Testing of Blends of Hydrogen and Natural Gas (HyTest)

Short Report

Dr Ali Ekhtiari,
Dr Eoin Syron,
Mr Liam Nolan,
Mr Paul O'Dwyer

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Introduction

Green hydrogen is currently gaining a lot of global attention as a possible way of achieving a net zero carbon energy system. The future scenario where all our energy needs are provided by renewable electricity backed up by a carbon free gas fuel is compelling. However, society still needs to find a way to transition to this future scenario. Incorporating and blending green hydrogen into the gas networks is an immediately accessible near term solution for storing and transporting renewable energy. Ireland already loses over 11%[1] of renewable electricity generated due to electrical network transmission and balancing issues, and given the future plans to harness both on-shore and off-shore wind resources, curtailment is expected to increase in the future. Blending green hydrogen into the gas network can also provide an existing outlet/demand for renewable energy developers and green hydrogen producers who wish to be first movers in the green hydrogen sector. In order to prepare for this, Gas Networks Ireland teamed up with University College Dublin (UCD) Energy Institute to demonstrate the safe and reliable operation of residential end-user devices connected to the Irish gas network over a range of hydrogen concentrations from 2% to 20%. Measured parameters included the heating value, flue gas analysis, flame temperature and flame picture, pressure drop, minimum operating pressure, and safety and leak tests. All work was carried out at the recently refurbished Network Innovation Centre, Gas Networks Ireland, Brownsbarn, Citywest, Dublin and the UCD Integrated Energy Lab.

Hydrogen

The majority of hydrogen used in the world today is generated from fossil hydrocarbons; alternative carbon free sources are available and becoming ever more cost competitive. Hydrogen is often classified into different colours to identify its source.

Grey hydrogen is produced when natural gas is used as the feedstock for reforming methane using steam to produce hydrogen.

Blue hydrogen is the term given to hydrogen produced through the steam reforming of methane when the associated Carbon dioxide (CO_2) produced is captured and stored via Carbon Capture and Storage (CCS).

Green hydrogen is hydrogen produced without the release of CO_2. Typically this is through the use of renewable electricity for the electrolysis of water.

Comparison of hydrogen and natural gas

The chemical, physical and thermal properties of hydrogen and methane are compared in table (1). Values are given for the gas phase at 288 K (15˚C) and 1 atm. When hydrogen is blended with natural gas, the gas mixture has different properties than either pure methane or pure hydrogen.

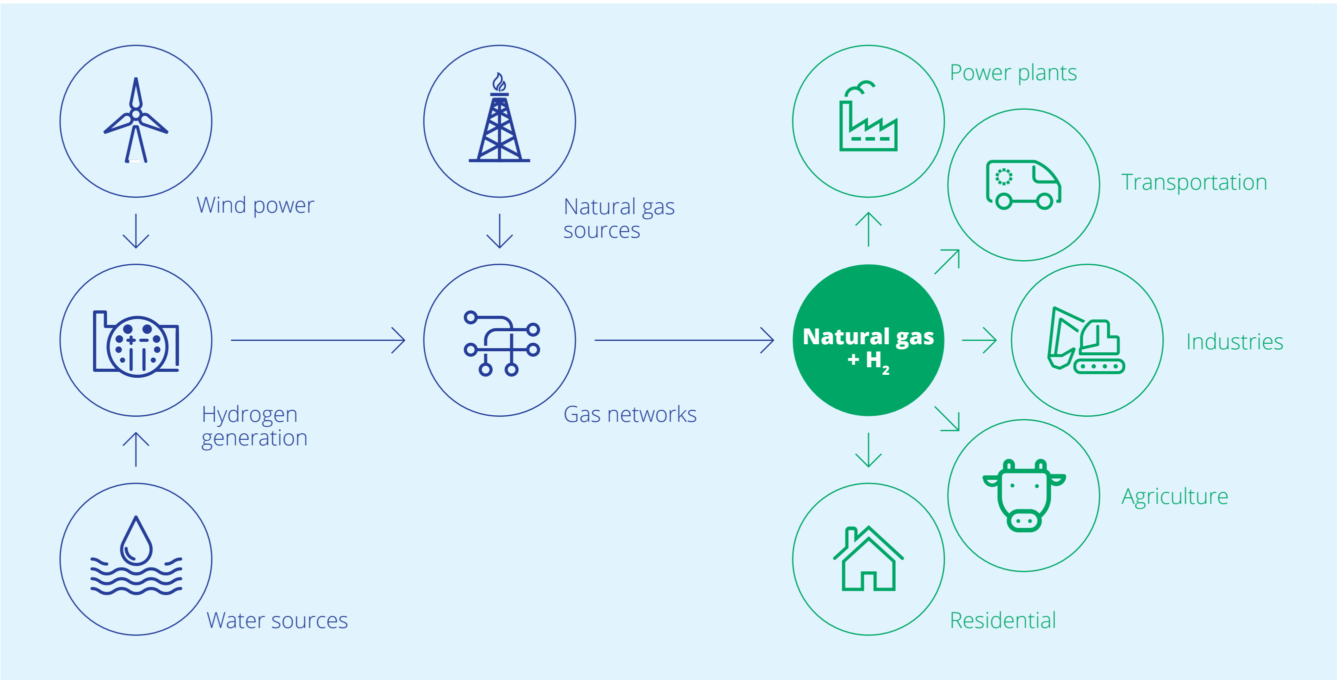

Figure 1. Schematic of Green Hydrogen process from production, injection into the pipelines to be used by different end-users.

1 EirGrid, "Annual Renewable Energy Constraint and Curtailment Report 2020"

Table 1. Hydrogen and methane thermodynamic properties.

Values are given for the gas phase at 15˚C and 1 atm.

Item	Unit	Hydrogen	Methane
Molecular weight	g/mol	2.016	16.04
Specific gravity		0.069	0.55
Specific volume	m^3/kg	12.1	1.52
Absolute viscosity	centipoise	0.009	0.011
Adiabatic combustion temperature	˚C	2100	1950
Calorific value (CV)	$MJ/\ m^3$	Gross: 12.1	Gross: 37.8
		Net: 10.2	Net: 34
Wobbe index	MJ/m^3	Upper: 48	Upper: 54
		Lower: 41	Lower: 48
Gas constant - R	J/kg.C	4126	518.28
Boiling point	°C	-252.75	-161.64
Critical temperature	°C	-240	190.56
Critical pressure	MN/m^2	1.3	4.6

Natural gas-hydrogen blends

Depending on the pipeline materials and engineering standards, 100% pure hydrogen can be transported in the distribution pipelines and existing polyethene distribution pipelines can accommodate blends of up to 20% Volume per volume of hydrogen without any undue safety concerns. However, there are thousands of devices connected to the gas network in homes and businesses across Ireland, and any potential impact on their operation by the addition of hydrogen into the gas network needs to be considered.

Overview of the project

This project evaluated the safety and stability of the gas supply and device operation with increasing hydrogen concentrations (2-20%).

For a range of natural gas and hydrogen mixtures, this project investigated the calorific value (CV) of the mixture, performed leak and safety testing, evaluated metering accuracy, conducted flue gas analysis, compared flame pictures and checked operating pressure and flow rate variables. Post-1996 gas appliances, including six condensing boilers, two gas fires, two gas cookers and two gas hobs, were tested in accordance with the Gas Appliance Directive/Regulations[2]. The overall objectives were to assess if:

1. Supplying a mixture of hydrogen and natural gas is a safe, secure and sustainable gaseous fuel for use in the residential market.
2. Domestic end-user equipment continues to operate over the range of hydrogen concentrations tested without any problem.

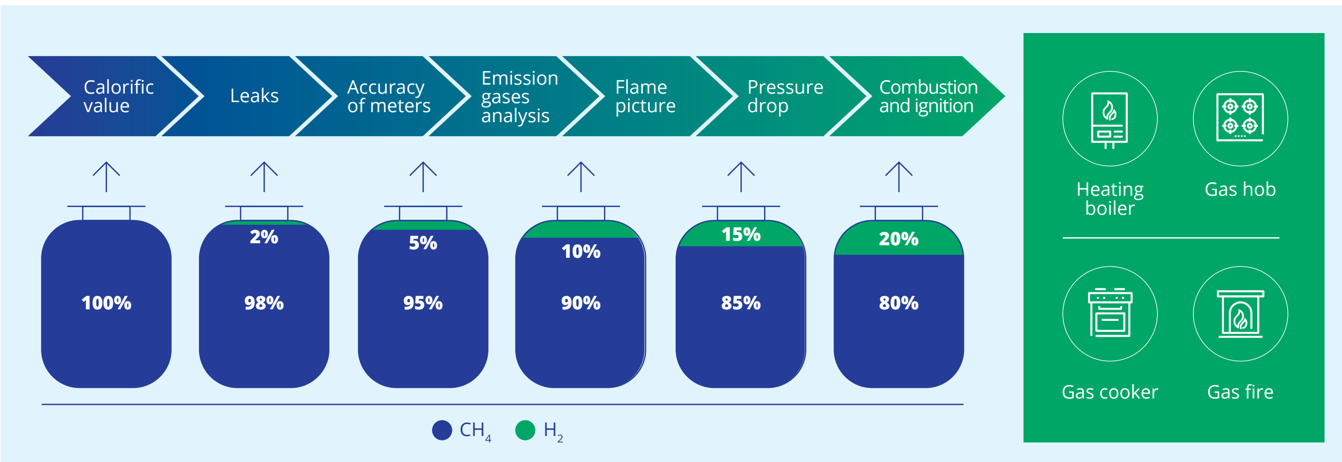

Figure 2. Overview of the hydrogen blend and the tests carried out in the HyTest project.

2 Gas Appliance Directive (GAD) 2009/142/EC and Gas Appliance Regulation (GAR) (EU 2016/426)

Figure 3. Appliances; (a) six condensing boilers, (b) an 18-year-old gas cooker, (c) a gas hob.

All appliances were serviced and commissioned before testing. The full-service assessment was done in line with the gas installation standard. After testing each boiler's gas emissions, the boilers were operated in continuous mode for a period of one hour.

Results

Calorific value and Wobbe Index

The calorific value is the heat produced by the combustion of a unit of fuel gas. To determine the calorific value of each gas mixtures, the gas flow rate to the boiler was measured as well as the water flow rate and the change in temperature through the boiler. Additionally, the time taken for each gas mixture to boil a known volume of water on a gas hob was measured. The given heat to water can be calculated by differentiating the inlet and outlet temperature of the water in the boiler. The calorific value of the gas is the heat transferred to the water divided by the volume of gas burned. Table (2) shows how calorific value and Wobbe Index (WI) change using different hydrogen blends.

Table 2. Gross calorific value (GCV) and Wobbe Index of hydrogen blends.

	From a gas chromatograph		
Gas blends	**GCV [MJ/m³]**	**WI [MJ/m³]**	**Relative density**
2% H_2	38.5	50.1	0.59
5% H_2	37.8	49.8	0.57
10% H_2	36.4	49.1	0.54
15% H_2	34.8	48.5	0.51
20% H_2	33.2	47.6	0.48

There is an approximate 15% drop in GCV using the 20% hydrogen blend compared with the natural gas. The Wobbe Index, calculated from the calorific value and the specific gravity of the gas, is an indicator of the interchangeability of fuel gases between gas burners. Figure (5) outlines the value of WI and GCV for the different blends. The Gas Quality Specification in the Irish Code of Operations requires the WI of natural gas at entry points to be between 47.2 and 51.4 MJ/m³ (the vertical dash lines in figure 5). All blends tested up to 20% hydrogen were within this existing WI threshold, which was an important indicator for the safe performance of the gas

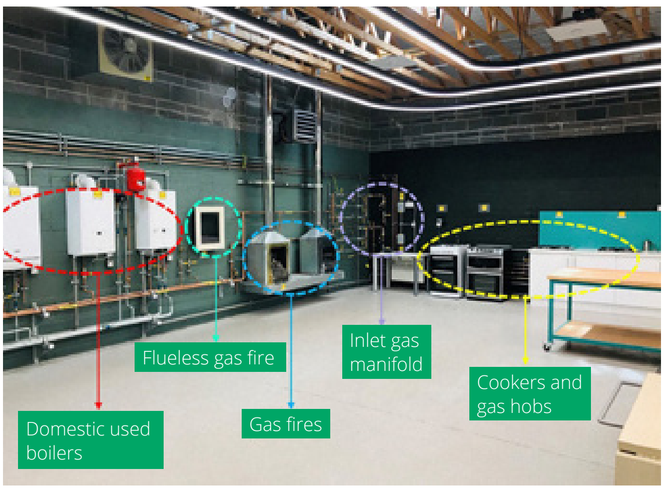

Figure 4. Network Innovation Centre facilities for testing renewable gases.

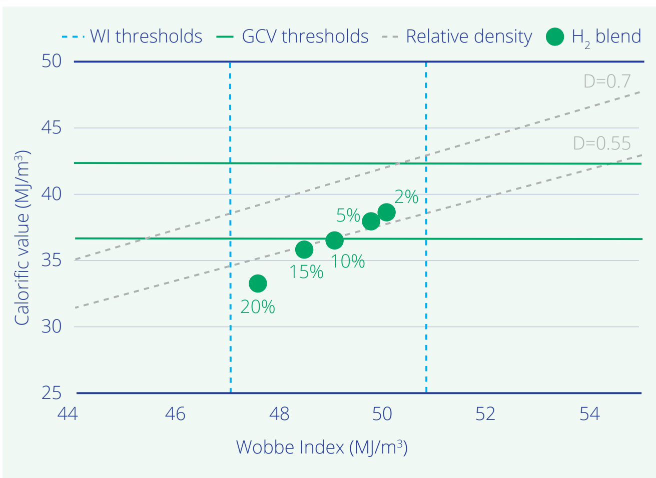

Figure 5. Calorific value and Wobbe Index of natural gas and hydrogen blends from HyTest.

Table 3. Hydrogen blends composition analyses using gas chromatography.

	Composition volume fraction [%]				
Composition	**2% H_2**	**5% H_2**	**10% H_2**	**15% H_2**	**20% H_2**
Hydrogen	1.99	4.71	9.15	15.1	21.1
Methane	91.1	88.7	84.9	79.5	73.6
Ethane	3.63	3.48	3.05	2.85	2.64
Propane	0.88	0.83	0.67	0.63	0.58
iso-Butane	0.22	0.22	0.207	0.194	0.18
n-Butane	0.16	0.15	0.131	0.123	0.115

NOTE: The gas composition results from the chromatograph show that the hydrogen concentrations were not exact, e.g. the hydrogen concentration for the test gas bottle labelled 20% H_2 was 21.1%.

appliances tested during the project. The Code of Operations requires a GCV between 36.9 and 42.3 MJ/m^3. Blends of 10% hydrogen and above were found to be below the lower GCV threshold. This is consistent with a decreasing energy content by volume of the blended gas as the percentage of hydrogen increases. Similar figures for the WI and GCV were achieved in the practical approach (the measurements).

Table (3) shows the composition fractions in the test gas bottles. These figures are tested and recorded in the lab using gas chromatography certified by INAB (Ireland National Accreditation Board) under ISO/IEC17025.

Boiling time of 1 litre of water:

The time it takes to boil one litre of water in steel kettles on the gas hobs for natural gas, and the hydrogen blends were plotted in figure (6). The flow rates of natural gas and hydrogen blends to the gas hobs were constant (0.003 m^3/min). The boiling time for natural gas is 349 seconds (00:05:49), while for 20% hydrogen is 398 seconds (00:06:38). The time difference between natural gas and 20% hydrogen blend is 49 seconds, about a +12% increase in time.

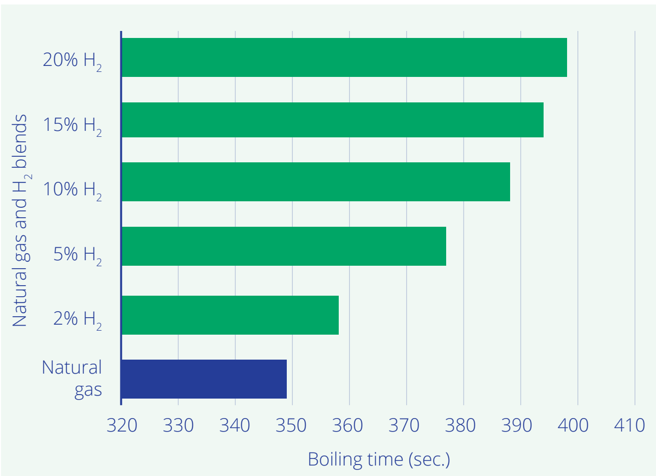

Figure 6. The recorded boiling temperature of one litre of water using different hydrogen blends and natural gas.

Leak and safety tests

The procedures for pressure leak testing (soundness test) are outlined in the national gas installation standards[3] and provide a method to test possible leaks in connections and fittings of a gas pipe by measuring static gas pressure over a specific time. For testing the existing installations of the test facility for each hydrogen blend, the following procedure was implemented:

Pressure leak tests include measuring the pressure decay in the gas pipe, in which both ends are closed.

- Ensuring all appliance isolation valves are open.
- Pressurise the pipe to the working pressure (~20 mbar).
- Allow a minimum of 2 minutes of stabilisation.
- Check the pressure transmitter/gauge and note the exact reading and time.
- After a minimum of 2 minutes, recheck the pressure transmitter/gauge.
- If there is no pressure drop, the leak test is passed.

The gas flows into the test section at an operating pressure of about 20 mbar. Then, by closing both ends of the pipe, all fittings, connections, and valves can be tested over 4 minutes. Both lines "A" and "B" were tested for this work package. There was no loss in pressure during the test for all gas mixtures and natural gas.

Metering with blends

This test compared the consistency of the metering performance of blends for a typical domestic gas flow meter (diaphragm gas meter) by comparing it with a thermal mass flow meter (Bronkhorst FG-111AC) connected in series. The thermal mass flow meter would be considered a highly accurate metering device with an error of less than ±0.5%.

As shown in table (4), for the baseline case with flows of natural gas, a deviation between the two meters of 0.00026 m^3/min (2%) was established. Comparing the two-meter readings (domestic and thermal mass flow meters) for the various hydrogen blends up to the 20% hydrogen blend shows no significant change in this deviation over the course of the

3 Irish standard I.S 813 Domestic Gas Installations

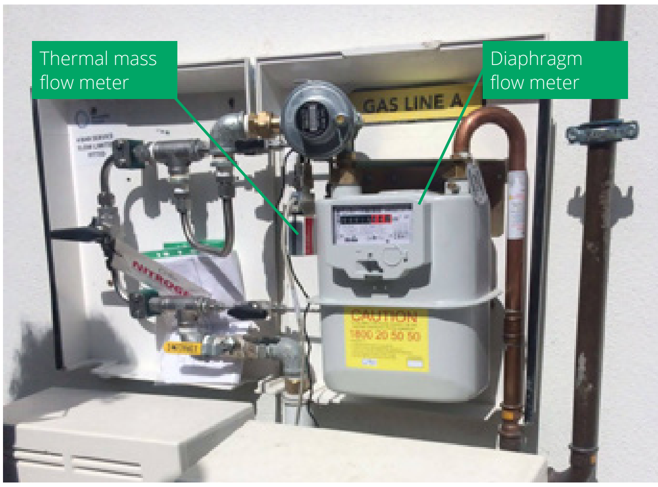

Figure 7. Flow meters are configured in series at the inlet point of the test installation.

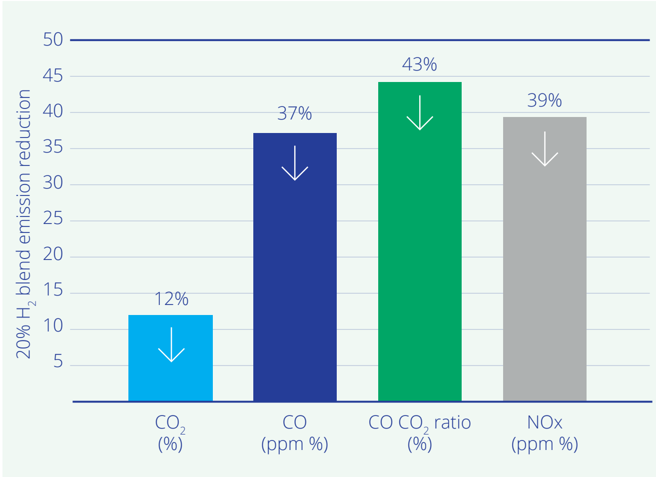

Figure 8. Average percentage reduction in emissions measured for the boilers tested with 20% hydrogen blend.

testing (ranging from 1.3% to 2.2%). The deviation of readings between the flow rates was 0.00026 m³/min (2%) for natural gas compared favourably with the 0.00022 m³/min (about 1.7%) result recorded for the 20% hydrogen blend.

Table 4. The deviation between meter readings: current installed domestic flow meter versus thermal mass flow meter.

Gas blends	Deviation (m³/min)	Deviation (%)
Natural gas	0.00026	2.0%
2% H_2	0.00016	1.3%
5% H_2	0.00019	1.5%
10% H_2	0.00021	1.8%
15% H_2	0.00020	2.2%
20% H_2	0.00022	1.7%

Gas emission analysis

Flue gas emission from the hot water boilers was recorded using a gas emission analyser (MRU OPTIMA 7) and is summarised in Table 3. The recorded data shows that there was a decrease in Carbon Dioxide (CO_2), Carbon Monoxide (CO) and Nitrogen Oxides (NOx) with increasing hydrogen concentration in the gas mixture.

Table 3 shows the gas emissions measured and the recorded average temperature of the exhaust gases produced by the boilers operating at maximum load, when burning different hydrogen blends. Figure (8) shows the average percentage reduction in emissions for various hydrogen blends with the boilers running at maximum load settings.

Table 3. Average flue gas emissions of boilers tested in the laboratory operating at maximum load.

Hydrogen blends (%)	Max. temp (C)	Max. CO_2 (%)	Max. CO (ppm)	CO:CO_2 (%)	NOx (ppm)
Natural gas	62.5	9.5	56.5	0.0006	22.2
2% H_2	61.4	9.3	57.2	0.0005	21.8
5% H_2	62.3	9.0	53.3	0.0005	17.8
10% H_2	62.8	8.8	46.7	0.0004	16.7
15% H_2	62.2	8.6	40.2	0.0004	15.5
20% H_2	62.7	8.4	35.5	0.0003	13.5

The change in emission from burning 20% hydrogen blends during this test is compared with 3 other international tests. HyDeploy project (Hydrogen test project in the UK), the H_2NG project (testing hydrogen blends in France) and the EU-funded ThyGA project (Testing Hydrogen admixture for Gas Applications). A comparison is shown in table (5). The figures for the H_2NG[4] are specific to the old Guillot boiler. The boiler in the THyGA project is a premix boiler.

All projects report reduced CO_2, CO and NOx concentrations in gas emission from boilers using 20% hydrogen blends. THyGA and the HyTest (Gas Networks Ireland/University College Dublin joint) project recorded NOx emission reductions of 43% and 40%[5], which are comparable. The CO_2 reduction recorded is nearly the same figure, about 12%, while this number for the HyDeploy project is 16%[6]. Furthermore, HyTest and THyGA projects reported a 37% and 42% CO reduction. When 20% of natural gas (volumetric value) is replaced by hydrogen, the energy value of a volumetric unit of the gas blend decreases by about 14%. Based on this energy density reduction, the quantity of CO_2 emissions reduction for a larger gas volume of equivalent energy to 100% natural gas is expected in the region of 7%.

4 GRHYD, "The first power to gas H_2 in France (H_2NG)," 2021.
5 THyGA, "Testing Hydrogen admixture for Gas Applications - Market segmentation of domestic and commercial natural gas appliances," 2021.
6 M. Pursell, "HyDeploy: Summary of Gas Appliance and Installation Testing," Health and Safety Laboratory, 2018.

Table 5. Emission reductions measured using 20% hydrogen blend.

20% H_2 blend compared to natural gas	CO_2 reduction	CO reduction	$CO:CO_2$ reduction	NOx reduction
HyTest (Gas Networks Ireland and UCD)	11.8%	37.2%	43%	40%
HyDeploy	16%	28%	32%	22%
THyGA report	decrease	42%	~39%	43%
H_2NG report	12%	20%	~15%	57%

Minimum operating pressure

For each gas appliance, the minimum pressure requirements were determined to maintain operation/combustion over the range of gas blends. The pressure in the gas line was slowly decreased until the appliance stopped working; the minimum operating pressure of each appliance was then noted.

As figure (9) shows, there are no marked differences in the minimum operating pressure of appliances burning hydrogen blends. It cannot be specified that by blending hydrogen, the minimum operating pressure is declining due to an increase of minimum pressure in some appliances, i.e. gas fire no. 2, the wall heater, boilers no. 4 and 5. The minimum operating pressure belongs to gas hobs and gas cookers with less than 1 mbar operating pressure (about 0.3 mbar still working). The operating pressure data from the 20% hydrogen blend compared to the natural gas show that there is no definite decrease/increase of minimum operating pressure while burning a 20% hydrogen blend in domestic appliances. It cannot be considered that the minimum operating pressure decreases or increases while using hydrogen blends.

Flame pictures

The ability to see the natural gas flame is an important safety feature, as it can trigger a visual fire alarm or alert an individual to a gas fire. A pure hydrogen flame is known to burn without a distinct colour. Therefore, it is important to determine the effect of hydrogen addition on the visibility of the natural gas flame. Pictures of the various blended gas flames have been taken under controlled lighting conditions to determine how much the addition of hydrogen influences the flame's colour and visibility.

No changes were observed in flame pictures during the burning of hydrogen blends and natural gas. Figure (10) shows the photographs of the flame using a simple laboratory Bunsen burner. Photographs of the cooker during the operation were taken during burning natural gas, and 20% hydrogen is shown in figure (11). The flame picture for hydrogen blends appears the same as 100% natural gas flame; therefore, there are no safety concerns.

Pressure drop tests

Blending hydrogen with natural gas impacts the physical parameters of the gas flowing in the pipe and the energy delivered per unit volume. To test if there was a significant impact on the pressure drop of gas flowing the pressure loss over a 10 meters length of domestic gas pipeline. A maximum pressure drop of 0.2 mbar occurred when a 20% hydrogen blend was flowing in the pipeline.

Conclusion

Hydrogen has the potential to be directly blended and used in distribution pipelines for domestic use. Blending green hydrogen reduces greenhouse gas emissions and helps in decarbonising gas networks. However, due to hydrogen's lower energy content, when hydrogen is blended with natural gas, the energy content per unit volume decreases.

The main objective of this project was to ensure that domestic appliances can operate safely and effectively with hydrogen blends up to 20%. This study shows no significant changes in operational variables such as pressure and flow rate using hydrogen blends. Gaseous emissions were reduced when

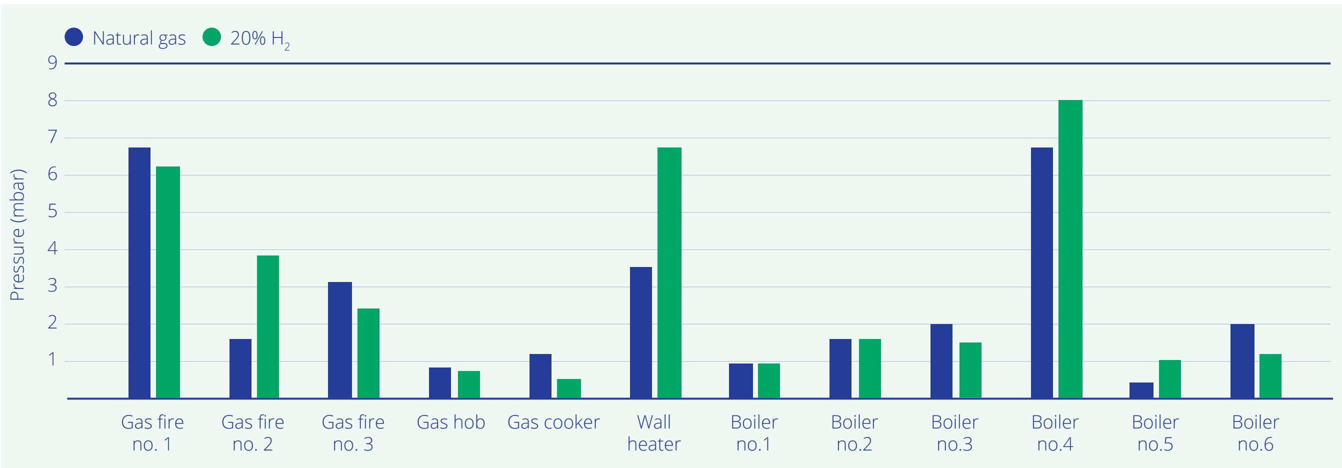

Figure 9. Minimum operating pressures in all appliances.

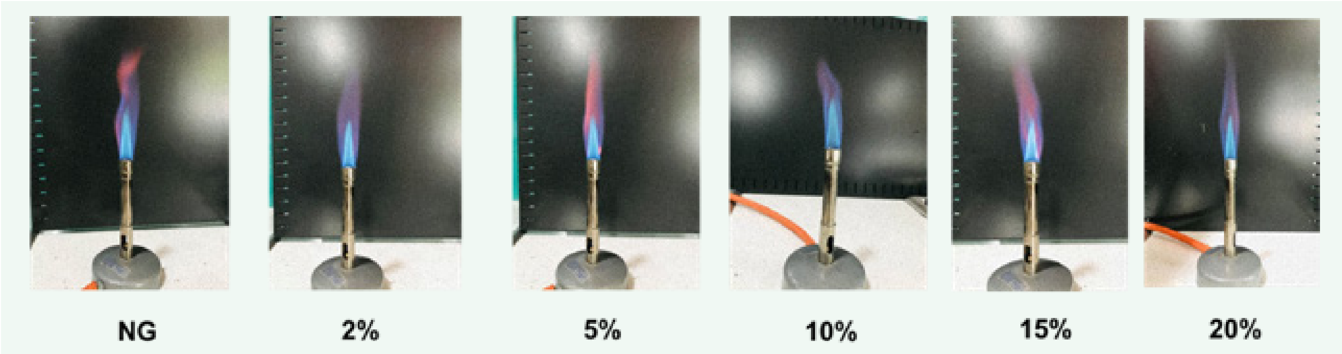

Figure 10. Flame pictures are taken from burning different hydrogen blends and natural gas.

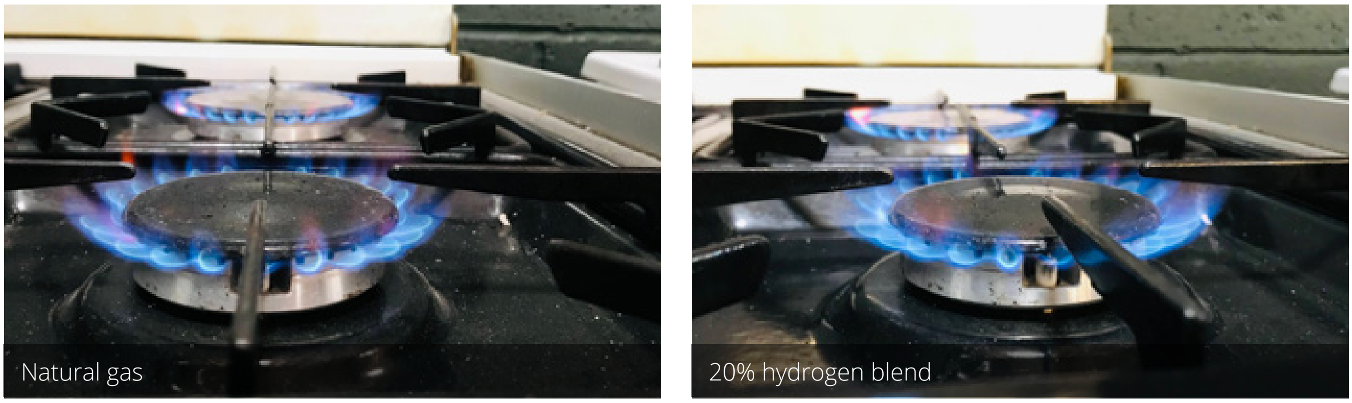

Figure 11. Gas cooker flames for the natural gas and a 20% hydrogen blend

using hydrogen blends, by on average 12%, 37%, and 40% reductions in CO_2, CO, and NOx, respectively, when burning the 20% hydrogen blend. There was a 15% reduction in Gross Calorific Value for the 20% hydrogen gas blend. All blends tested up to 20% hydrogen were within the existing Wobbe Index thresholds. There were no observed perceptible changes in the operation of the appliances using hydrogen blends, and current domestic meters demonstrated compatibility with hydrogen blends for volume measurement.

Following the works carried out for the project, focussing on the assessment of the safe operation of domestic gas appliances with hydrogen blends (up to 20%), the key findings are:

- The domestic gas appliances tested operated safely and effectively with various hydrogen blends tested ranging from 2% to 20% hydrogen by volume.
- There was a substantial emissions reduction obtained by blending hydrogen with natural gas.
- The average emission reduction found was a 12% reduction in CO_2, a 37% reduction in CO, a 43% reduction in the $CO{:}CO_2$ ratio, and a 40% reduction in NOx emissions.
- There were no changes observed in the minimum operating pressure of appliances while burning the hydrogen gas blends.
- No leakage was detected during pre-testing or during operations for all pipework, connections, fittings, and valves at operating pressure.
- The domestic gas flow meter was consistently accurate when used for measuring gas volume flows containing up to 20% hydrogen compared to natural gas.
- The flame motion and colour of the hydrogen gas mixtures stayed similar to natural gas.

Next steps and recommendations

Future potential projects and areas of interest

- Testing of higher than 20% hydrogen blends and testing 100% hydrogen.
- Testing industrial and commercial end-users' equipment, including investigating the impact of the Wobbe Index variations and compensating for the reduction in energy per unit volume by controlling the gas flow rate.
- Testing renewable hydrogen and biomethane blends with natural gas considering gas emission and gas quality.
- Leakage and safety testing considering equipment long-term material compatibility with hydrogen.
- Further research of the natural gas customer appliance populations in the domestic and industrial / commercial sectors.