HyDeploy: The UK’s First Hydrogen Blending Deployment Project

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Abstract

The HyDeploy project is the UK’s first practical project to demonstrate that hydrogen can be safely blended into the natural-gas distribution system without requiring changes to appliances and the associated disruption. The project is funded under Ofgem’s Network Innovation Competition and is a collaboration between Cadent Gas, Northern Gas Networks, Progressive Energy Ltd, Keele University (Keele), Health & Safety Laboratory and ITM Power. Cadent and Northern Gas Networks are the Gas Distribution Network sponsors of the project. Keele University is the host site, providing the gas-distribution network, which will receive the hydrogen blend. Keele University is the largest campus university in the UK. Health & Safety Laboratory provides the scientific laboratories and experimental expertise. ITM Power provides the electrolyser that produces the hydrogen. Progressive Energy Ltd is the project developer and project manager. HyDeploy is structured into three distinct phases. The first is an extensive technical programme to establish the necessary detailed evidence base in support of an application to the Health & Safety Executive for Exemption to Schedule 3 of the Gas Safety (Management) Regulations (GS(M)R) to permit the injection of hydrogen at 20 mol%. This is required to allow hydrogen to be blended into a natural-gas supply above the current British limit of 0.1 mol%. The second phase comprises the construction of the electrolyser and grid entry unit, along with the necessary piping and valves, to allow hydrogen to be mixed and injected into the Keele University gas-distribution network and to ensure all necessary training of operatives is conducted before injection. The third phase is the trial itself, which is due to start in the summer of 2019 and last around 10 months. The trial phase also provides an opportunity to undertake further experimental activities related to the operational network to support the pathway to full deployment of blended gas. The outcome of HyDeploy is principally developing the initial evidence base that hydrogen can be blended into a UK operational natural-gas network without disruption to customers and without prejudicing the safety of end users. If deployed at scale, hydrogen blending at 20 mol% would unlock 29 TWh pa of decarbonized heat and provide a route map for deeper savings. The equivalent carbon savings of a national roll-out of a 20-mol% hydrogen blend would be to remove 2.5 million cars from the road. HyDeploy is a seminal UK project for the decarbonization of the gas grid via hydrogen deployment and will provide the first stepping stone for setting technical, operational and regulatory precedents of the hydrogen vector.

Keywords: HyDeploy; hydrogen blending; demonstration project

Received: 5 January, 2019; Accepted: 8 March, 2019

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Introduction

The use of fossil fuels throughout the twentieth century was the driving force behind the unprecedented change in social structure and improvements in quality of life witnessed. The power to harness such a high-energy-density, storable and abundant energy source transformed every aspect of society. No longer was personal movement limited by animal feed and no longer was mechanization limited by human strength. The global economy transformed from a supply limited world to one of almost limitless potential. It would be difficult to underestimate the impact that fossil fuels have had on societal development and to simply characterize them as ‘bad’ or ‘evil’ would be myopic.

The benefits society reaps from the use of such a cheap and convenient energy source are not without consequences. The oxidation of hydrocarbons releases heat that can either be used directly or converted to work, although the process of oxidation also produces carbon dioxide and water vapour. The production of carbon dioxide is the single largest consequence that results from the use of fossil fuels. The production of carbon dioxide outside of the natural ecological cycle allows infrared radiation to be trapped within the atmosphere leading to a rise in global temperatures. Temperature is the largest determinant of any physical process—too much and everything breaks down into subatomic soup, too little and nothing moves or interacts. Organic life only exists within a relatively narrow temperature range, so processes that interfere with the natural temperature range of the Earth in perpetuity are not consistent with the Earth’s ability to sustain life.

Given that energy use is a fundamental requirement for social development, and carbon-dioxide production scales with fossil-fuel energy use, the generation of carbon dioxide is inherent within the current models of economic prosperity. It is this relationship that rests at the heart of the decarbonization problem—how to live in a prosperous world without promoting the production of carbon dioxide.

In most modern economies, energy is delivered by three systems: the electricity grid; the gas grid; and the oil extraction, processing and transportation supply chain. Decarbonizing electricity has been the principal focus of policy makers since climate change entered the public lexicon. Within the UK, this is being achieved by closing coal power stations and replacing them with gas, wind, solar and biomass. This strategy has been very successful and has led to a 50% reduction in the carbon intensity of electricity from 2013 to 2017 [1]. The outcome of these activities is to demonstrate that material change can be achieved with the right focus and regulatory mechanisms. Figs 1 and 2 illustrate the results that have been achieved within the electricity market.

The decarbonization of heat remains one of the largest unsolved climate-change problems. The reason heat is so difficult to decarbonize is because the gas grid in its current form is so well suited to the demanding needs of its users.
to conversion of industrial users and potentially full network conversion.

The UK gas grid has a history of hydrogen in the form of Towns Gas. Prior to the discovery of the North Sea reserves, the UK’s gas supply came from gasified coal called Towns Gas. This gas contained up to 50 mol% hydrogen, although the carbon-monoxide content resulted in a safety risk to the public. The discovery of the North Sea reserves redefined the energy landscape of the UK as abundant, low-cost natural gas replaced coal mining and gasification. GS(M)R defined what could be transported within the natural-gas grid. The defined composition was based on the prevailing make-up of natural gas from the North Sea, which does not naturally contain hydrogen, so GS(M)R capped the upper limit of hydrogen content to 0.1 mol%, primarily for measurement purposes. The rationale for this cap is therefore a regulatory expedience, as North Sea gas contains essentially no hydrogen. Hydrogen represents a low-carbon alternative within the context of climate change so the 0.1-mol% limit is now rightly being challenged.

Beyond heat, hydrogen has the potential to aid the decarbonization of both electricity and transport. Electricity decarbonization could be achieved either via hydrogen-fuelled gas turbines or industrial fuel cells—providing both baseload and flexible supply to complement intermittent renewables. Transport decarbonization could be achieved either via providing low-carbon electricity during charging times or directly in fuel cells.

Whichever technological pathways prevail within a low-carbon economy, it is clear that hydrogen has the potential to play a central cross-system role.

1 Project structure

The purpose of HyDeploy is to demonstrate that hydrogen can safely be blended into the UK’s gas grid at 20 mol% without prejudicing the safety of end users or modifying appliances. The structure of the project is such that customers’ safety has been the leading focus of all project areas and technical lines of enquiry. The project has been divided into three phases:

(i) Phase 1: Securing regulatory permissions;
(ii) Phase 2: Construction and preparation;
(iii) Phase 3: The trial.

1.1 Phase 1

Phase 1 has been an 18-month scientific programme designed to build the necessary evidence base to demonstrate that hydrogen is safe to blend into the Keele University private gas network for the purposes of the trial period. The programme consisted of three main elements: laboratory work; network appliance testing; and risk analysis—all leading to an exemption application to the Health & Safety Executive (HSE) to sanction the injection of hydrogen up to 20 mol%.

The extensive laboratory work undertaken was led by the Health & Safety Laboratory (HSL) and centred on understanding the implications of a 20-mol% hydrogen blend relative to natural gas. This work involved testing a range of domestic appliances, including gas boilers, cookers and fires. Alongside appliances, a materials programme of experimentation was undertaken to understand the mechanical-property implications of soaking known materials in a blend of hydrogen and natural gas. The materials programme was informed by an asset survey of the Keele network to ensure all gas-seeing materials on the network would be tested prior to the trial. This built confidence that the network and all operating components, such as control valves, would maintain operational integrity throughout the trial.
The laboratory work also included understanding the gas characteristics of a 20-mol% hydrogen blend relative to natural gas. This work allowed recommendations to be formed within the context of operational procedures to produce supplementary guidance for operatives on the Keele network. This work stream provided a pathway to translate basic science into operational implications and ensure procedures were robust and appropriate.

An important experimental work stream related to gas detection. Accurately detecting gas concentrations is a technical foundation of safely operating a network. All relevant detectors underwent a rigorous regime of testing to ensure any implications resulting from the presence of hydrogen could be accounted for and incorporated into the detection instrument.

In tandem with the technical work stream, a thorough programme of appliance testing on the Keele site was carried out. Local Gas Safe engineers worked in collaboration with the gas-testing experts Kiwa Gastec to conduct a series of safety and performance tests on appliances fed from the network at Keele that will have hydrogen blended into. Access was gained to 95% of the 101 domestic properties and evidence gathered on the remaining properties, which provided the necessary confidence that the installations and appliances would be safe and reliable.

The house-to-house testing consisted of carrying out a landlord’s Gas Safe test on all boilers to understand the baseline level of operational performance for appliances on the network. Any appliance deemed unfit or unsafe was remedied, with all works paid for by the project. The appliances were then tested with a series of test gases to understand how each individual appliance responded to the introduction of hydrogen. No appliance required remedial work to be undertaken as a result of the blended gas. All necessary remedial work was due to the appliance being unsafe or unfit. Leak tests were performed on the installations whilst charged with natural gas and then blended gas. All appliances that passed on natural gas also passed on blended gas. Any appliance that failed on natural gas was repaired and made tight; following remedial works, the appliance was retested to ensure integrity.

The house-to-house testing also conducted bottle testing on the commercial boilers fed from the Keele network, the largest of which was 600 kW, as well as catering appliances. Once again, every appliance that was safe on natural gas (operational performance and leakage testing) was also safe on a blend containing 20 mol% hydrogen.

The final element of Phase 1 was to aggregate all of the experimental results and operational testing to undertaken a Quantitative Risk Assessment (QRA) of the Keele network. The QRA was developed by gas industry safety expert Dave Lander Consulting alongside Kiwa Gastec.

The risk assessment involved building a fault tree of the gas-distribution network using referenced data. The model was then scaled to the Keele network to quantify the baseline risk level of the network. Keele was chosen as the host site in part because it is a very safe site. Each input parameter was meticulously reviewed and, if necessary, modified to account for any hydrogen effect. Once each permutation and mitigation measure had been incorporated into the model, a comparison with the baseline risk was carried out.

The QRA demonstrated that the conveyance of blended gas up to 20 mol% hydrogen did not prejudice the safety of the end users.

The evidence base generated throughout Phase 1 was presented to the HSE. Through a rigorous challenge and review process, the HSE granted an exemption to the hydrogen limit in Schedule 3 of the GS(M)R to allow hydrogen to be blended into the Keele network up to 20 mol% for the purposes of the trial. The granting of the exemption marked the end of Phase 1 and the beginning of Phase 2.

1.2 Phase 2

Phase 2 of HyDeploy is the construction and operational preparation phase of the project leading up to injection into the Keele network (Fig. 4) during the summer of 2019.

The physical equipment to be installed includes:

(i) the 0.5-MW electrolyser;
(ii) a grid entry unit that will mix the hydrogen with incoming natural gas;
(iii) sample points around the network to allow monitoring during the trial.

![Fig. 4 Keele university G3 network](https://academic.oup.com/ce/article-abstract/3/2/114/5487479/15/March/2020)
Alongside this primary equipment, further experimentation equipment will be installed. The in-trial experimentation will consist of materials testing, to understand how real-world conditions of blended gas affect mechanical properties of common materials. As well as materials work, accelerated testing of specifically installed domestic boilers will be conducted.

The process of design and construction has been to national and international design standards with As Low As Reasonably Practicable (ALARP) principals being applied throughout. This focus on rigor has resulted in robust engineering solutions being developed. A thorough Factory Acceptance Testing (FAT) programme for equipment has also been developed.

The operation of a gas-distribution network requires the use of procedures to respond to incidents and undertake work. During Phase 1, all relevant operating procedures were reviewed with experts from Cadent, Northern Gas Networks (NGN) and Keele. This resulted in the generation of targeted supplementary guidance and modification to gas-detection instrumentation to account for hydrogen effects. During Phase 2, all relevant operatives, both within Cadent, Keele and third-party contractors, will be trained against the developed guidance.

The training and verification of operatives are key outputs of Phase 2 and hydrogen will only be injected once verification of training has been received. Ensuring all relevant operatives are fully competent to work on a network containing a hydrogen blend is a key safety measure that must be achieved to ensure a safe and successful trial.

Baseline surveying and network monitoring will be conducted throughout Phase 2 to build a detailed picture of the business-as-usual network. This dataset will allow accurate comparison with network and survey data taken during the trial.

As part of Phase 2, further Gas Safe checks will be offered to all residents on the affected Keele network. By repeating the Gas Safe checks, the trial will build further confidence in the integrity of the network.

Construction, training and networking preparation will be carried out until the summer of 2019, when the trial will officially commence.

### 1.3 Phase 3

Phase 3 is the trial itself, which is due to continue for 10 months. The objective of the trial is to demonstrate that hydrogen can be safely blended into a natural-gas grid at 20 mol% without prejudicing the safety of the end users.

The reason for starting the trial in the summer is to avoid the winter peak gas demand—when demand for services is at its highest. By running the trial for 10 months, the summer low of gas demand along with the winter peak can be captured.

Throughout the trial, a rigorous regime of monitoring, inclusive of the process equipment, network and appliances, will be undertaken. This level of operational scrutiny will ensure the network and end appliances always maintain safe functionality. Surveys of the network along with other monitoring techniques will be conducted and compared to the pre-trial baseline to allow any incremental effect due to the presence of hydrogen to be detected.

Following a successful trial of injection, the physical equipment will be decommissioned and moved on. The network will then be returned to natural-gas operation.

### 2 Scientific results

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. An outline of the key results within each area follows.

#### 2.1 Appliances

The laboratory appliance testing had two overarching objectives:

(i) to understand the performance implications of introducing a hydrogen blend, across a wide range of appliances; and

(ii) to understand the limit of operability for a select number of appliances with regard to hydrogen content within the fuel.

The first work stream 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.

Each appliance was fitted with instrumentation to provide accurate characterization 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 stabilizes flames due to the higher flame speed, testing was conducted on an oxygen deficiency sensor (ODS) that cut off fuel supply when the flame receded from a thermocouple due to lack of oxygen. When tested under extreme conditions of a fully blocked flue in a sealed room, all fires but one cut off the fuel supply.
below the 200 parts per million (p.p.m.) carbon-monoxide requirement.

The fire that did not cut off the fuel below 200 p.p.m. presented a baseline reading of just below the cut-off at 180 p.p.m.; it therefore was an outlier to industry standards. All of the fires on the Keele site fitted with ODS devices were verified to cut off below the 200-p.p.m. limit. However, the testing indicated that fires with ODS devices will require further test work to fully understand the baseline variability of the devices for wider roll-out.

The gas-cooker results indicated 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. Figs 5 and 6 show the resulting flame appearance of pure methane (Fig. 5) compared to methane with 28.4 mol% hydrogen (Fig. 6). The difference is marginal, which is indicative of the wider gas-cooker results.

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. This metric is monitored as part of servicing; although still within manufacturers’ guidelines, servicing engineers need to understand that this reduction is to be expected.

The critical-temperature readings assessed components such as the burner plate and the heat exchanger. Much like the gas cooker, variation was observed but not enough to indicate incremental degradation or performance issues. As expected, the flame-ionization 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 that use flame-ionization current to control the fuel/air ratio, there was an observed difference in control behaviour but not enough to be deemed a safety concern. Consideration should be given for further test work on such control schemes.

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. For the selection of appliances tested, flame-out due to light back began at 80 mol%, although some appliances only flamed out at 100 mol% hydrogen. The limit of operability for the appliances tested was far beyond the operating limits of up to 20 mol%. This work is foundational and further limit testing with a wider range of appliances would be beneficial to better understand the operational limits of current gas appliances.

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.

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 allow appropriate supplementary guidance for operational procedures to be produced, where needed.
The focus of the gas-characteristics work stream was to understand the pertinent safety-related characteristics of the gas relative to natural gas; this included:

(i) dispersion characteristics in the event of a leak;
(ii) flammability characteristics;
(iii) 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 was 85% relative to methane, it was determined that a turbulent leak containing 20 mol% hydrogen could be up to 10 vol% greater. However, given the lower enthalpy of combustion of hydrogen relative to natural gas, the potential energy-release rate was in fact lower for 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 in the order of 100s of metres to enable enough gravitation potential to separate the two gases from each other. This is consistent with other 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 to 4.75 vol%. Although this magnitude of change is comparable to the baseline variability of natural-gas data, a conservative position was adopted to recommend a reduction in the LFL limit from 5 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.

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 that is applicable to real-world situations is limited, so a conservative assessment was carried out. It was found that the overpressure profile of blended gas resulted in higher peak overpressures relative to natural gas. The greatest potential risk of the overpressure characteristic of a gas 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 British Standard 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 work stream were aggregated 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 currently experienced by the Keele network.

2.3 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 p.p.m. range to vol% range through to carbon-monoxide measurements. All commonly used instruments on both the Cadent and NGN networks were tested; a selection is shown in Fig. 7.

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

Fig. 7 Gas-detection instruments. (a) Survey detectors; (b) fixed detectors.
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 oversensitive. This does not present a direct safety concern, as the effect is conservative; however, issues concerning nuisance alarms and operative confidence in the instruments are import concerns. For the purpose of the trial at Keele, a linearly affected instrument was chosen and the appropriate calibration calculated to ensure the output measurement would be robust to any blend up to 20 mol% hydrogen. The manufacturer will calibrate the detectors to the desired level to certify the detectors are fit for purpose.

The carbon-monoxide sensor used in common detection instrumentation is an electrochemical cell that oxidises the carbon monoxide and measures the rate of hydrogen-ion production. When hydrogen encounters the sensor, it breaks down and produces further hydrogen ion, 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 that could result in response procedures being invoked. The potential risk is therefore nuisance and operative confidence in the detector readings.

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

The identified carbon-monoxide detector will be used in conjunction with an 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 provide the necessary level of measurement accuracy to allow all current action levels to be maintained. A dedicated training package of familiarization has been developed for all operatives and contractors associated with the operation of the Keele network. Following delivery of the training package, operatives will be deemed competent in the use of related procedures and gas detection equipment.

Following the successful identification of available detectors and the development of the associated training, a process of industrial engagement with manufacturers began. This process seeks 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.

2.4 Materials

The interaction of hydrogen with materials is an area of critical importance that must be understood when evaluating hydrogen injection. The initial stage in this work stream was to undertake a thorough 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:

(i) assess hydrogen uptake into powder and rod samples up to 75°C and up to 9 weeks of soaking;
(ii) soak specimens in a chamber for up to 6 weeks followed by mechanical testing;
(iii) assess any implications for electrofusion jointing and pipeline ‘squeeze-off’ techniques.

The soaking chamber is shown in Fig. 8.

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. The materials that did absorb a level of hydrogen released it upon heating.

The soaking of samples, as pictured in Fig. 8, 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:

(i) total elongation at failure;
(ii) modulus of elasticity;
(iii) ultimate tensile strength;
(iv) proof strength.

Fig. 8 Materials-soaking chamber
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 will be experienced due to the introduction of a hydrogen blend at 20 mol%.

The electrofusion and squeeze-off testing is relevant for operations associated with polyethylene (PE) pipelines. Fig. 9 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 pipeline’s integrity to be isolated and sequentially returned to service.

During Phase 3, further materials work will be undertaken via soaking 42 sample specimens in the actual blended gas over the course of the 10-month trial. Twenty-one samples will be removed half way through the trial and the other half removed at the end. Each batch will undergo the same mechanical-property testing as was conducted in Phase 1. The purpose of testing two batches is 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.

Further testing is recommended for materials with corroded surfaces, as surface effects play a role in the absorption mechanics of hydrogen. To facilitate the wider deployment of hydrogen blending, further materials test work would be needed to test materials not present on the Keele network. This additional testing would be needed to extend the evidence base beyond the Keele network and out onto the public network.

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

### 3 Equipment design

The process design of HyDeploy consists of the installation of a 0.5-MW electrolyser, supplied by ITM Power, along with a hydrogen grid entry unit (H₂GEU), supplied by Thyson. The process of hydrogen production and injection is graphically represented in Fig. 10.

The totality of the installation, which will be constructed at Keele, is inclusive of:

(i) a take-off line redirecting the main feed into the network to the compound containing the equipment;
(ii) the 0.5-MW electrolyser, which will split water using electricity to produce hydrogen and oxygen; the oxygen will be vented and the hydrogen passed into a buffer tank;
(iii) the control scheme of the H₂GEU will measure the incoming natural-gas Wobbe Index and calculate how much hydrogen can be blended into the natural gas whilst remaining within the GS(M)R Wobbe range;
(iv) up to 20 mol% will be mixed with the natural gas; the blended gas will then pass through a ‘volume loop’ to allow a final check of the composition to take place before returning the blended gas to the main feed line into the Keele network;
(v) if, at any time, the blended gas is out of specification, the network supply will be automatically returned to natural gas and the out-of-spec gas purged from the system;
(vi) if, for any reason, there is a process upset that prevents operation of the electrolyser or H₂GEU, the network supply will be automatically returned to natural gas.

Within the volume loop of the H₂GEU, there will be a housing containing material specimens. These material specimens will be exposed to real-world blended gas for the course of the trial. Half of them will be removed halfway through the trial for tensile testing, whilst the other half will be removed at the end of the trial for the same tensile testing.

The process of designing the equipment has been a collaborative effort with all relevant international and British Standards applied. A full Hazard and Operability Study along with a Layers of Protection Analysis have been carried out to ensure rigorous application of ALARP principals was performed throughout the design process.

All equipment to be installed will undergo a FAT, which will ensure the functional specification of the equipment has been achieved through the manufacturing process. Only once a positive result has been obtained through the FAT will equipment be certified to be installed on the Keele network.

Once the trial at Keele has concluded, the equipment will be decommissioned and the network returned to operation on natural gas. The electrolyser and H₂GEU will be transported to the first trial location for HyDeploy, to commence public trials.
4 Blending project pipeline

4.1 HyDeploy 2

HyDeploy is the foundational project for hydrogen-blending deployment in the UK. It will create the initial evidence base to demonstrate that hydrogen can be blended into a live operating gas-distribution network at 20 mol% in a safe and non-disruptive manner.

The next step is to replicate HyDeploy on a larger public network. HyDeploy 2 is the connecting step between trial-scale deployment and commercialization—further building the necessary evidence to demonstrate hydrogen blending. HyDeploy 2 will consist of the same project development team as HyDeploy, with Cadent and NGN as the network sponsors, Progressive Energy as the project developer and with the scientific programme lead by HSL. HyDeploy 2 will be the largest gas project ever funded through the Ofgem Network Innovation Competition, with confirmation of funding received in November 2018. The strategic objective of HyDeploy 2 is to bring hydrogen injection to the same level of regulatory approval as biomethane injection. This would create the regulatory framework for commercial-scale production to be developed and injected into the gas grid without undertaking network checks or further evidence gathering.

The route map for HyDeploy 2 (Fig. 11) is to carry out two further trials over the course of 4 years, starting in 2019—in total supplying ~1500 households with blended gas. The magnitude of pre-trial appliance testing on blended gas will be incrementally rolled back, through separate exemptions for each trial. This incremental approach through two trials is required, as, ultimately, sufficient confidence must be generated to justify deployment without any pre-injection appliance testing.

Throughout HyDeploy 2, a large body of laboratory work will be undertaken to support the exemption process for each trial. The purpose of this work will be to broaden the initial evidence base developed through HyDeploy within the context of public networks. For example, further materials work will be needed to assess all potential materials on the Local Transmission System (LTS) and understand any implications of blended-gas contact.

Successful delivery of HyDeploy 2 will lay the foundation for commercial deployment and injection of hydrogen blends at a material scale.

4.2 HyNet

HyNet is the commercial realization of hydrogen blending into the natural-gas network and is being developed in collaboration between Cadent and Progressive Energy in the north-west of England.

HyNet will be the first project on a national scale to develop hydrogen production for the purposes of decarbonizing both industrial clusters and domestic heat. Using Auto Thermal Reformer Technology (ATR) in conjunction with a Carbon Capture and Storage infrastructure, as shown in Fig. 12, the output of the initial HyNet project will be to achieve:
(i) carbon savings of +1 MTCO$_2$/yr;
(ii) non-disruptive decarbonization of 2 million homes in the Manchester–Liverpool region;
(iii) decarbonization of industrial clusters via hydrogen conversion.

The HyNet programme will create an underlying carbon-dioxide transport and storage infrastructure to enable further carbon savings. The design of the project will be inherently expandable, allowing further development of hydrogen production and carbon capture to accommodate geographical expansion.

Operation of the hydrogen-production facility is scheduled for the mid-2020s, which will allow carbon savings to be realized in line with the 2018 Committee on Climate Change report on the UK decarbonization progress [5]. The project scope will be inclusive of ATR technology generating 800 MW(th) of hydrogen, to be distributed in a purpose-built hydrogen network feeding directly into industrial clusters and injecting into the LTS at four strategic locations to allow a blend to be provided to 2 million homes.

The strategic objective of HyNet is to build upon the HyDeploy project series to deploy hydrogen in homes on a national scale, in a non-disruptive manner. By avoiding the need to modify existing domestic appliances, a large barrier to deployment of hydrogen is removed. Once deployed, HyNet will create the foundational infrastructure necessary to facilitate and promote deeper carbon savings via the hydrogen vector.

5 Conclusions

HyDeploy has successfully reached the end of Phase 1, with the granting of the UK’s first ever exemption for hydrogen injection to a gas network by the HSE. The exemption is specifically for the trial at Keele for the duration of the trial, although HyDeploy has demonstrated that regulatory approval for hydrogen blending up to 20 mol% is possible.

The current conclusions from the undertakings of Phase 1 indicate that:

(i) through meticulous review and consideration, procedures for the operation of a hydrogen-blended network can be developed;
(ii) gas detection to support network operation is possible with current technology and is further enhanced by the operational attributes of the Keele network;
(iii) no materials-related issues have been identified on Keele’s network at operational pressures for natural gas containing up to 20 mol% hydrogen;
(iv) properly installed and maintained domestic appliances are just as safe whilst operating with a blended gas of up to 20 mol% hydrogen.

The extent of applicability of the above conclusions is currently bounded to the Keele network, as the evidence base generated was necessarily focused on undertaking a safe trial at Keele University.

Through the process of HyDeploy, the underlying evidence base will be broadened to be representative of the wider public network. This will build regulatory confidence in hydrogen blending to ultimately facilitate commercial deployment through HyNet and beyond. For further reading on the topic of hydrogen blending please see [6–12].

Acknowledgements

Acknowledgement should be given to the Office of Gas & Electricity Markets for providing the funding for both HyDeploy and HyDeploy, to enable the programme described to be delivered. Acknowledgement should also be given to the project partners: Cadent Gas, Northern Gas Networks, Health & Safety Executive—Science Division, Keele University and ITM Power, as well as the technical contributors Otto Simon Limited, Kiwa Gastec and Dave Lander Consulting, along with advisory organizations who have contributed to HyDeploy.

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