HyDeploy

Demonstrating non-disruptive carbon savings through hydrogen blending // August 2021

Contents

Foreword

Trevor McMillian

We're delighted that Keele University has been able to play a crucial role in the first UK trial to blend hydrogen into the existing natural gas network.

The system has safely supplied the blended gas to 100 homes and 30 university buildings across our campus, with residents reporting positive results regarding their experience.

The project has been a perfect fit for Keele University's sustainability ambitions as an institution, and we're proud that we've been able to use our unique campus as a genuine living laboratory for this landmark project.

Steve Fraser

Cadent is proud to lead the consortium of HyDeploy partners which includes Northern Gas Networks, Progressive Energy Ltd, Keele University, HSE – Science Division and ITM Power.

HyDeploy is a world leading project which has successfully demonstrated for the first time, that blending up to 20% volume of hydrogen with natural gas is a safe and greener alternative to the gas we use now. The robust evidence base gathered at Keele has paved the way for the next phase of the project to begin with hydrogen blending currently taking place on the public gas network in Winlaton, near Gateshead.

Hydrogen is ready to take its place alongside other forms of zero carbon energy in meeting the needs of the UK population, reducing CO_2 emissions and contributing to reaching the Government's net zero target of 2050.

Trevor McMillian
Vice Chancellor, Keele University

Steve Fraser
Chief Executive Officer, Cadent

Project Partners

Cadent

Keele University

Northern Gas Networks

ITM POWER
Energy Storage | Clean Fuel

PROGRESSIVE ENERGY

HSE

Mark Horsley

We're excited to have been involved in the first project to demonstrate how blending hydrogen with natural gas can make a valuable contribution to the decarbonisation of our gas network.

The project successfully allowed customers to continue enjoying the benefits of their gas supply without any disruption or changes in behaviour.

The next phase of HyDeploy, on our gas network in Winlaton, is now underway. Almost 700 homes, a school and some small businesses are making history by becoming the first community to receive hydrogen blended with natural gas via a public gas network, providing further crucial evidence to allow blended gas to be used more widely.

HyDeploy is a vital stepping stone on the journey to our ultimate goal of operating a 100% hydrogen gas network to deliver net zero home heating for our customers.

Mark Horsley
Chief Executive Officer,
Northern Gas Networks

Executive summary

The project has successfully developed the safety case and delivered a hydrogen blend via the gas network into customers' homes. The demonstration of safety for the specific network was based on robust evidence and clear operational procedures.

Alongside the enabling safety case, the HyDeploy project has demonstrated the first steps of hydrogen deployment are safe, technically feasible and non-disruptive, both for the network and domestic users.

The key outcomes of the HyDeploy project were:

1. Successful achievement of the **first regulatory approval** from the HSE to operate a live gas network above the current hydrogen limit of 0.1 vol%. The approval allowed blending up to 20 vol%.
2. **Development of the technical and procedural precedents** to generate evidence for review by the HSE, which have informed subsequent safety case submissions through HyDeploy2 and the wider hydrogen safety case industry.
3. The design, fabrication, installation and operation of the **UK's first hydrogen grid entry unit.**
4. Integration of novel hydrogen production and blending technologies to create the **first hydrogen delivery system,** based on electrolytic generation into a live gas grid.
5. Safe delivery of the UK's first hydrogen blend trial to **100 homes and 30 faculty buildings.** The trial delivered over 42,000 cubic metres of hydrogen and abated over 27 tonnes of CO_2.
6. **Collaboration with appliance and equipment providers** to build a robust evidence base to demonstrate equipment suitability.
7. Evidencing the **suitability of hydrogen blends with domestic appliances** as well as larger commercial appliances including catering equipment and boilers up to 600 kW.
8. Evidencing the **suitability of hydrogen blends with medium and low-pressure distribution systems,** relating to key performance metrics such as: pressure control; odour intensity and uniform gas compositions.
9. **Promotion of supply chain innovation** through facilitating trials to develop gas detection and analysis technologies.
10. Establishing a robust social science evidence base to **understand the attitudes and experience of consumers actually 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. If rolled out to all GB homes, hydrogen blending would unlock 29 TWh pa of low-carbon gas, yielding carbon savings equivalent to removing 2.5 million cars from the roads and unlocking the pathway for wider hydrogen deployment within the national energy systems.

1.0 Introduction

1.1 Project background

The HyDeploy project at Keele 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.

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.

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 on the gas distribution system, therefore the successful outcome of the broader HyDeploy programme is now crucial to facilitating the delivery of the government's hydrogen policy objectives.

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.

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.

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 transitionary project turning hydrogen from a concept to reality for the UK energy system.

1.2 Energy Landscape

According to Government emissions data (BEIS, 2021) in 2019 natural gas combustion produced 66.5 $MtCO_2$, sharing first place with passenger vehicles (67.0 $MtCO_2$) 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 at the time 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 major economy 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.

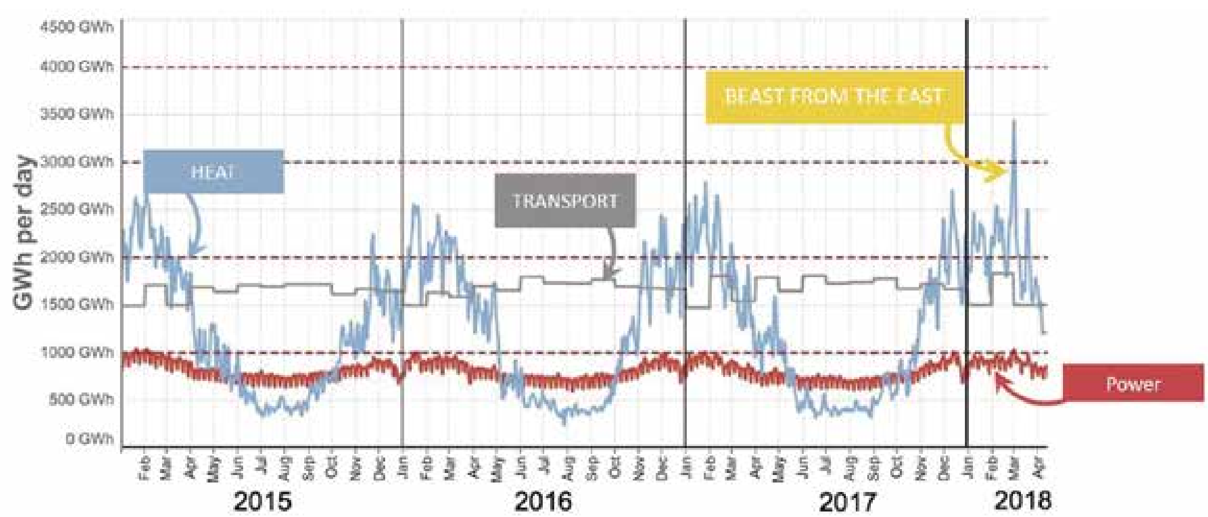
Domestic heating, industrial and heavy transport have always been deemed to be the 'hard to reach' elements of the national emissions profile. This is because of the user requirements within each of these energy demands.

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.

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

Figure 1



F3: UK Energy Demands

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 importance of hydrogen blending at the start of the HyDeploy programme was not widely 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 Government hydrogen objectives. In the 10 point plan announced in November 2020, 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 Energy White Paper. HyDeploy (including HyDeploy2) is the 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 Government hydrogen objectives. This is testament of the industry leading progress HyDeploy has made in progressing the deployment of hydrogen within the UK gas network.

1.3 Project objectives

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 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 distribute and utilise hydrogen above the specified regulatory limit within the UK and the first gas network to distribute and utilise hydrogen since the conversion from towns gas was completed in 1976.

2.0 Phase 1: Safety Case 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.

2.1 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/m^3).

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. Figure 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.

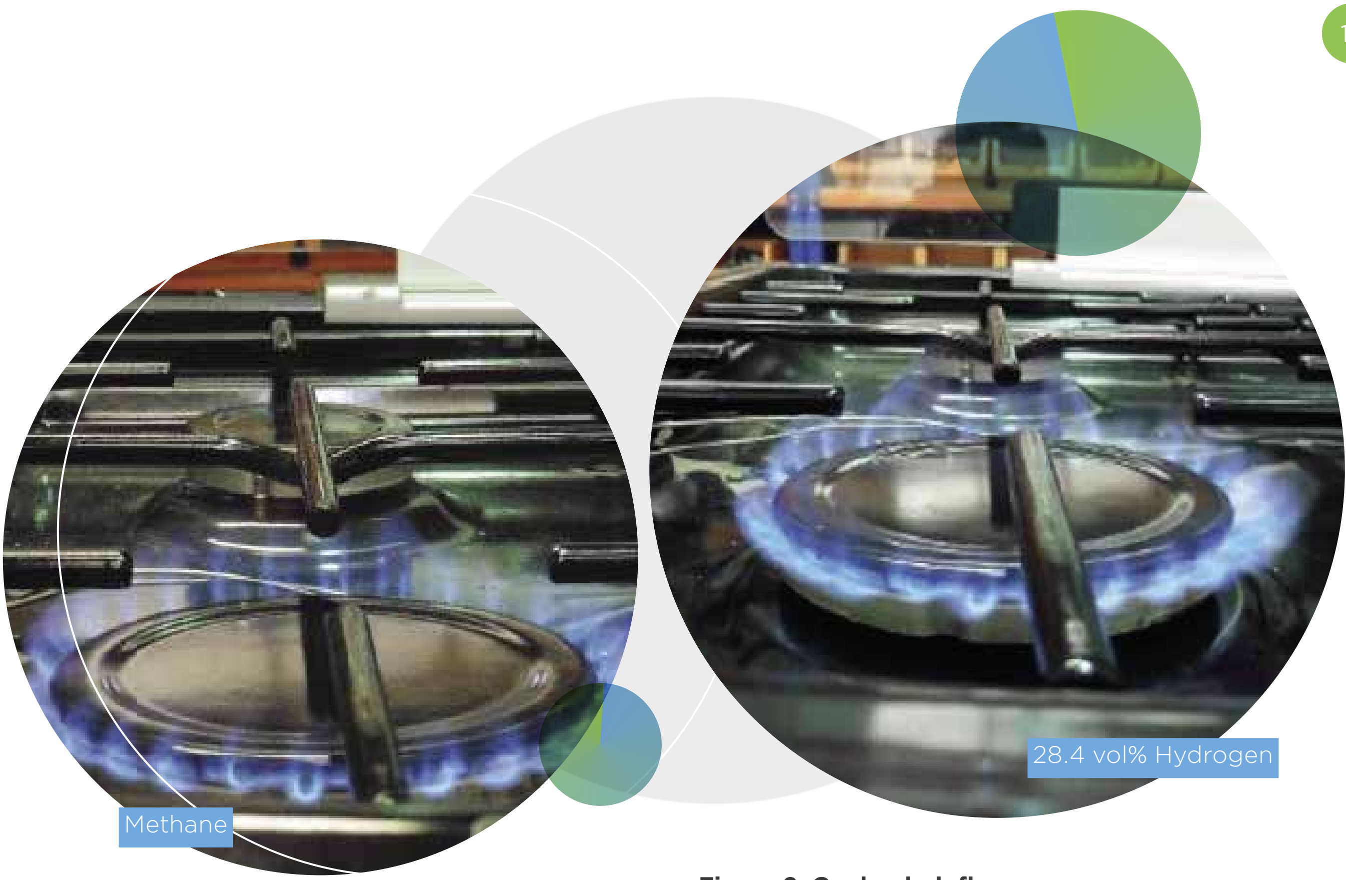


Figure 2: Cooker hob flames

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 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.

2.2 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.

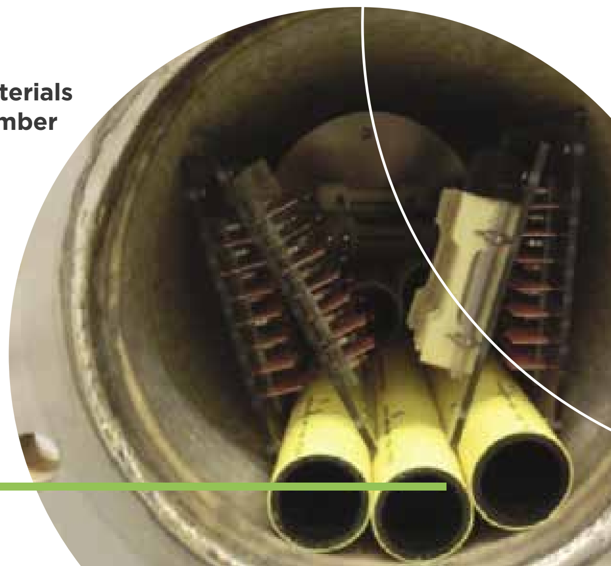
2.3 Materials and assets

The interaction of hydrogen with materials is an important area which must be understood when evaluating hydrogen blending. 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. 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 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.

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.

Figure 4: Squeeze off demonstration

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.

2.4 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.

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.

Figure 5: Gas detector

This doesn't present a safety concern as the effect is conservative, however issues concerning nuisance alarms and operator confidence in the instruments are important 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 oxidises 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 development of a prototype detector by one of the major gas detection manufacturers, which subsequently underwent field testing.

2.5 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 into 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 1.

Table 1: 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. These results were scrutinised by the HSE Regulatory Assessors in making their determination of safety.

2.6 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 communication 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 the Keele University Ethics Committee 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

2.7 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 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.

Figure 7: Customer engagement

2.8 GS(M)R Exemption

Throughout the development of the evidence base, the project team engaged closely with the HSE Inspectors 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

3.0 Phase 2: Equipment and Site Preparations

3.1 Equipment Design, Build and Testing

The equipment that was required to enable the Keele trial to be undertaken was a 0.5 MWe electrolyser provided by ITM Power, based on proton-exchange-membrane (PEM) technology, and a hydrogen grid entry unity (GEU) provided by Thyson Technology Ltd.

Given the novel and innovative nature of the equipment, both the electrolyser and GEU were based on supplier-bespoke designs. All relevant engineering codes and standards were followed, however the cutting-edge nature of the equipment meant that, at the time of design, no formal set of engineering design codes were available to define the functional specification of either an electrolyser or GEU. Therefore, first principal engineering and expertise were necessary to enable both pieces of equipment to be designed so they were fit-for-purpose.

The electrolyser was built at the ITM Power Sheffield workshop, where it's factory acceptance testing (FAT) was also undertaken prior to arrival at site. The GEU was built at the Thyson Technology Ellesmere Port workshop. Whilst the equipment had some similarities to a biomethane grid entry unit, the requirement to reliably blend hydrogen at set levels was novel.

Final design and fabrication of the GEU were based on the specification developed during the Exemption process. The equipment completed fabrication and had its initial FAT using inert gases at Thyson's facility. This was followed by a second FAT phase at NGN's Low Thornley site in Winlaton. 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. All of the FAT works were completed at Winlaton without any interaction with the local downstream gas supply.

Figure 9:
Build and testing

Both the electrolyser and GEU were successfully designed and fabricated, ultimately leading to two successful FATs. Particular attention was needed to ensure the mechanical, electrical and instrumentational interfaces of the two pieces of equipment were designed with the overall system in mind to ensure a smooth integration process of the engineering systems.

Following the successful FAT of the electrolyser and GEU, the equipment was brought to site for mechanical installation, integration and commissioning. The final stage was to conduct the necessary Site Acceptance Testing (SAT) to confirm the compound was ready to commence operations.

3.2 Compound installation

A secure 20 x 20 m compound was built at Keele University to house both the GEU and electrolyser, along with all associated equipment.

Figure 10: Integrated compound

The compound consisted of civil foundations alongside the installation of all necessary process equipment for the generation and blending of the hydrogen. 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. The complete compound is shown in Figure 10.

The electrolyser was installed in the HyDeploy compound at Keele University, this included a power supply unit (PSU) as well as a 5 m^3 buffer tank operating at 20 barg to enable sufficient capacity 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 11: Installed electrolyser system

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.

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.

3.3 Network monitoring

Network monitoring equipment was installed across the blend 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.

Figure 12: GEU internals

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 13.

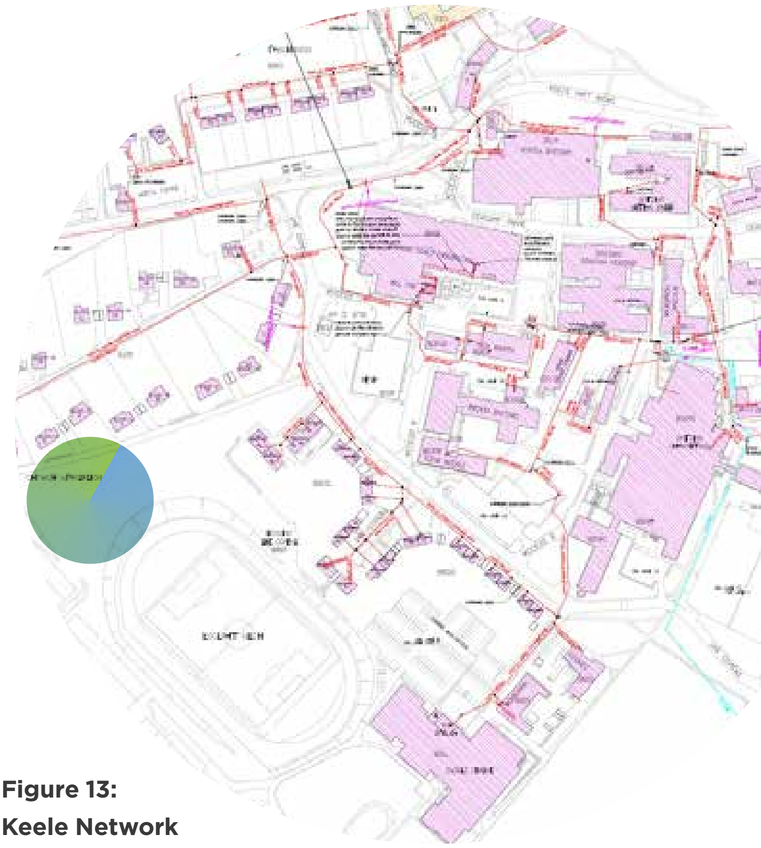


Figure 13: Keele Network

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 14.

Figure 14: Network monitoring facilities

3.4 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 15: 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.

4.0 Phase 3: Hydrogen Blend Trial

4.1 Blend Progression

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 within 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.

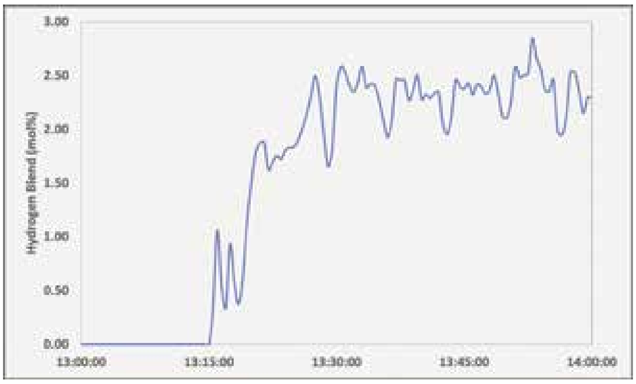


Figure 16: Initial blend on the 30th October 2019

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 an appropriate 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 17 below.

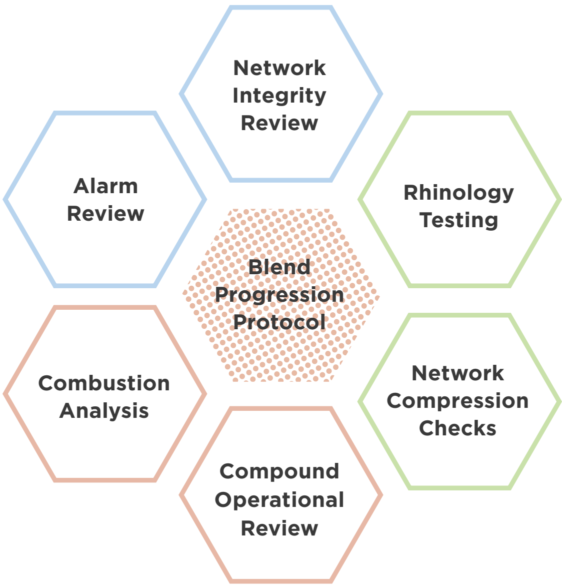


Figure 17: Blend progression protocol

Following each stage of progression, the imposed maximum blend level restriction was lifted, from the initial 2 mol% through to all restrictions being 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 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.

4.2 Compound Operations and Gas Demands

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.

4.2.1 Hydrogen Generation

The hydrogen for the trial was generated using a 0.5 MWe electrolyser. The basic engineering architecture of which consisted of:

- A generation 'stack', which is the part of the process that carries out the actual conversion from water to hydrogen and oxygen.
- Auxiliary equipment such as water purification and hydrogen conditioning, these processes are both upstream and downstream of the generation stack.
- General operational equipment such a lighting

Separate electricity meters were installed to allow monitoring of the power consumption for each of the above elements. For the purpose of simplification, the auxiliary and general equipment has been grouped as the 'balance of plant'.

Figure 18 is the production curve of the generation, where the hydrogen generation efficiency is given as a function of the operational load factor.

The efficiency is the energy content of the hydrogen produced (HHV – 12.7 MJ/m^3) divided by the electricity input. The load factor for each data point constitutes the average over a monitoring period of a few weeks. The orange line represents solely the generation stack and the blue line is the total system (generation stack plus balance of plant).

Therefore, at a maximum load factor of 100%, the generation efficiency was found to be 77% and the overall electrolyser system efficiency found to be 63%. The efficiency reduces at lower load factors, as would be expected of any process equipment. The overall performance statistics of the electrolyser over the course of the trial are given in Table 2.

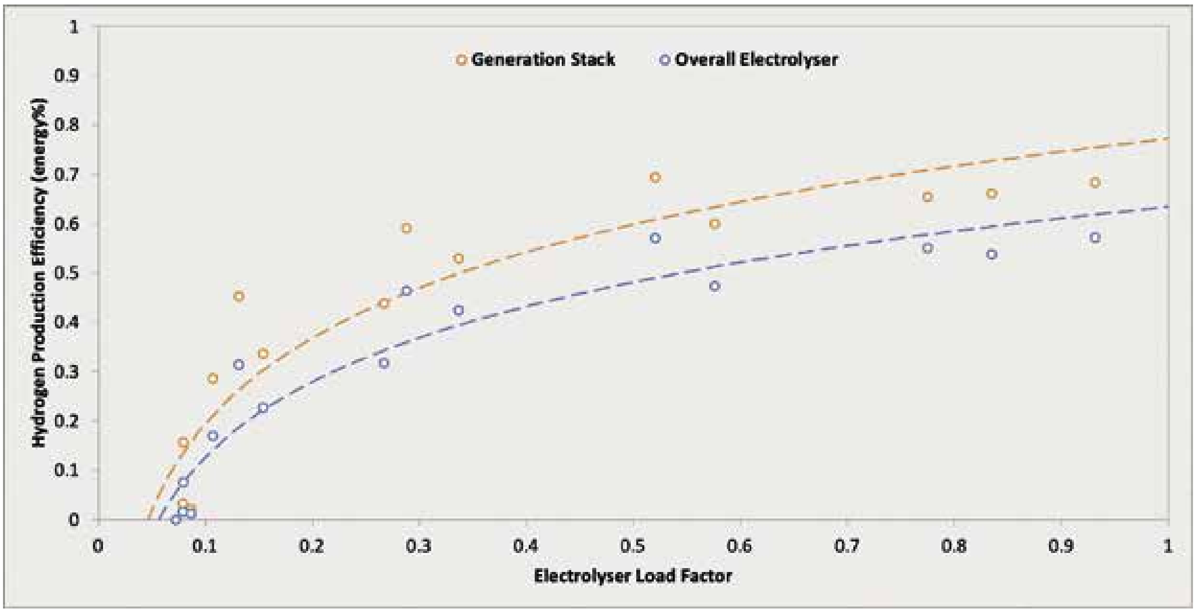


Figure 18: Electrolyser operational efficiency

Electrolyser Consumption	Value	Units
Water	136	m^3
Power (Generation Stack)	256	MWh_e
Power (Balance of Plant)	71	MWh_e
Power (Total)	327	MWh_e
Electrolyser Consumption	**Value**	**Units**
Hydrogen	148	MWh_{th}

Table 2: Electrolyser performance statistics

It is worth noting that the installed electrolyser was designed in 2017/2018. Electrolyser technology is developing, and as such is being refined and improved at pace by technology providers. It is understood that current electrolyser designs are capable of achieving higher operational efficiencies, however insufficient public data is available on real world performance to undertake a comparison.

Various other projects across the country are looking to establish reliable hydrogen production for the technology. The operational learning from the Keele trial informed the strategy for the Winlaton trial within HyDeploy2. Given that the primary purpose of the trial at Winlaton is to establish the impact of hydrogen on the downstream network, rather than hydrogen production itself, provision was made for industrial hydrogen supply at Winlaton to maximise network operations.

4.2.2 Hydrogen Blending

The hydrogen was blended into the natural gas supply using a GEU designed and built by Thyson Technology Ltd. The process flow of the blending system was:

1. Measure the incoming natural gas quality to determine the maximum percentage of hydrogen that could be blended within gas quality limits – principally the GS(M)R normal lower Wobbe limit of 47.2 MJ/m³ and the Exemption hydrogen limit of 20 mol%.
2. Inject the necessary flow of hydrogen into the natural gas stream and pass the blend through three parallel static mixers to ensure compositional homogeneity.
3. Measure the blend gas qualities using an analyser system to ensure compliance within both GS(M)R specifications and the Exemption hydrogen limit. This process required a total measurement resident time on the order of 9 seconds, therefore the flowing gas had to be passed through a ‘volume loop’ to provide this resident time before it could be supplied to the network.
4. Following confirmation of a compliant blend, the gas was supplied to the downstream network.

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 on a timeframe basis measurable in seconds at this depth of the gas network.

The gas demand profile, particularly it’s 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.

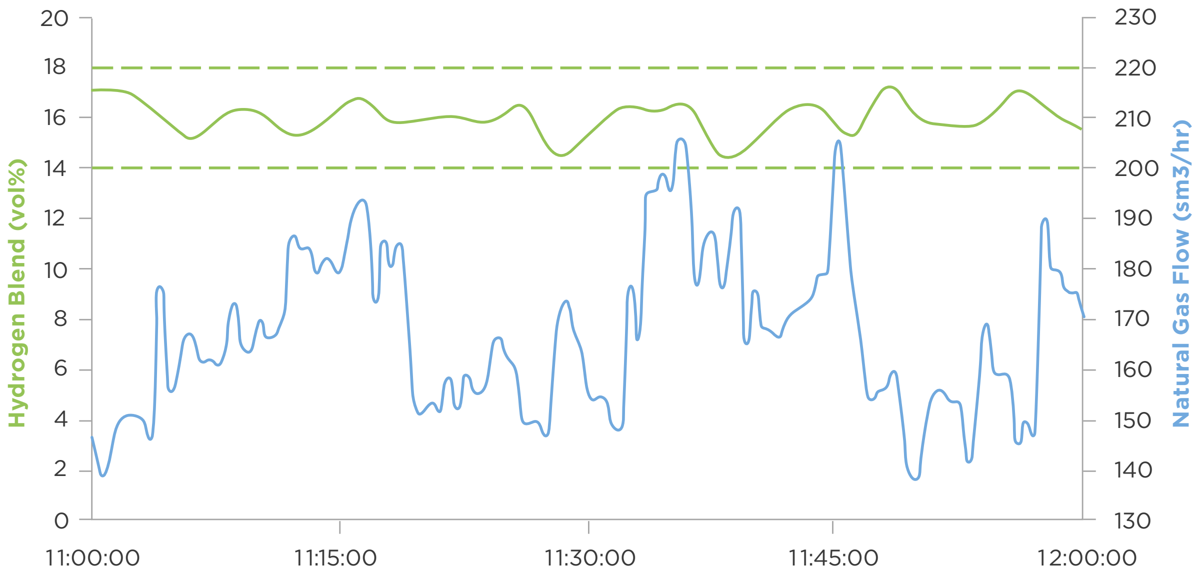


Figure 19: Natural gas demand profile and blend percentage

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 17. 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. 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).

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

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.

4.3 Network Analysis

4.3.1 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.

4.3.2 Pressures

To monitor network pressures six presure 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 20.

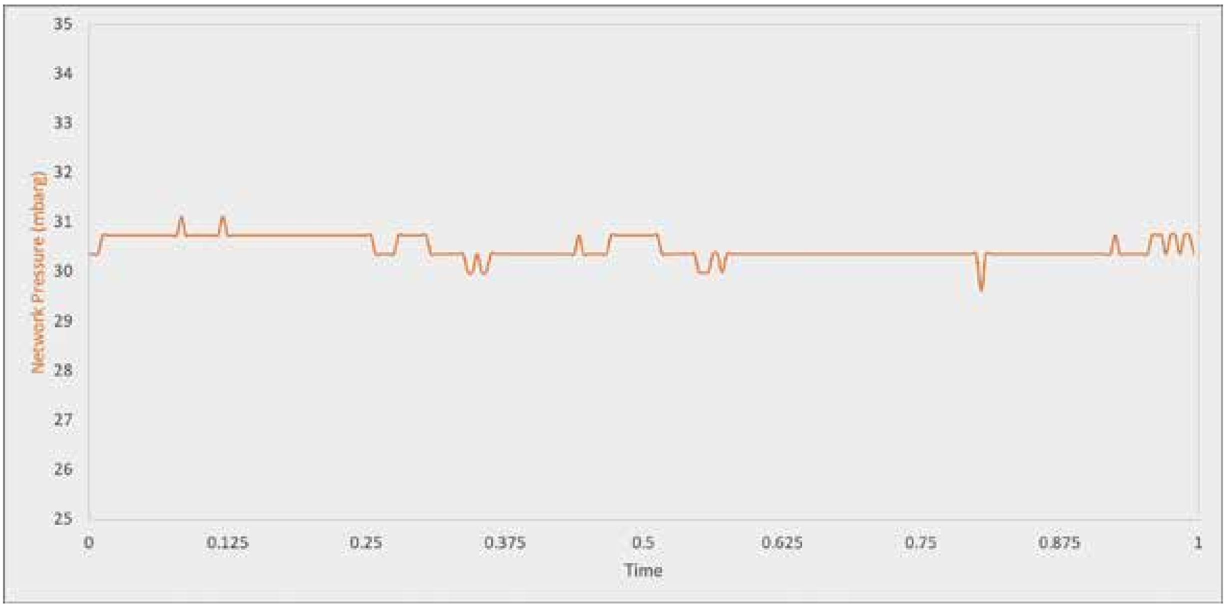


Figure 20: Typical network pressures

4.3.3 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 in the Keele Chemistry department.

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.

4.3.4 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 14 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.

4.3.5 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.

4.3.6 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.

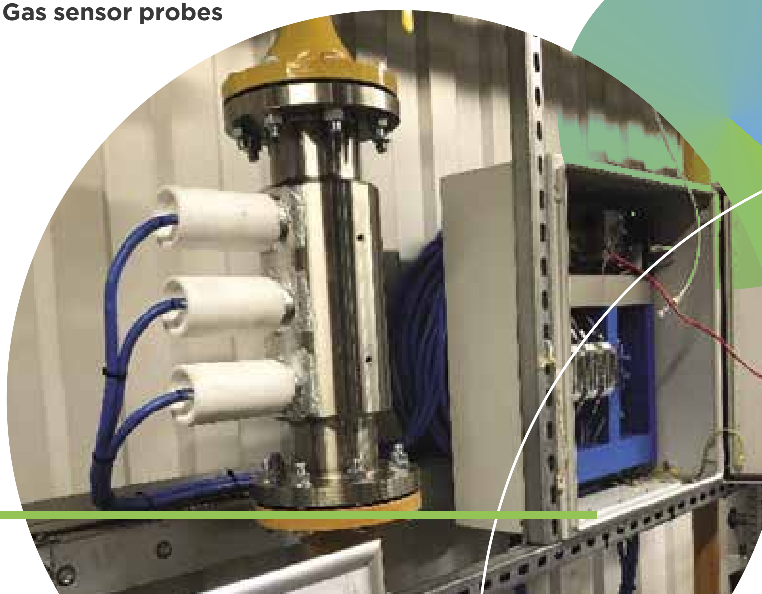
4.3.7 Gas Sensor Trial

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 14. 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 21 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 of 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.

4.4 Appliance Performance

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.

4.4.1 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.

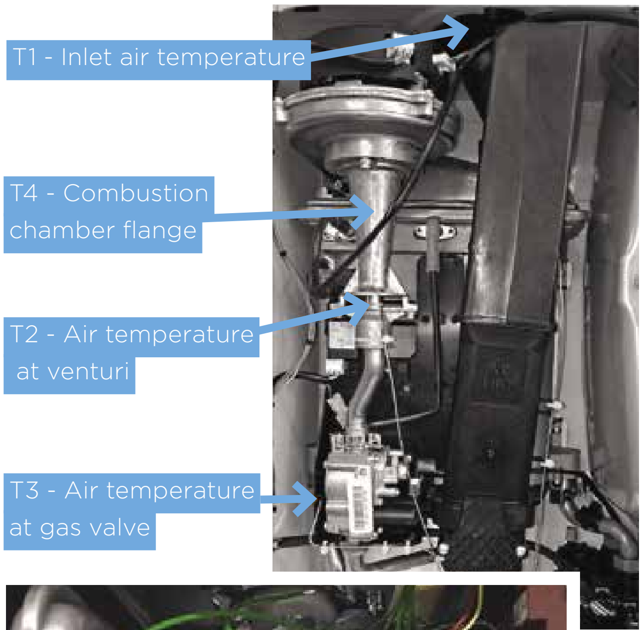


Figure 23: Full boiler installation

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.

4.5 Customer Engagement & Social Science Research

4.5.1 Customer Engagement

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. A detailed communications strategy was developed and used to govern the programme.

Figure 24: Resident engagement

During Phase 1 the primary objectives of the communication plan were to: provide personal contact with the residents on the trial network; build relationships, and provide necessary information on the trial timings, expectations and implications such as billing.

A detailed communications plan was enacted to support the house-to-house survey which allowed free-of-charge servicing of appliances and pipework, critical safety information to be gathered, and field testing of appliances. Any remedial work identified through the initial servicing was undertaken by the project free-of-charge.

Multiple modes of communication were leveraged to maximise engagement with the residents, from letters, leaflets, social media and most importantly personal contact from the project's liaison officer. This established sound communication lines to facilitate engagement through the trial preparation stages

During Phase 2 the project provided regular updates to the residents through the established channels of engagement. As the primary project work related to the physical preparations for the trial, the primary updates related to the expected operational timings. The annual free-of-charge servicing initiated in Phase 1 was continued through Phase 2, even though no hydrogen blending was being undertaken. This was to ensure the integrity of the downstream appliances and pipework prior to the trial, and to maintain the one-to-one lines of communication previously established.

During Phase 3 the communications channels remained open. In March 2020 Covid-19 restrictions were enacted that reduced the ability to personally contact residents, and the project took the proactive decision to ensure respect for the residents at a potentially sensitive time. Feedback after the trial indicated that the residents would have preferred increased updates through the trial, which demonstrates how well engaged the residents were in feeling a part of the project. The offer of free servicing continued through the trial. An in-person resident's event was planned, but had to ultimately be online. A good turnout was achieved and an engaging conversation between the project and residents. Overall, no formal complaints or issues were highlighted by the residents – providing sound evidence of the non-disruptive nature of hydrogen blending.

4.5.2 Social Science Research

To formally analyse the experience of residents taking part in the trial, along with their views and feelings relating to consuming blended gas, a social science programme of research was undertaken by Keele University.

This consisted of 16 pre-trial interviews to baseline the residents' views and expectations, and 8 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 had resulted from participation in the trial.

> "It works. There's been no impact in terms of us, we've not lost gas at all, there have been no issues with heating whatsoever to the house".

RESIDENT COMMENT AT THE END OF THE HYDEPLOY TRIAL

This was the first opportunity of its kind to understand how consumers perceive hydrogen as an energy vector in their homes from those who will be directly and imminently affected by it.

Overall, participants expressed positive views of their households being part of the HyDeploy project at Keele University. Whilst initially many noted there was no formal opt-out process from trial involvement, the majority observed that they would have opted in given the choice anyway. Residents generally acknowledged and welcomed the decarbonization benefits of the trial.

Most participants reported little disruption both prior to and during the trial and valued the feeling of contributing to climate action without needing conscious effort. Some participants viewed the trial and their (and Keele University's) involvement in an extremely positive light, going beyond just acceptance of the trial to expressing excitement. Such positive reactions may be linked to pride in a place to which they feel attached, or the 'halo' effect of making a positive contribution as an individual (or organization).

Some residents reported some initial anxiety about the project, understandable due to the first-of-a-kind nature of the trial. However, the residents noted that as time had gone on, this anxiety had reduced significantly as understanding about the process increased and reassurances were received.

Key areas of initial anxiety expressed by a number of interviewees surrounded safety concerns around hydrogen – which were allayed following the provision of information and engagement. However, other residents did not share such concerns about safety, expressing an underlying assumption that the project would be safe.

Previous research shows that potential increases in the cost of energy is the most important concern that people had when asked about their views on using hydrogen blends in the home. However, in the interviews with residents in the Keele University HyDeploy trial, cost was rarely mentioned.

The relatively limited expression of concern about cost may be due to the billing arrangements of the trial which favoured the participants (although this was not known by residents at the time of the first interviews), or due to the Keele campus community being a relative economically advantaged community, or due to other concerns being more strongly articulated and focused upon. Pre-trial interviews were undertaken a month before billing arrangements for the trial had been confirmed with Ofgem and communicated to residents, therefore some uncertainty on billing arrangements would have likely been present in the residents responses. The majority of residents felt that their gas use behaviour had not changed during the trial. Some respondents felt that their wider environmental awareness, and awareness of the environmental impact of heating, had been increased through the project communication.

The residents interviewed towards the end of the trial were asked whether they would be willing to have 100% hydrogen gas in their homes, after an explanation that 100% hydrogen would involve a greater level of disruption through changes to infrastructure and appliances.

As with responses to other topics, views on 100% hydrogen were mixed, although the greatest number of participants said they would be willing to have 100% hydrogen in the home. However, even where residents were supportive of 100% hydrogen they felt that they needed more reassurance about safety and effectiveness because of the more significant changes required.

> "If the science is saying that it's going to work and it's good for us, and it's better for the planet. Then, absolutely, I'd be so ready for 100%".

RESIDENT COMMENT AT THE END OF THE HYDEPLOY TRIAL

Concerns about the level of comfort and efficiency of heating with 100% hydrogen were also expressed. The majority of residents felt that they were likely more supportive of 100% hydrogen having already experienced hydrogen in the home through the hydrogen blend received due to the HyDeploy project, suggesting that blending has the potential to increase social acceptance of hydrogen.

> "I'm contributing by doing nothing. Where else do you get to do that?"

RESIDENT COMMENT ABOUT THE HYDEPLOY TRIAL

The social science research results demonstrate that the majority of residents found the initial communication of the project to be very effective in addressing any potential concerns. For the majority of residents, the Customer Liaison Officer's one-to-one approach appeared a particularly effective method of communication in continuing to alleviate any concerns about the project that residents had.

Many residents expressed a keen interest in the project and noted that they would have preferred more engagement on the progress of the project throughout the trial. This highlights that many residents saw themselves as key, engaged stakeholders in the project with an interest in being kept informed, rather than being passive participants.

The complete results of the social science study will be published separately to inform the wider industry and policy makers concerning deployment strategies for hydrogen.

4.6 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 CO_2.

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.

5.0 Project Performance Breakdown

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

Table 4: Project performance breakdown

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, at Keele University researchers undertook research into customer perceptions of low carbon energy and the trial itself. Customer 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.

Table 4: Project performance breakdown (Continued)

Programme element	Progress
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 Front End Engineering Design ('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 25th June 2018. This was followed by a period of robust interrogation including over 140 clarification questions, to 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 1st November 2018.
5. Regulatory and billing arrangements	**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. **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.
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.

Programme element	Progress
8. Installation of hydrogen injection equipment	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. In parallel site works were undertaken, including provision of utilities and connections, and the compound itself. During summer 2019 and early autumn, the individual equipment items were transported and installed onsite. 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.
9. Installation of network monitoring equipment	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. 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' assessment 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.

Table 4: Project performance breakdown (Continued)

Programme element	Progress
10. Pre-injection processes	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. The gas detection solution agreed as part of the Exemption was implemented, with equipment procured and installed at the University Security, such that First Call Operative ('FCO') attending site had appropriate access to equipment ready to use. 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. In order to transition from equipment installation through to 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).

Programme element	Progress
12. Data gathering during the trial	A full suite of data has been collected during the trial. This includes: **Compound operation -** Electrolyser and GEU operation, including evidence of satisfactory blend control. **Network operation -** Satisfactory Rhinology, compositional evidence across the network, demonstrating maintenance of the blend level as well as monitoring general network operation. **Appliance operatio -** Appliance temperatures and flue gas checks on commercial and test boilers were measured. No CO alarms were reported throughout the trial. 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.
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 and commenced in April 2019.
15. Keele site reinstatement/ Handover	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.

Table 4: Project performance breakdown (Continued)

Programme element	Progress
16. Dissemination and reporting	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: HyDeploy: The UK's First Hydrogen Blending Deployment Project. 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. 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. 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. The project was also presented internationally in Madrid, Bangladesh, Hong Kong and Adelaide. The Advisory Board convened regularly throughout the project, facilitating direct engagement with both national and international stakeholders. During the trial itself, recording and filming was undertaken with the BBC and CNN.
17. Project management	Effective project management is necessary to deliver a project with six partners and multiple work streams. The governance structure was provided by the Steering group which met quarterly. 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.

6.0 Policy Drivers to Unlock Hydrogen Blending

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 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:

> '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 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. The most notable aspects are shown in Figure 25, with grid blending explicitly referenced.

Policy impacts

- Aiming for 5GW 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** Support industry to begin a large village hydrogen heating trial, and set out plans for a possible pilot hydrogen town before the end of the decade

Figure 25: Key hydrogen-related points in the 10 point plan

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

The Energy Minister has recently set up the Hydrogen Advisory Council[2] "to inform the development of hydrogen as a strategic decarbonised energy carrier for the UK." The Government's hydrogen strategy was released in August 2021.

Blending provides the basis to establish and build out hydrogen production capacity, address 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 the BEIS Heat Strategy[3], in its RHI consultation, and in a 2018 report for the National Infrastructure Commission[4], 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 project[5] seeks to demonstrates 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 project[6] will demonstrate how hydrogen in the gas network can be integrated with operation of the electricity network to maximise the benefits to both.

[2] https://www.gov.uk/government/groups/hydrogen-advisory-council

[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/

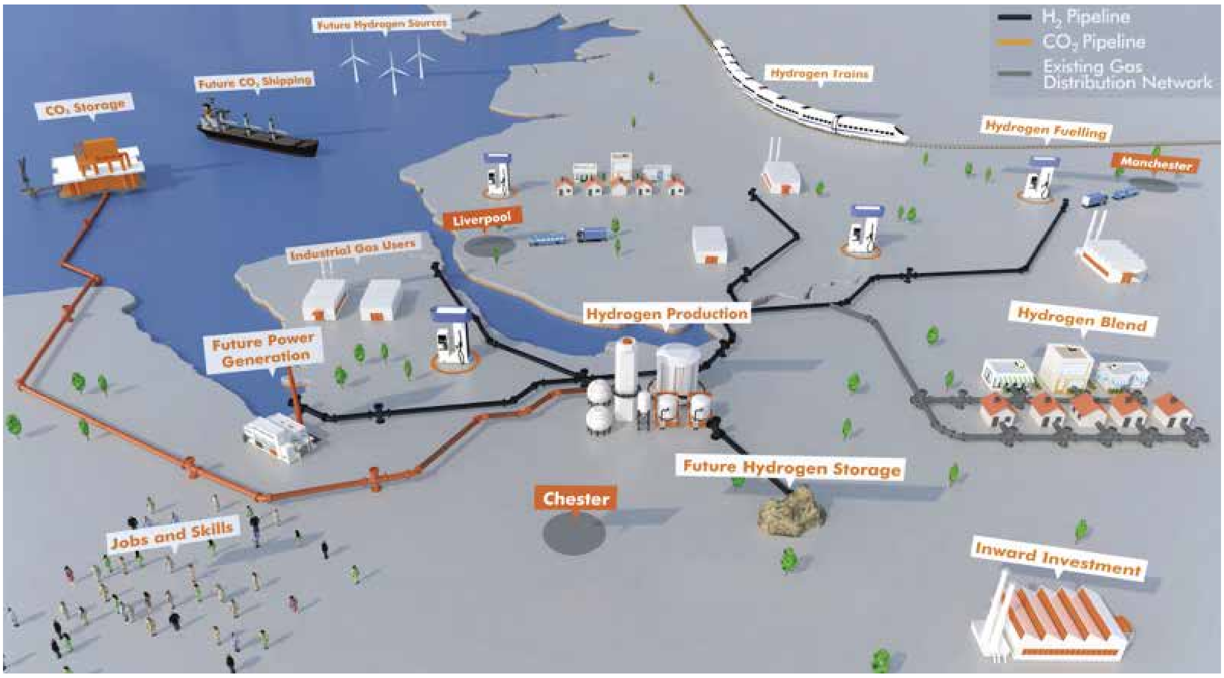


Figure 26: HyNet schematic

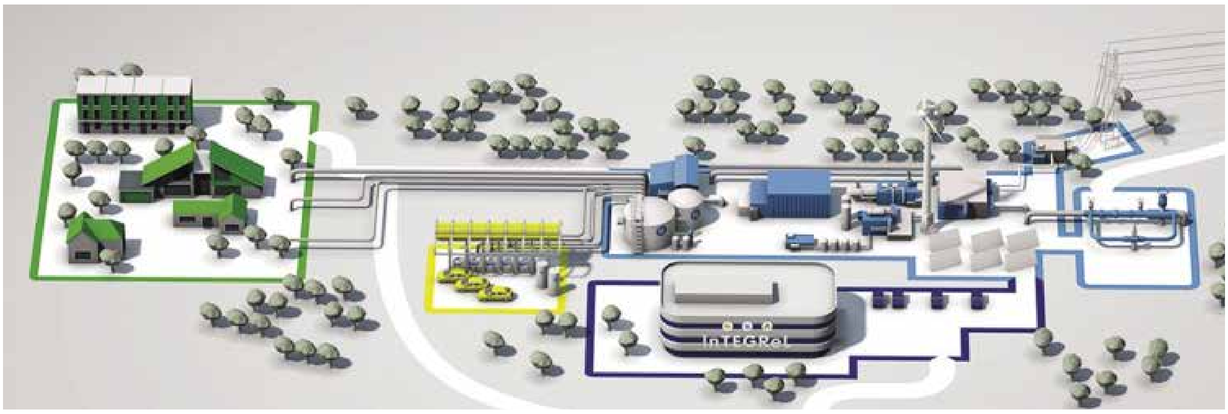


Figure 27: InTEGReL site plan

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.

A 'minded-to' consultation on hydrogen business models was published alongside the Hydrogen Strategy. 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.

7.0 Project Dissemination

Disseminating the project's experience and outcomes to a broad set of stakeholders is critical to ensuring the value and learning of the HyDeploy programme is leveraged to promote the deployment of hydrogen blending. Key decision makers, interested parties, expert organisations and the general public are all important stakeholder groups that were engaged with throughout the programme.

Engagement ensured learnings and outcomes could be disseminated and discussed as required to build confidence and further the collective understanding of hydrogen blending's role in enabling a hydrogen economy.

7.1 Technical dissemination

The technical output of the project has been disseminated via a number of engagement vehicles such as webinars, conferences, journal papers and technical articles. A number of which are referenced and expanded upon below. The formal evidence findings will be placed with the Institute of Gas Engineers and Managers (IGEM) to facilitate industry developments.

7.2 Stakeholders and 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 takes place in Westminster in 2021.

7.2.1 Keele University and 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.

7.2.2 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.

7.2.3 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.

7.2.4 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.

7.2.5 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.

7.2.6 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.

7.2.7 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 warrantees 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 Heating and Hotwater Industry Council ('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.

7.2.8 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.

7.2.9 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.

7.2.10 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 BBS 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.

7.2.11 Example Articles and 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?dockey=1323-13855923-0HEV6CMSMJA02OB6UEJBNK3L4G

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

7.2.12 Key Documentation

The following project documents are publicly available.

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

Table 5: Key documentation

8.0 Overall Project Performance

The HyDeploy project has been successful in demonstrating the viability of hydrogen blending within a live gas network, utilising existing infrastructure to provide non-disruptive carbon savings.

The project is at the vanguard of low carbon gas development in the UK, as shown by successfully gaining approval and subsequently safely operating the first hydrogen blend trial in UK history – providing a hydrogen blend to 100 home and over 30 university facility buildings.

This represented the first use of a hydrogen containing gas in a live gas network since the conversion from towns gas was completed in 1976.

The primary outputs of the project were:

1. Successful achievement of the **first regulatory approval** from the HSE to operate a live gas network above the current hydrogen limit of 0.1 vol%. The approval allowed blending up to 20 vol%.
2. **Development of the technical and procedural precedents** to generate evidence for review by the HSE, which have informed subsequent safety case submissions through HyDeploy2 and the wider hydrogen safety case industry.
3. The design, fabrication, installation and operation of the **UK's first hydrogen grid entry unit.**
4. Integration of novel hydrogen production and blending technologies to create the **first hydrogen delivery system,** based on electrolytic generation into a live gas grid.
5. Safe delivery of the UK's first hydrogen blend trial to **100 homes and 30 faculty buildings.** The trial delivered over 42,000 cubic metres of hydrogen and abated over 27 tonnes of CO_2.
6. **Collaboration with appliance and equipment providers** to build a robust evidence base to demonstrate equipment suitability.
7. Evidencing the **suitability of hydrogen blends with domestic appliances** as well as larger commercial appliances including catering equipment and boilers up to 600 kW.
8. Evidencing the **suitability of hydrogen blends with medium and low-pressure distribution systems,** relating to key performance metrics such as: pressure control; odour intensity and uniform gas compositions.
9. **Promotion of supply chain innovation** through facilitating trials to develop gas detection and analysis technologies.
10. Establishing a robust social science evidence base to **understand the attitudes and experience of consumers actually using hydrogen blends.**

HyDeploy has been pivotal in demonstrating the feasibility to deploy hydrogen blending – to unlock hydrogen adoption with the UK energy system. This has materially influenced the growing recognition of the strategic importance of blending. The overall project started in 2017 and is due to complete the second phase (HyDeploy2) in 2023, the project timeline therefore should directly facilitate the HM Government's hydrogen ambitions of unlocking blending by 2023.

The Keele trial has laid the technical, procedural and regulatory precedents for hydrogen blend adoption within a live gas network. The foundations of HyDeploy have been built on through HyDeploy2, which seeks to undertake a further demonstration on a public network – providing a hydrogen blend to 668 homes and number of larger users.

The final objective of the overall HyDeploy programme is develop the enabling evidence base to demonstrate the safe transportation and utilisation of hydrogen blends within the gas distribution network. A straight line can be drawn from the ground breaking progress of the Keele University trial within HyDeploy, to the overall objective of unlocking non-disruptive carbon savings equal to removing 2.5 million cars from the road.

HyDeploy

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