fully briefed.</p> <p>In order to transition from equipment installation through to</p>

Programme Element	Progress
	blending a comprehensive project approval protocol was developed. Fifty-eight individual items required sign off for the project Steering Committee to sanction first blend into the network.
11. Injection plant and equipment operation	Project sanction was secured to commence injection in October 2019. From this point and throughout the trial the hydrogen generation and injection equipment were operated and optimised to deliver a successful trial. The compound equipment underwent regular monitoring to ensure sound operations and allow any situations requiring investigation and potential remedial works to be undertaken without delay. Both the hydrogen generation and injection equipment underwent all necessary annual checks as per their Written Schemes of Examination (WSoE), Operations & Maintenance (O&M) manuals and the Pressure Systems Safety Regulations (PSSR).
12. Data gathering during the trial	<p>A full suite of data has been collected during the trial. This includes:</p> <p>Compound operation: Electrolyser and GEU operation, including evidence of satisfactory blend control.</p> <p>Network operation: Satisfactory Rhinology, compositional evidence across the network, demonstrating maintenance of the blend level as well as monitoring general network operation.</p> <p>Appliance operation: Appliance temperatures and flue gas checks on commercial and test boilers were measured. No CO alarms were reported throughout the trial.</p> <p>Throughout the trial the equipment operated safely, ensuring that the blend limit was not exceeded. No loss time injuries took place over the full trial. There were no issues on the network, satisfactory rhinology was evidenced, network composition was well controlled and no unusual issues on the network were identified. The appliances all performed as expected, with no CO alarm issues, nor adverse customer feedback. Materials samples were installed in the gas line and were analysed post-trial.</p>
13. Incremental injection	Under the blend progression protocol the blend levels were incrementally increased through 2 mol%, 5 mol%, 10 mol%, 12 mol%, 15 mol% and then finally all restrictions within the 20 mol% limit were lifted in February 2020.
14. Plan follow-up project on public network	Based on the extensive understanding developed in the HyDeploy programme at Keele, the plans for the public trials were developed. HyDeploy2 successfully secured funding

Programme Element	Progress
	and commenced in April 2019.
15. Keele site reinstatement/ Handover	<p>The electrolyser was turned off on the 5th March 2021 and the compound isolated from the network on the 8th March 2021. All network installations were then safely decommissioned and the site returned to its pre-trial state. The compound was safely shutdown from an operational perspective and physical isolation breakpoints were implemented between the compound supply/return pipework and the natural gas supply to Keele University.</p>
16. Dissemination and reporting	<p>A number of technical papers were developed to disseminate the findings from the Exemption process. This included a paper in Clean Energy, 2019, (Vol. 3, No. 2, 114–125) entitled: <i>HyDeploy: The UK's First Hydrogen Blending Deployment Project</i>. A series of articles were delivered through the IChemE, and further papers presented at the International Conference on Hydrogen Safety. Articles have also been written for the Gas Safe Register magazine along with formal technical bulletins issued as a result of research undertaken through the trial.</p> <p>A two-day technical workshop was delivered in January 2019 and attended by around 100 gas industry experts from the UK and abroad, disseminating the key findings. A workshop was also held for officials involved in hydrogen at BEIS during the summer of 2019.</p> <p>The project was presented at a range of events during this period including those organised by the HSE, IGEM, CIBSE, EUA, Energy Efficiency Alliance, the Pipeline Industry Guild, Association of University Engineers, Utility week, BlueFlame, “Hydrogen Reality – Why Now?”, UKRI Supergen, “Delivering the Hydrogen Economy North West”, Staffordshire Chamber of Commerce, The National Hydrogen conference, an IChemE webinar, The Hydrogen APPG.</p> <p>The project was also presented internationally in Madrid, Bangladesh, Hong Kong and Adelaide.</p> <p>The Advisory Board convened regularly throughout the project, facilitating direct engagement with both national and international stakeholders.</p> <p>During the trial itself, recording and filming was undertaken with the BBC and CNN.</p>
17. Project management	<p>Effective project management is necessary to deliver a project with 6 partners and multiple work streams. The governance structure was provided by the Steering group which met quarterly.</p>

Programme Element	Progress
	A well-managed system of monthly project meetings with associated programme and budget reporting was in place throughout all three project phases. A comprehensive project risk register was used to manage the programme and maintain line of sight of programme risks, which enabled proactive management plans to be implemented. Subsidiary working groups were established and managed to progress individual work streams.

4.3 Performance Against SDRCs

The performance of the project partners against each of the Successful Delivery Reward Criteria (SDRCs) is set out in the following table:

Table 5: Progress against SDRCs

SDRC	Title	Target Date	Description & Evidence
9.1	Communications Plan	24.11.2017	<p>The communications plan submitted outlined the project's engagement strategy across all three project phases. Due to the first-of-a-kind nature of the project, the communications strategy evolved over the course of the project as information was gathered relating to stakeholders and public knowledge/perceptions.</p> <p>The strategy outlined a stakeholder map, with the trial residents identified as the primary stakeholder group. A detailed communications plan was then defined to ensure the appropriate depth and mode of engagement was being undertaken throughout each phase of the programme.</p>
9.2	Laboratory Appliance Tests	30.03.2018	<p>The laboratory experiments of the appliances formed a central element of the safety case evidence submitted to the HSE in the first phase of the programme. The experimental work was specified by HSE – Science Division and undertaken by Kiwa Gastec. A representative set of appliances was tested for both performance and safety criteria. The results of which provided strong supportive evidence of the ability of</p>

SDRC	Title	Target Date	Description & Evidence
			current appliances to safely operate with a 20 mol% hydrogen blend.
9.3	Onsite Survey programme	25.05.2018	<p>A comprehensive programme of onsite works was carried out to both; engage with residents; and collect critical information of the integrity and performance of installations (appliances and pipework).</p> <p>A detailed appliance survey was conducted to support the laboratory testing. Alongside this survey, field testing was conducted which involved an independent Gas Safe organisation testing the pipework integrity (leak testing) and appliance performance. Testing was conducted with both natural gas and a hydrogen blend containing 28.4 vol% hydrogen. All appliances and pipework found to be safe and tight with natural gas were also found to be safe and tight with a hydrogen blend. This survey work formed a critical piece of evidence demonstrating the suitability of the Keele installations to safely accept a hydrogen blend.</p>
9.4	Exemption & QRA	29.06.2018	The overall structure of the Exemption and supporting QRA was provided. This highlighted the diverse and robust evidence base collected to support the QRA and wider Exemption application.
9.5	Exemption Approval	31.08.2018	The Exemption certificate was provided as proof of the successful safety case application, as shown in Figure 8.
9.6	Gateway to Phase 2	31.08.2018	Following the successful granting of the Exemption by the HSE, steering committee approval was provided to proceed to the second phase of the programme – the construction of the compound at Keele.
9.7	Hydrogen system installation	26.04.2019	Within one year of the second phase commencing a secure compound had been built consisting of the UK's first hydrogen grid entry unit (GEU), designed and built by Thyson Technology Ltd, as

SDRC	Title	Target Date	Description & Evidence
			well as integration with a 0.5 MW PEM electrolyser, designed and built by ITM Power. The hydrogen system installation was the first in the UK to generate and blend hydrogen into a live gas network.
9.8	Completion of Field Trial	28.02.2020	<p>The field trial commenced on the 31st October 2019 and finished on the 5th March 2021. The trial successfully demonstrated that hydrogen blends could be safely distributed and utilised within the existing gas network infrastructure. In total 42,000 scm of hydrogen was delivered to the Keele network, which abated over 27 tonnes of CO₂.</p> <p>Critical operational evidence was collected through the trial relating to the operational performance of both the distribution network and downstream appliances. Through the trial a rigorous monitoring regime of network evidence such as: rheology; pressure surveys, and gas compositional data, demonstrated the suitability of the network in transporting hydrogen blends. Alongside this, ongoing evidence was collected relating to the downstream users, both meters and appliances. Safety and performance data was collected, including the development of a bespoke boiler research facility in collaboration with the four major UK boiler manufacturers, to demonstrate the long-term suitability of appliances operating with a hydrogen blend.</p> <p>The field trial was impacted by COVID-19, where a 10-week operational hiatus had to be imposed due to contractor availability and site access during the first national lockdown. Additionally, lock down reduced gas utilisation on site until autumn 2020. With agreement from Ofgem and HSE, the trial end date was extended to counterbalance this hiatus, allowing the necessary trial evidence to be collected.</p> <p>The field trial was in alignment with the</p>

SDRC	Title	Target Date	Description & Evidence
			safety case submission, and provided demonstratable evidence that hydrogen blends can be safely distributed and utilised within existing gas infrastructure.
9.9	Public network trial definition	31.03.2020	This objective was significantly exceeded. Not only was a trial defined, but funds were secured and the programme implemented. The public trial is the Winlaton demonstration to be undertaken through the HyDeploy2 programme, where a hydrogen blend will be supplied to 668 homes from the Summer of 2021 (subject to HSE approval). This demonstration will further progress the adoption of hydrogen blends and provide further demonstratable evidence of the suitability of users and the MP/LP gas network for accepting a hydrogen blend.
9.10	Dissemination & Close out report	31.03.2020	A final close down report was provided which summarised the progress and findings of the project, as well as the extensive engagement undertaken to disseminate the findings of the programme.

The safety case evidence related SDRCs (9.1 – 9.4) were delivered on time and demonstrated the robust technical approaches employed to both gather the necessary evidence to support the safety case submission but also engage with residents to ensure they were being provided with project intelligence.

The exemption approval and transition to Phase 2 of the project (SDRCs 9.5 and 9.6) were successfully delivered in full, albeit a few months after the programmed date. This was due to the extended engagement process with the HSE that was necessary to review the safety case evidence submitted. Given the first of a kind nature of this process, this is unsurprising, but Ofgem were kept apprised of the situation.

The equipment installation confirmation SDRC (9.7) was provided and demonstrated the robust engineering process that had been undertaken to progress through Phase 2 (design, build and installation) of both novel hydrogen production and mixing technologies in less than one year.

The final SDRCs that summarised the field trial results, definition of public trial and dissemination (SDRCs 9.8 – 9.10) were impacted by the COVID-19 operational hiatus, however were provided within the agreed revised submission deadlines. These SDRCs quantified the operational and performance metrics of the successful trial as well as the

thorough engagement process undertaken by the project to engage across UK stakeholders (academic institutions, regulators, standard setting bodies, GDNs, supply chain stakeholders, policy makers and the general public) as well as international stakeholders.

5.0 Modifications to the Planned Approach to the Project

The project has delivered against the original planned approach, however inevitable modifications took place over the course of the programme in response to external events, new information and evidence generated.

During the first phase, the depth of evidence necessary to secure an Exemption from the HSE to the hydrogen limit within GSMR Schedule 3 became clearer. Before HyDeploy no such Exemption had ever been applied for or secured, therefore no precedents had been established on the depth and breadth of evidence necessary. In total the first phase required an additional £300k to ensure the degree of technical evidence supporting the safety case submission was sufficient. These funds were brought forward from later in the programme and managed within budget through careful management and stewardship as described below. The evidence ultimately led to a successful application; therefore, sound experience was generated to inform future programmes of work.

The GEU was the first-of-a-kind development in the UK and therefore did not have an established design process or standards to work from, as such – fundamental engineering was required to ensure its fitness for purpose. The electrolyser was also a novel technology, given the low number of electrolysers that were deployed at the time. Therefore, each design process, and the integration design between the two, were novel and innovative. As such, accurate cost estimation was challenging. In total an additional £500k was required to complete the design, construction and installation of the compound equipment. The impacts of this were also managed across the entire programme budget.

To ensure the overall programme was delivered within the original budget a value engineering exercise was conducted to ensure sufficient budgetary capacity was allocated to deliver the core requirements of the programme. Where items were identified that were valuable but secondary opportunities to the core programme, industry collaboration was sought to enable them to be delivered at a lower cost to the project. This process enabled the necessary budgetary overruns from the first two phases to be absorbed and protection to be given to the core deliverables, whilst still maximising the value of the programme.

The trial schedule did not account for a global pandemic. Six months into the trial the first national lockdown was announced. This led to a significant reduction in contractor resource as well as curtailed site access. The project took the decision to safely hibernate operations until confidence could be increased in the ability to provide operational support and access. Overall, this operational hiatus lasted 10 weeks. Additionally, lower site utilisation throughout the summer period meant that gas demand did not pick up until autumn 2020. In response to this modification, the project agreed with both Ofgem and HSE to extend the end date of the trial to March 2021 to allow operational data to be collected to evidence the suitability of infrastructure to accept hydrogen blends.

Overall, the programme responded well to emerging information and successfully managed a

first-of-a-kind trial through a global pandemic which impacted partners, subcontractors, individuals and wider society. Due to the innovative nature of the programme, modifications had to be made in response to evidence and external events. However, all modifications were appropriately managed and did not impact upon the project's ability to deliver on its requirements.

6.0 Financial Performance

The table below shows the progress against budget to the end of the project.

The complex and extensive scientific programme associated with the Exemption submission required a greater level of effort than originally anticipated. Some rebalancing of the scientific effort across the programme enabled this to be addressed. As flagged during the annual progress reports, the GEU was more expensive than anticipated, and the costs during the build phase were higher than budget. The overall budget was managed to accommodate this by making savings where possible. One of the key mitigants was collaborative work with manufacturers and suppliers relating to the experimental programme to offset costs. Similarly, the installed equipment meant that data collection during the trial was considerably lower cost than originally budgeted. Inevitably individual programme elements varied compared with the original budget, but this was actively managed via a process of monthly reporting and review, enabling proactive decisions to be made to deliver the project to plan.

The total budget of the project was £7,634,538.00, which consisted of £6,871,084.00 grant funding via the Ofgem Network Innovation Competition (NIC) and £763,454.00 collective contributions from Cadent and NGN. Although the timeline of the programme had to be extended, largely in response to external circumstances such as Covid-19, the project was delivered without any increase in the budget. This was achieved through careful financial and risk management, and the collective fiscal controls implemented by the partner organisations. The relative breakdown of spend across the programme elements is shown in Table 6 for ease of comparison between the original budget allocation and the actual spend.

Table 6: Financial performance

Programme Element	Total Spend	Total Budget
1. Site Communications and stakeholder engagement	4.4%	3.5%
2. Activities to develop Exemption	23.6%	19.3%
3. Specification and design of H ₂ Production & Entry Units	7.0%	3.0%
4. Write safety case and apply for Exemption.	1.6%	1.5%
5. Regulatory and billing arrangements	0.3%	2.3%
6. Predevelopment installation activities	1.3%	1.6%
7. Secure project gateway clearances	1.6%	2.8%

8. Installation of Hydrogen Injection Equipment	30.4%	25.0%
9. Installation of Network Monitoring equipment	4.2%	6.1%
10. Pre-Injection processes	0.1%	0.9%
11. Injection plant & equipment operation	3.3%	4.8%
12. Data gathering during the trial	1.8%	3.7%
13. Incremental Injection	0.4%	2.9%
14. Plan follow-up project on public network.	0.2%	1.2%
15. Keele Site reinstatement / handover	1.3%	1.8%
16. Dissemination and reporting	1.3%	4.5%
17. Project Management	12.3%	10.2%
18. Contingency	4.9%	4.9%
Total	100.0%	100.0%

7.0 Business Case

Under the Climate Change Act, as modified in 2019, the UK is committed to achieving Net Zero emissions by 2050. This requires decarbonisation of all aspects of the energy sector.

The role of hydrogen in achieving this has received increased attention over the last few years. In its Net Zero report, the Committee on Climate Change (CCC)¹ identified that Hydrogen as a necessity and not just an option to meet Net Zero. For the UK to deliver on its commitments, it proposed a requirement for 270 TWh/yr of low carbon hydrogen, noting the areas where it was most likely to be required:

¹ Net Zero - The UK's contribution to stopping global warming, CCC May 2019

'In order to develop the hydrogen option, which is vital in our scenarios, significant volumes of low-carbon hydrogen must be produced.... for use in industry and in applications that would not require initially major infrastructure changes (e.g., power generation, injection into the gas network and depot-based transport).'

More recently in the Prime Minister's 10 Point Plan, hydrogen was identified as one of the 10 key planks required on the journey to Net Zero. Importantly, this document set interim targets to unlock progress in the shorter term. Most notable aspects are shown in the call out box, with grid blending explicitly referenced.

The 10 Point Plan for a Green Revolution

Policy impacts. Aiming for **5 GW Hydrogen production capacity by 2030** in partnership with industry. **Lower carbon heating and cooking with no change in experience for domestic consumers through hydrogen blends and reducing the emissions of the gas used by up to 7%.**

Target Milestones:

2021 Publish our Hydrogen Strategy and begin consultation on Government's preferred business models for hydrogen

2022 Finalise hydrogen business models


2023 Work with industry to complete testing necessary to allow up to 20% blending of hydrogen into the gas distribution grid for all homes on the gas grid

2023 Support industry to begin hydrogen heating trials in a local neighbourhood

2025 We hope to see 1 GW of Hydrogen production capacity

2025 Will support industry to begin a large village hydrogen heating trial, and set out plans for a possible pilot hydrogen

Figure 23: Ten point plan



2023

Work with industry to complete testing necessary to allow up to 20% blending of hydrogen into the gas distribution grid for all homes on the gas grid

The Energy Minister has recently set up the Hydrogen Advisory Council² *"to inform the development of hydrogen as a strategic decarbonised energy carrier for the UK."* Government is seeking to issue its hydrogen strategy in Summer 2021.

Blending provides the basis to establish and build out hydrogen production capacity, address

² <https://www.gov.uk/government/groups/hydrogen-advisory-council>

regulatory hurdles, build the wider hydrogen supply chain and importantly provide an opportunity for customers to become accustomed to hydrogen being part of the energy mix. Over time, building on this platform, it is expected that parts of the gas system will migrate to full hydrogen. This will require resilient hydrogen supplies, the next level of regulatory and operational changes as well as suitable appliances. Programmes such as H21, H100 and Hy4Heat are designed to progress these network and appliance issues. Manufacturers such as Worcester Bosch and Baxi have both developed “hydrogen ready” boilers to facilitate that transition, as well as other appliance manufacturers developing hydrogen cookers and fires.

Delivering low carbon heat via gas utilises existing network assets cost effectively and means that customers do not require disruptive and expensive changes in their homes. Alternatives such as electrification using heat pumps will make a significant contribution but in reality to deliver Net Zero will require a combination of technologies. However, as recognised in BEIS Heat Strategy³, in its RHI consultation, and in a 2018 report for the National Infrastructure Commission⁴, electrification requires substantial consumer capital outlay and disruption, as well as substantial reinforcement of the electricity grid and additional generation capacity – recognising the combined implications of electrification on passenger vehicles.

The HyDeploy approach is to take benefit from the existing gas network by reducing the carbon intensity of heat delivered through blending of hydrogen, delivering up to 29 TWh per annum of low carbon heat. This approach requires no changes to appliances and the gas network, providing a non-disruptive solution to customers. It can operate seamlessly with a range of future heat scenarios, and provides a deliverable pathway. The HyNet project⁵ seeks to demonstrate how blending into the local distribution zone to decarbonise domestic heat can work in combination with higher blends and full hydrogen in industry to deliver deeper decarbonisation. It also provides a platform for flexible hydrogen fuelled power generation to balance intermittent renewables, as well as facilitating complementary zero carbon solutions for transport. NGN’s InTEGReL project⁶ will demonstrate how hydrogen in the gas network can be integrated with operation of the electricity network to maximise the benefits to both.

³ The Future of Heating, DECC 2016

⁴ Cost analysis of future heat infrastructure options, Report for, National Infrastructure Commission, Element Energy Limited, E4Tech, March 2018

⁵ www.hynet.co.uk

⁶ <https://www.northerngasnetworks.co.uk/ngn-you/the-future/integrel/>

Figure 24: HyNet schematic

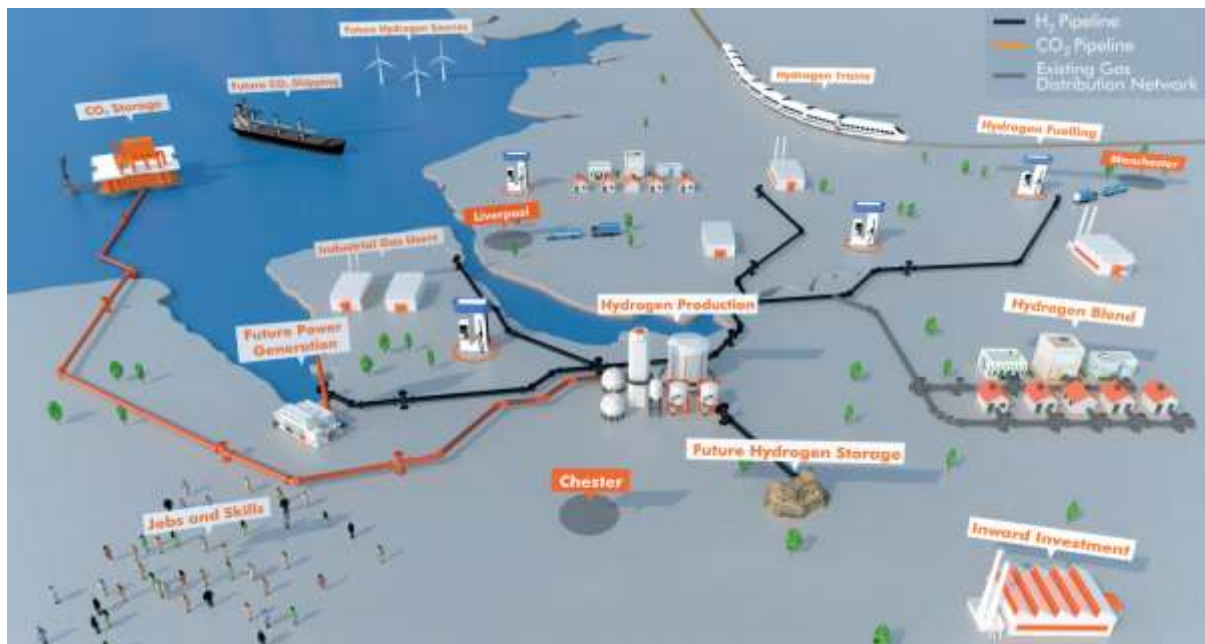


Figure 25: InTEGReL site plan



To deliver hydrogen will require an appropriate policy regime. BEIS is undertaking work on business models to achieve this. This work has gathered pace in 2020 and 2021. BEIS now have a dedicated team supported by contracted consultants. The objective is to issue a 'minded-to' consultation on hydrogen business models alongside the Hydrogen Strategy in Summer 2021. Such a business model is critical to transitioning from demonstration programmes such as HyDeploy into deployment, consistent with the new 10 Point Plan.

Alongside the safety case it is essential that an appropriate regulatory framework is established to facilitate hydrogen blending. Critically this relates to the established of a pragmatic business model for hydrogen supply that enables the private sector to invest with confidence in the necessary production capacity. Alongside hydrogen production, energy billing will be a central area of regulatory focus. Under the current regime of energy billing that results from the Calculation of Thermal Energy Regulations (CoTER) it is likely that regional blending constraints will emerge. Both of these wider regulatory considerations, alongside others, are being discussed at the BEIS Gas Blending Group, which is supported by the HyDeploy consortium.

8.0 Lessons Learnt for Future Innovation Projects

Consumers are engaged with the decarbonisation agenda. The continued engagement with the local community and undertaking of dedicated social science research has provided a useful barometer to understand the views and attitudes of consumers as they relate to their energy supplies. Consumers are far more engaged on the topic of decarbonisation than would have been assumed only a few years ago, and in general consumers are being more enthusiastic and vocal about the need to decarbonise all energy supplies. This demonstrates the importance of programmes such as HyDeploy in delivering against this increasing expectation.

The importance of collaborative working. The delivery of the Keele trial has only been possible through the collaborative spirit of the project, with a strong delivery team consisting of organisational partners who have been working together for a number of years alongside key subcontractors. Through leveraging individual and organisational knowledge and expertise, no problem has shown to be insurmountable.

Expect the unexpected. No one was expecting a global pandemic. However, a strong experienced team is able to address challenges successfully. Good people make all the difference.

Every penny counts. The first two phases of the programme, consisting of securing the Exemption and procuring the compound equipment, ultimately went over budget due to necessary additional expenditure. It was only because the project was extremely carefully managed, with a clear forward programme and budget forecasting process, that this could be addressed. This financial scrutiny had to be applied to all areas of the project, with all partners empowered to deliver in the most efficient manner possible. This focus on saving budget where possible whilst delivering on the project's commitments provided the capacity to be able to sanction an operational extension to mitigate the impact the Covid-19 pandemic had on the trial over the Summer of 2020.

9.0 Project Replication

HyDeploy has successfully demonstrated for the first time that hydrogen blends can be safely distributed and utilised within existing gas networks. The strategic objective of the programme was to establish this principle to facilitate the national unlocking of hydrogen blends, in aid of kick starting the hydrogen conversion journey. The evidence underpinning the safety case that enabled the trial to take place will be lodged with IGEM in the Hydrogen Knowledge Centre, this is to ensure the industry have an opportunity to both; peer review the evidence; and leverage it for further safety case submissions.

The concept of demonstrating hydrogen blends has been taken forward into HyDeploy2, where a public trial at Winlaton within North East will be undertaken (subject to HSE approval). The learning and outputs of the first trial at Keele University will be leveraged to deliver a further successful demonstration in Winlaton.

Ultimately if a hydrogen blend of 20 vol% was replicated across the distribution network a total of 29 TWh pa of low carbon gas would be unlocked without disruptive changes for consumers.

This represents a material contribution to the Net Zero journey and would abate 6 MtCO₂ pa, which is the equivalent of removing 2.5 million cars from the roads. It is the strategic intent of the project that the safety case evidence and successful demonstration of live hydrogen blending at Keele University act as a launchpad for national hydrogen blending to achieve these meaningful carbon savings whilst unlocking a pathway to deeper hydrogen adoption.

10.0 Planned Implementation

The adoption of hydrogen blends across the gas distribution network has been shown to be feasible through HyDeploy, but has not been fully unlocked. Further evidence will be required to enable full deployment of hydrogen blends across the network. This evidence gathering will be undertaken through HyDeploy2 and will focus primarily on network materials, assets, industrial and commercial users, as well as high pressure tier procedures. The implementation pathway of hydrogen blending is on track to deliver against the ambitious plans set out in HMG Ten Point Plan and Energy White Paper to unlock hydrogen blending nationally by 2023.

11.0 Dissemination

11.1 Technical Dissemination

The below table outlines the stipulated dissemination topics, their report references, and the mode of information dissemination to take place.

Table 7: Dissemination topics

Topic	Topic Findings	Dissemination Route
Assessing safe appliance performance	Detailed in Exemption reports: 1. HyD-Rep06-Appliances, 2. HyD-Rep06-AppA, 3. HyD-Rep06-AppC, 4. HyD-Rep06-AppE & 5. HyD-Rep06-AppG	Shared in pan-industry workshop January 2019. To be provided to the IGEM Hydrogen Knowledge Centre
Assessment of long-term appliance behaviour	Detailed in Exemption report: 1. HyD-Rep06-AppD	To be provided to the IGEM Hydrogen Knowledge Centre
Assessment of installations & tightness tests	Detailed in Exemption reports: 1. HyD-Rep06-AppB 2. HyD-Rep06-AppF	Shared in pan-industry workshop January 2019. To be provided to the IGEM Hydrogen Knowledge Centre

Topic	Topic Findings	Dissemination Route
Extension of tightness testing to 100% hydrogen	Following review with Keele University during preparations for the appliance field testing, the decision was taken to not include 100% tightness testing due to schedule constraints and potential consumer disruption implications.	N/A
Materials and Embrittlement and network jointing	Detailed in Exemption reports: 1. HyD-Rep05-Materials 2. HyD-Rep05-AppA 3. HyD-Rep05-AppB	Shared in pan-industry workshop January 2019. To be provided to the IGEM Hydrogen Knowledge Centre
Risks of poor mixing	Detailed in Exemption report: 1. HyD-Rep04-AppC	Shared in pan-industry workshop January 2019. To be provided to the IGEM Hydrogen Knowledge Centre
Analysis equipment for monitoring hydrogen blend	Outlined in Section 3.2.3 of this report	Project close down report.
Explosibility	Detailed in Exemption reports: 1. HyD-Rep04-Gas Characteristics 2. HyD-Rep04-AppA 3. HyD-Rep05-AppB	Shared in pan-industry workshop January 2019. To be provided to the IGEM Hydrogen Knowledge Centre
Appropriate detection	Detailed in Exemption reports: 1. HyD-Rep09-AppC 2. HyD-Rep09-AppD 3. HyD-Rep09-AppE 4. HyD-Rep09-AppH	To be provided to the IGEM Hydrogen Knowledge Centre
Metering	Detailed in Exemption report: 1. HyD-Rep05-Materials	To be provided to the IGEM Hydrogen Knowledge Centre
Network management & emergency	Detailed in Exemption reports:	Shared in pan-industry workshop January

Topic	Topic Findings	Dissemination Route
procedures	1. HyD-Rep09-Procedures 2. HyD-Rep09-AppA 3. HyD-Rep09-AppB 4. HyD-Rep09-AppF	2019. To be provided to the IGEN Hydrogen Knowledge Centre
Development of a mixing & injection unit suitable for the GB distribution system	Detailed in Exemption report: 1. HyD-Rep07-Equipment	To be provided to the IGEN Hydrogen Knowledge Centre
Operation and performance of electrolyser dynamic conditions	Summarised in Section 3.3.2 of this report	Project close down report.
QRA	Detailed in Exemption report: 1. HyD-Rep02-QRA	Shared in pan-industry workshop January 2019. To be provided to the IGEN Hydrogen Knowledge Centre
The Process and Precedent of securing an Exemption	Detail within all of the safety case Exemption reports	To be provided to the IGEN Hydrogen Knowledge Centre
Operational evidence from actual operation	Outlined in Section 3.3 of this report	Project close down report.
Design of a public network trial	Detailed within the Exemption reports for HyDeploy2	To be provided to the IGEN Hydrogen Knowledge Centre

11.2 Stakeholders & Dissemination

The HyDeploy project has engaged extensively with a wide variety of stakeholders throughout the programme. This engagement took the form of one-to-one meetings, conference presentations, webinars, workshops, committee meetings, journal articles, industry articles, interviews, social media, leaflets, letters and progress reports. A final event is planned at Keele in the summer of 2021.

11.2.1 Keele University & Its Consumers

Throughout all stages of the programme, engagement with the residents affected by the project was the priority of the communications strategy. This was due to the need to thoroughly engage with the residents to ensure they were informed of the demonstration and were given the opportunity to ask questions and seek clarity on the intent and structure of the programme. During the first phase multiple rounds of door-knocking were conducted to personally engage with all residents, alongside this, leaflets and letters were provided as well as opening of social media channels of engagements.

This engagement continued throughout the second and third phases, where the residents received specific communications at key milestones such as achieving the exemption, commencing blending and ceasing the trial. In-person communications were restricted somewhat due to covid restrictions, however due to the established online and written channels of engagement, bilateral communications could continue and a resident's events was held online to allow personal engagement within social distance protocols. Lectures and talks were provided to the wider university community to provide an opportunity to engage with the broader university and disseminate information relevant to the energy transition, which created an opportunity for debate and discussion within an academic setting.

11.2.2 Gas Network Owners & Operators

Gas network owners and operators have been kept abreast of the findings and learning of the programme. As both Cadent and Northern Gas Networks are project partners, both GDNs have been integral in the programme and the establishment of its findings. The other three gas network owners (WWU, SGN and National Grid) were all represented on the project Advisory Board, which was active throughout the project. This in-project forum provided a means of dissemination. The project and its finding have been presented at many industry conferences and events, where network owners and operators were in attendance.

11.2.3 Gas Shippers & Suppliers

One of the key advantages of selecting Keele University as the site for the HyDeploy trial was to reduce the necessary commercial interfaces that needed to be addressed. Therefore, the necessary billing arrangements for the trial could be managed through a bilateral understanding between Keele University and Ofgem. As part of HyDeploy2 the project team have engaged with the gas shipper and supplier communities through the formal Xoserve channels in aid of developing the appropriate billing process for the public trial.

11.2.4 Regulatory and Standards Bodies

Both regulatory and standard bodies have been key stakeholders for engagement and dissemination. Regulatory bodies such as the HSE have been instrumental to the programme where the Exemption process provided a mechanism for engagement. The HyDeploy project has engaged extensively with Standards bodies such as IGEM and BSI. Concerning IGEM, the HyDeploy project team are represented on both the Gas Quality Working Group and the Hydrogen Committee and have presented findings at many IGEM events and conferences. Concerning BSI, the HyDeploy project team are represented on the GSE/30 committee that is the umbrella committee for natural gas downstream installations.

11.2.5 Policymakers

Providing information and learning to policymakers has enabled a broader understanding of hydrogen blending and its strategic importance to be developed. The project team is represented on a number of BEIS committees and groups, such as the Gas Blending Group and the Ministerial Hydrogen Advisory Council (including working groups such as the Standards and Regulations and Hydrogen Roadmap working groups). Direct engagement with a number of heat and decarbonisation-related BEIS teams has taken place, including a designated workshop to disseminate findings to BEIS teams. Within the government's Ten Point Plan and Energy White Paper hydrogen blending by 2023 has been explicitly stated as a policy objective. Therefore, the outcome of the HyDeploy and HyDeploy2 projects e.g., unlocking national hydrogen blending by 2023, has now translated to stated national policy.

11.2.6 Energy and Network Trade Bodies

Both the Energy Utilities Alliance (EUA) and Energy Networks Association (ENA) are represented on the project Advisory Board and therefore have been able to understand the findings of the project. HyDeploy and its findings are also represented on the Gas Goes Green programme coordinated by the ENA. Multiple articles have been written for trade bodies and institutes which were published in industry journals.

11.2.7 Appliance Manufacturers & Trade Bodies

A significant level of support from appliance manufacturers and trade bodies such as the Heating and Hotwater Industry Council (HHIC) and the Council of Gas Detection and Environmental Monitoring (CoGDEM) has been received throughout the project. Appliance warranties were maintained through the trial by manufacturers, which demonstrated their confidence in operations with a hydrogen blend. Through extensive engagement a collaborative research facility was constructed with the four major boiler manufacturers to investigate any long-term implications of a hydrogen blend on domestic boilers. The HyDeploy project has been presented multiple times at committee meetings within trade bodies such as the HHIC. Formal technical guidance has been provided to the Gas Safe community from research peer reviewed by the boiler and gas detection manufacture communities, where a Technical Bulletin (TB 157) was published with HHIC as a co-author.

11.2.8 Academic Institutes

Academic papers have been developed from the work of the HyDeploy project, these papers have been published in peer reviewed journals such the Clean Energy Journal and the International Conference on Hydrogen Safety, as well as the Oxford Energy Institutes journal. These publication routes have provided an opportunity for the HyDeploy work to be peer reviewed by academic bodies and enabled the technical findings of the programme to be disseminated within academic institutes.

11.2.9 International Bodies

International engagement has taken the form of discussing and presenting the HyDeploy project to; European energy bodies and committees; American gas networks and engineering institutes, the Australian Gas Infrastructure Group, and to stakeholders within Hong Kong.

These dissemination channels have enabled HyDeploy to gain a global presence and positioned the UK as being at the leading edge of international efforts to deploy hydrogen. Bilateral engagement has also taken place with similar projects such as the Dunkirk trial run by Engie in France, this has enabled learning and information sharing to be established to the benefit of the international hydrogen blending community.

11.2.10 Customers and Consumers

Consumers are the ultimate stakeholder in the HyDeploy project, as the purpose of the project is to unlock non-disruptive decarbonisation for consumers – enabling lower carbon emissions with no need for disruptive changes to consumers habits or homes. Therefore, more consumer-focused engagement has taken place with mainstream media outlets such as the Guardian, BBC, CCN, Financial Times and Telegraph. A BBC article on HyDeploy ‘*Climate change hope for hydrogen fuel*’ was the most read article for a number of days within the Science & Environment section of the BBC website. Roger Harrabin presented a piece for BBC Radio 4’s Today Programme over Christmas 2019 from the University, engaging with Residents and Canteen staff using hydrogen. The project featured prominently in CNN’s internationally broadcast series “The Global Energy Challenge”, with drone footage of the facility, as well as detailed filming of the installation and boiler test-house. Project videos and communications content have also been developed and promoted through social media channels to provide platforms for engagement with the broader consumer base.

11.3 Example List of Articles & Papers

1. <https://academic.oup.com/ce/article/3/2/114/5487479>
2. Gas Safe Magazine, May 2019
3. Gas Safe Magazine, July 2020
4. <https://www.thechemicalengineer.com/features/heating-with-hydrogen/>
5. <https://www.bbc.co.uk/news/science-environment-50873047>
6. <https://markets.ft.com/data/announce/detail?dockkey=1323-13855923-0HEV6CMSMJA02OB6UEJBK3L4G>
7. <https://www.telegraph.co.uk/business/2018/01/06/hydrogen/>
8. <https://www.theguardian.com/environment/2020/jan/24/hydrogen-uk-gas-grid-keele-university>
9. https://lite.cnn.com/en/article/h_3347a7649050ff96d886c6114ad0cf50
10. <https://www.dailymail.co.uk/sciencetech/article-8757923/Cadent-calls-Government-allow-200-times-hydrogen-household-gas.html>
11. <https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/010920-hydeploy-project-could-open-door-to-larger-scale-hydrogen-projects-sources>
12. <https://registeredgasengineer.co.uk/technical/technical-bulletin-157-co-co2-and-combustion-ratio-checks-using-an-electronic-combustion-gas-analyser-ecga-when-carrying-out-works-on-a-natural-gas-appliance-being-supplied-with-natural-gas-conta/>
13. <https://www.hvpmag.co.uk/Checking-in-on-the-progress-of-the-HyDeploy-project/11819>
14. <https://www.theengineer.co.uk/hydeploy-keele-hydrogen/>
15. <https://www.edie.net/news/8/UK-s-first-grid-injected-hydrogen-trials-begin-in->

- Staffordshire/
16. <https://www.energylivenews.com/2020/01/06/uk-first-hydrogen-injected-into-gas-grid-as-landmark-trial-gets-underway/>
 17. <https://fuelcellsworks.com/news/successful-completion-of-the-hydeploy-hydrogen-blend-trial-at-keele-university/>
 18. <https://www.thechemicalengineer.com/news/uk-s-landmark-trial-to-heat-buildings-with-hydrogen-is-fully-operational/>
 19. <https://www.stokesentinel.co.uk/news/local-news/could-future-heating-homes-keele-3700810>
 20. <https://environmentjournal.online/articles/a-green-energy-trial-will-use-hydrogen-to-heat-100-homes-in-staffordshire/>
 21. <https://environment-analyst.com/uk/106389/uk-hydrogen-trials-enter-a-bold-new-era>
 22. <https://renewablesnow.com/news/uk-hydrogen-blended-gas-project-starts-operation-682129/>
 23. <https://www.powerengineeringint.com/world-regions/europe/ground-breaking-7m-hydrogen-project-goes-live-in-uk/>
 24. <https://www.chemistryworld.com/news/uk-project-aims-to-cut-the-cost-of-producing-clean-green-hydrogen/4011788.article>
 25. <https://registeredgasengineer.co.uk/invitation-to-join-hydrogen-webinar/>
 26. <https://www.climateaction.org/news/uks-first-grid-injected-hydrogen-pilot-gets-underway>
 27. <https://www.bloomberg.com/news/articles/2019-04-25/hydrogen-as-a-heating-source-gets-a-boost-in-u-k-from-lawmakers>

12.0 Key Documentation

The following project documents are publicly available.

Table 8: Key documentation

Document	Date of Publication	Description
Full submission	November 2016	Final Network Innovation Competition full submission to Ofgem.
First project progress report	December 2017	First project progress report.
Second project progress report	December 2018	Second project progress report.
Third project progress report	December 2019	Third project progress report.
Fourth project progress report	December 2020	Fourth project progress report.
Safety case evidence paper	June 2019	Summary of safety case evidence base.

13.0 Contact Details

If you have any questions on the project or would like access to any project documents please contact:

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