IFS Phase 1 Real Time Natural Gas and Hydrogen Sensor

Feasibility Report for Publishing

Project Reference:	RD90003006_FR001
Issue Date:	30th September 2022
Revision:	1

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Revision History			
Revision:	Prepared By:	Approved By:	Date
1	Harry Jones	Tom Knight	30/09/2022
Initial Issue			

Contents

1 Abbreviations

UK: United Kingdom

US: United States

IFS: Industrial Fuel Switching

FBM: Future Billing Methodology

GC: Gas Chromatograph

NPL: National Physical Laboratory

ISO: International Organisation for Standardisation

O_2: Oxygen

CO_2: Carbon Dioxide

N_2: Nitrogen

H_2S: Hydrogen Sulphide

CO: Carbon Monoxide

H_2O: Moisture

H_2: Hydrogen

LNG: Liquefied Natural Gas

NG: Natural Gas

CV: Calorific Value

WI: Wobbe Index

TRL: Technology Readiness Level

RA: Risk Assessment

WP: Work Package

CAD: Computer Automated Design

PO: Purchase Order

PCB: Printed Circuit Board

LDZ: Localised Distribution Zone

CVDD: Calorific Value Determination Device

PPM: Parts Per Million

VOL: Volume

RH: Relative Humidity

LOD: Limit of Detection

fF: Femtofarad

pF: Picofarad

aF: Attofarad

UV: Ultraviolet

LED: Light Emitting Diode

PRM: Primary Reference Materials

PEM: Proton Exchange Membrane

AFR: Air Fuel Ratio

EU ETS:	European Emissions Trading Systems
LEL:	Lower Explosive Limit
SI:	Sooting Index
ICF:	Incomplete Combustion Factor
CAPEX:	Capital Expenditure
OPEX:	Operating Expenditure
OEM:	original Equipment Manufacturer
AI:	Artificial Intelligence
DBB:	Double Block and Bleed

2 Project Introduction

2.1 Key Information

Project Start Date:	28th March 2022
Project Duration:	6 months
Project End Date:	30th September 2022
Total Funding:	£294,898.61 (Updated Forecast at Beginning of Project: £294,786.55)
Payment Milestones:	
11/04/2022	£93,313.83
30/06/2022	£131,443.10
30/09/2022	£70,029.62
Lead Organisation:	Bohr Limited
Sub-contractors:	Endet Limited, TNO, Progressive Energy and NPL

2.2 Project Overview

This project is to enable fuel switching. As we transition first to a 20% hydrogen in natural gas and then 100% hydrogen fuel, industry is currently restrained due to the inability to correctly monitor/control the fuel they are using. This is a problem that has been acknowledged several times but remains unsolved and remains a fundamental barrier to industrial fuel switching and the adoption of Green Gases. In the DNV-run workshop “Industrial and Commercial Gas Quality” all stakeholders (gas engines/turbines, control systems/industrial applications, burners/boilers/glass/ceramics/emissions, Government, regulatory/gas transporters and storage/chemical feedstock) identified that a major blocker to the introduction of low carbon fuels would be both the lack of measurement technologies currently installed and the inadequacy of the existing solutions. Existing Gas Chromatography-based solutions are fundamentally too slow to allow the introduction of blended fuels and even ignoring this, there are too few installed and the expense and complexity of both installing and operating the devices would prohibit broader roll out. Previous demonstration-scale industrial fuel switching has allowed new gas chromatography systems to be installed and the blend to be very precisely controlled eliminating “real world” conditions to allow the “bigger picture” fuel switching experiment. However, continuing to ignore this issue and to implement fuel switching on a national level requires industrial users to accurately monitor their fuel cheaply and effectively to allow them to control flow and/or adjust burner characteristics. Without such a solution, fuel switching will not happen or will cost more than it provides in benefit.

Bohr’s technology offers very simple “plug and play” useability which can give practically real time gas quality/composition analysis allowing users the ability to know exactly what gas they have entering their facility and act accordingly. This will enable accurate billing, and enhanced process control ensuring optimum efficiency/quality.

Further, as the transition progresses to 100% Hydrogen solutions, there will be new measurement challenges. 100% hydrogen will not truly be 100%, there will be contaminants that must be measured. Additionally, new standards will be implemented to control emissions. Our sensor technology can be used to monitor numerous gas components such as contaminants in the fuel gas or trace hydrogen in flue gas which will be a measurement requirement to ensure efficient and environmentally friendly burner control. Our technology will offer this, which does not currently exist at an enabling price point, further blocking the possibility of implementing fuel switching on a major scale.

2.3 Project Team Overview

Bohr is a lean, agile and innovative company, dedicated to helping achieve Net Zero. The Bohr team have over 150 years Clean Energy, Natural Gas, Hydrogen and Biomethane experience between them. Having successfully set up companies, developed world leading technology, created global sales and orchestrated the funding of 100's of £millions to support green energy operations, the team brings valuable experience to the industry and the green gas revolution.

As the world progresses towards the goal of Net Zero, the only way to hit targets involves a significant technological evolution. We are working on several enabling technologies that will help unlock Clean Energy and we have a dedicated R&D team supporting our significant investment in the future. Further to this, we also offer specialist in-house systems integration capabilities, with an emphasis on innovation and as a result, ensuring improvements in performance, productivity, reliability, and safety whilst also reducing costs.

The company is mainly senior engineers with experience in mechanical, electrical, software, chemical and materials engineering.

Bohr have worked with TNO (Delft, The Netherlands https://www.tno.nl/en/), Endet Limited and Progressive Energy (Stonehouse, UK https://www.progressive-energy.com/) on the core sensor technology which forms the basis for this project. TNO delivered the early-stage development and Bohr has the experience and capability to take early TRL technology and then fully develop and commercialise the product. Bohr will combine the core sensor technology with several aspects of existing IP and finalise the development in the coming months/years.

NPL will also be used as the testing centre for much of the laboratory tests required. We already have a history of working with NPL on previous projects and therefore, have a good understanding of their requirements, facilities and capabilities.

2.4 Project Need & Objectives

Real-time measurement for properties of green energy gases admixed with natural gas are of critical importance to the safety of the gas blend being used, but also will be pivotal in enabling a fair billing framework for consumers and process control efficiency. Further to this, at 100% hydrogen, there are additional challenges that need addressing. The amount of hydrogen in a fuel and the impurities in produced hydrogen are vital for safety, efficiency and life of functional power production. Our technology is centred upon providing fast, user-friendly, low cost means of measuring the properties in such fuel sources, as well as measuring the impurities when transitioning to 100%. Endet, the technical interface with key sub-contracts on this project, has a representative on the committee “CEN-CLC SF JTF H2 quality needs for industrial end-use”, and have been involved in understanding H2 quality in terms of industrial fuel switching. Bohr intend to use the results to support and help direct phase 2 of IFS.

The product is a unique hydrogen and natural gas analyser which can be retrofitted onto live, existing infrastructure. The product is small, inexpensive and simple to operate, allows practically real-time control/monitoring of gas composition for production, blending/injection, storage, transport/distribution and at end use. The technology is versatile and can give near real time compositional data of hydrocarbons, hydrogen, CO2 and Nitrogen and is being further developed for trace impurity measurement in 100% hydrogen. The quality of hydrogen for some applications and measurement techniques are specified in ISO standards, e.g. ISO 14687 & ISO 21087. Our technology potentially supersedes Best Available Technology for these applications and beyond that, existing technology that can monitor the quality according to those requirements/standards is a fundamental blocker (cost, complexity, availability) to a broad roll out of the hydrogen economy.

As a whole, the hydrogen strategy, regardless of how it is actually implemented over the next decades, will require 10s of thousands of quality measurement points and the core technology does not exist to support that. Our novel solution will potentially deliver a product that eliminates all of the major issues associated with current available technology.

The core technology has been developed over the past 5 years by TNO and the base sensor technology is covered by 2 patents. It was initially developed for biogas applications, but to develop a product that can analyse more compounds (i.e. impurities in 100% hydrogen) to monitor the quality of the hydrogen product, requires additional sensor coatings. The trace H_2S and H_2O sensor coatings have undergone initial laboratory trials and demonstrate performance that suggests that they can be further developed into a solution suitable for hydrogen quality analysis. Trace H_2O is at TRL5 having undergone testing of the sensor hardware combined with the coating. Trace H_2S is at TRL4 with the analytical performance of the coating and hardware having been validated, but the reversal from differing concentrations still to be tested. The low-level Methane and Carbon Monoxide sensor (from ppm to 1% levels) has undergone initial testing on the surface coating and shows promising results and is currently at TRL4. Combining this with the base hardware and testing at 10-100 µmol/mol (10-100 ppm) Methane in hydrogen, along with the reversal testing of the H_2S sensor, will bring all sensor technology from TRL4 to TRL5 as part of the feasibility study.

Alongside this, a desktop exercise will be performed to understand the feasibility of combining a previously developed Oxygen sensor into the product. This requires no additional testing, but the desktop study and theoretical evaluation will also form part of the feasibility study for inclusion in the demonstration phase if applicable.

By the completion of the Feasibility study, locations for Phase 2 demonstration trials, will have been finalised, along with site surveys to understand the industrial user and their existing equipment, control philosophy and general site requirements. This will allow a design brief to be completed for each site allowing a detailed costing exercise to be completed (conceptual design of the solution to be installed at each site, along with accurate costing for each installation including the design, build, internal test, site install and test, operation, maintenance and data aggregation and finally, decommissioning). Alongside this, by bringing all the sensor technology (i.e. impurity sensors and properties measurement) to a common TRL5+ by the end of the feasibility study, we can finalise the hardware to be utilised in the demonstration phase which will allow a batch of product to be accurately costed. Initial conversations with certification bodies will be complete and quotations received to achieve product certification (i.e. hazardous area approval).

If successful, the technology will overcome a significant hurdle to the wider adoption of hydrogen both when ad-mixed into Natural Gas and as a 100% fuel, by delivering a product which is small and low-enough cost to allow dramatic improvement to the operation of the wider gas distribution system.

By the end of phase 2 demonstration, the sensor technology for all measurements is anticipated to be at TRL 9.

Due to the project teams experience, the extensive testing already completed to date and also early stakeholder engagement, we know that the proposed approach is technically feasible and achievable in the industrial fuel switching timeframes.

To summarise the objectives of phase 1 and to direct readers to the relevant section of this report please see below;

- Create functional specification.
- Methane slip assessment: review the feasibility of the capacitive sensor array for the detection of trace concentrations of Methane.
- Oxygen assessment: review if this solution is compatible with the capacitive sensor array.
- Carbon Monoxide assessment: review if this solution is compatible with the capacitive sensor array.
- Humidity assessment: review best performing coating and implement into the sensor array.
- Hydrogen sulphide: Initial testing and optimisation of sensor coating for H_2S reversal.
- Engage with customers for demonstration phase and conduct site visits to potential demonstrator locations.
- Engineering design for demonstration phase, including detailed design of product.
- Costing demonstration phase and standard product, including proposal from BASEEFA.
- Complete trace Methane test programme.
- Complete trace H_2S test programme.
- Solution analysis, including RA, cost analysis, pro/con.
- Product commercialisation and roll out plan, including route to market.
- Job creation and carbon benefit analysis.
- Produce feasibility study report.

2.5 Project Work Packages (WP)

2.5.1 WP1 – Bohr Limited

WP1 is the overall management of the project, including managing the timetable, risks, deliverables and producing this final report.

2.5.2 WP2 – Bohr Limited

WP2 was to develop the content of the Phase 2 Demonstration and the technical/commercial progression of the sensor. This included working with stakeholders/customers to identify sites for the demonstration, developing the engineering design of both the sensor and the demonstration facilities, designing and building the test rig and assembling the sensors.

2.5.3 WP3 – TNO & Bohr Limited

WP3 had the following deliverables:

- Methane slip: An assessment of the feasibility of the capacitive sensor array for the detection of trace concentrations of Methane.
- Hydrogen sulphide: This sensor solution needed to be optimised for lower concentrations of H_2S, and made it fully reversible. The composition of the coating already available needed to be optimised.
- Humidity: The best performing coating was selected and implemented into the sensor array.
- Oxygen & CO: initial tests have been performed in earlier research. An assessment was be made if this solution is compatible with the capacitive sensor array.

2.5.4 WP4 – Progressive Energy, Endet & Bohr Limited

WP4 had the following deliverables:

- Concept Development. Endet assisted Bohr in the concept design of the instrument assembly, assessing technology options to ensure the package solution provided the necessary functionality at lowest cost.
- Functional Specification. Endet assisted in the development of the functional specification of the sensor alongside the other delivery partners to ensure the functionality of the sensor is able to provide meaningful value to the Hydrogen industry as standards and requirements evolve.
- Stakeholder Engagement. Endet & Progressive utilised extensive networks of key industry stakeholders, most notably standard setting bodies, to ensure the sensor and broader instrument assembly is in line with industry expectations.

2.5.5 WP5 – NPL, Endet & Bohr Limited

WP5 had the following deliverables:

- 45 days of research work
- Part 1: Testing of trace Methane in hydrogen sensor in μmol/mol region
- Part 2: Testing of trace hydrogen sulphide sensor in μmol/mol region
- Endet provided technical interface with NPL during testing regime.

2.6 Project Costs

During the application phase, the total project costs were proposed as follows;

- Total Labour (Bohr), Excluding Overheads: £59,812.41
- Total Overheads: £12,022.21
- Total Material Cost: £19,930.00
- Total Capital Equipment Cost: £0.00
- Total Subcontract Cost: £193,438.00
    - TNO: £110,210.00
    - NPL: £40,208.00
    - Progressive: £29,520.00
    - Endet: £13,500.00
- Total Travel & Subsistence Cost: £9,696.00
- Total: £294,898.61

However, since the initial proposal was submitted, a number have factors changed Bohr's projection.

This was discussed with BEIS at the earliest opportunity and Bohr were authorised to amend the project cost forecast and reallocation accordingly.

Revised projections are as follows:

- Total Labour (Bohr), Excluding Overheads: £71,021.34
- Total Overheads: £14,279.21
- Total Material Cost: £25,180.00
- Total Capital Equipment Cost: £0.00
- Total Subcontract Cost: £174,610.00
    - TNO: £96,860.00
    - NPL: £43,918.00
    - Progressive: £10,332.00
    - Endet: £23,500.00
- Total Travel & Subsistence Cost: £9,696.00
- Total: £294,786.55

2.7 Risk Assessment

ID NO.	RISK or HAZARD DESCRIPTION	IMPACT	EXISTING CONTROL MEASURES	PROBABILITY LEVEL	IMPACT LEVEL	PREVENTION MEASURES	ASSIGN TO
1	Failure to get customer engagement for trials	Limited test sites, minimising data capture and delaying commercialisation	Progressive control (directly or indirectly) several test sites. Early engagement with customers appears promising	Low	Medium	Early engagement during feasibility study	TW
2	Coatings fail to perform as expected	Limiting the analytes that the sensor can analyse, limiting future applications	Technology already at TRL 4 and so development to TRL 5 as part of feasibility study is aimed to mitigate future risk. Early laboratory testing up to TRL 4 promising. Its not black&white, all sensors can be adjusted and improved	Low	High	Early testing and development. Certain coatings may require additional development at start of demonstration phase to raise TRL level - this would not impact demonstration phase timetable	TK/AB
3	Coatings fail to perform as expected during NPL tests	Limiting the analytes that the sensor can analyse, limiting future applications	Initial testing and optimisation to be performed at TNO prior to testing	Low	High	Additional development at start of demonstration phase to raise TRL level - this would not impact demonstration phase timetable	TK
4	Availabiltiy of resource	Failure to deliver all tasks on time	Project plan in place. All stakeholders already engaged and resource assessment completed	Low	Medium	TNO & NPL are extremely large organisations and able to re-allocate or move resource to cover any unexpected absence	TK/HJ
5	COVID (or similar)	Impact to resource, 3rd party services, ability to travel	Video conferencing, ability to work from home	Low	Low	tbc	TK/HJ
6	Competing technology released	Minimise market share and future value	All stakeholders are engaged in the industry and up to date with technical developments. Not aware of any technology that offers the same broad benefits	Medium	Medium	Ensure comprehensive commercialisation plan established with robust routes to market and pricing, promote technology globally and comprehensively	TW
7	Failure to complete all the TNO sensor development on time. Due to the nature of the R&D programme, there is always a risk that unknown technical impacts arise	Delaying the start of the NPL tests	Flexibility in current project plan to accommodate slight slip. NPL can start testing on methane sensor and H2S sensor independently and in any order if required. TK to manage TNO test programme regularly	High	Low	Allow the test programme at NPL to be flexible to allow reorganisation of testing sequence. Ensure test rig is ready early	HB
8	Key staff (Tom Knight and Arjen Boersma) availability (i.e. through illness or injury)	Sensor development and/or overall feasibility project delivery risk	TK has full coverage and involvement by Tony Wimpenny who has significant experience running similar projects. AB has worked alongside Huib Blokland for 5-years on the sensor development. Junior scientists also available to supplement the test programme	Low	Medium	Ensure deputies remain fully engaged in the project	TK/HJ
9	Limited supply chain and global shortage of electronic components for PCB manufacturer	Sensor production for phase 2	Already purchasing long lead components and working with the supply chain to provide more options moving forward	Low	Medium	Supply chain engagement, already requested quotations for PCB manufacture. Bohr to progress with procurement in advance of phase 2 decision	HJ

This above risk assessment was continuously updated and reviewed throughout the duration of the project, with new mitigation measures being implemented as and when required. The final risk assessment was as follows:

Risk	Impact					
Likelihood		L	M/L	M	H/M	H/M
	L	1	1	0	0	0
	M/L	0	1	1	0	0
	M	0	0	0	0	0
	H/M	0	0	0	0	0
	H/M	0	0	0	0	0
Issues		0	0	0	0	0

Project Name	me Natural Gas and Hydrogen	Last updated	07/07/2022
Lead Company	Bohr Limited	Summary RAG	G

Risks

Risk Identification			Assessment		Mitigation				Risk/Issue Score		Review		
ID	Risk/Issue Description	Date Raised	Impact	Likelihood	Mitigation/ treatment	Post Mitigation Impact	Post Mitigation Likelihood	Mitigation Status	Risk Score	Risk Rating	Date of update	Next Review Date	Update and actions
~~ID 1~~	~~Failure to get customer engagement for trials~~	~~28/03/2022~~	~~Moderate~~	~~Closed~~	~~Early engagement during feasibility study~~	~~Marginal~~	~~Very Unlikely~~	~~Complete~~	~~2~~	~~G~~	~~01/07/2022~~		~~Customer engagement complete and very positive~~
~~ID 2~~	~~Coatings fail to perform as expected~~	~~28/03/2022~~	~~Critical~~	~~Closed~~	~~Early testing and development. Certain coatings may require additional development at start of demonstration phase to raise TRL level - this would not impact demonstration phase timetable~~	~~Marginal~~	~~Very Unlikely~~	~~Complete~~	~~2~~	~~G~~	~~07/07/2022~~		~~Initial assessment of coatings are complete and promising results obtained - testing now to prove coatings to be carried out by NPL.~~
ID 3	Coatings fail to perform as expected during NPL tests	28/03/2022	Critical	Unlikely	Additional development at start of demonstration phase to raise TRL level - this would not impact demonstration phase timetable	Marginal	Very Unlikely	Planned	8	AR	10/08/2022		Testing to be carried put by NPL during August
~~ID 4~~	~~Availabiltiy of resource~~	~~28/03/2022~~	~~Critical~~	~~Closed~~	~~TNO & NPL are extremely large organisations and able to re-allocate or move resource to cover any unexpected absence~~	~~Negligible~~	~~Very Unlikely~~	~~Complete~~	~~1~~	~~G~~	~~01/07/2022~~		~~Resource secured for duration of the project~~
ID 5	COVID (or similar)	28/03/2022	Marginal	Unlikely	Video conferencing, ability to work from home	Negligible	Very Unlikely	Planned	4	A	10/08/2022		No comment
ID 6	Competing technology released	28/03/2022	Critical	Possible	Ensure comprehensive commercialisation plan established with robust routes to market and pricing, promote technology globally and comprehensively	Moderate	Unlikely	Complete	6	AR	10/08/2022		All stakeholders are engaged in the industry and up to date with technical developments. Not aware of any technology that offers the same broad benefits
~~ID 7~~	~~Failure to complete all the TNO sensor development on time. Due to the nature of the R&D programme, there is always a risk that unknown technical impacts arise~~	~~28/03/2022~~	~~Marginal~~	~~Closed~~	~~Allow the test programme at NPL to be flexible to allow reorganisation of testing sequence. Ensure test rig is ready early~~	~~Negligible~~	~~Very Unlikely~~	~~Complete~~	~~1~~	~~G~~	~~10/08/2022~~		~~All sensors delivered in the necessary time frame~~
ID 8	Key staff (Tom Knight and Arjen Boersma) availability (i.e. through illness or injury)	28/03/2022	Moderate	Very Unlikely	Ensure deputies remain fully engaged in the project	Negligible	Very Unlikely	Planned	3	G	10/08/2022		TK has full coverage and involvement by Tony Wimpenny & Harry Jones who has significant experience running similar projects. AB has worked alongside Huib Blokland for 5-years on the sensor development. Junior scientists also available to supplement the test programme
~~ID 9~~	~~Limited supply chain and global shortage of electronic components for PCB manufacturer~~	~~28/03/2022~~	~~Moderate~~	~~Closed~~	~~Supply chain engagement, already requested quotations for PCB manufacture. Bohr to progress with procurement in advance of phase 2 decision~~	~~Marginal~~	~~Very Unlikely~~	~~Complete~~	~~2~~	~~G~~	~~07/07/2022~~		~~Low level methane sensors already in Bohr possession, H2S build in progress and all parts available.~~

2.8 Desktop Study

This desktop study was produced to help evidence the requirement for a real-time natural gas and hydrogen sensors and to demonstrate how it will enable the roll out of green energy gases.

As set out in the Government's Hydrogen Strategy, the UK intends to develop the first ever 'Hydrogen Economy' [1]. This is an economy which relies on Hydrogen as the main commercial fuel, which is a much more sustainable alternative to current energy sources. This 'Hydrogen Economy' is estimated to be worth £900 million by 2030, creating around 9000 new jobs [2]. To achieve this, a significant technological evolution is required, as the majority of commercial and domestic appliances currently installed will not operate on 100% hydrogen [3]. As a result, the government has studied the possibility of blending lower percentages of hydrogen into the network, and studies such as the HyDeploy trial at Keele University and Winlaton have shown that most appliances currently installed operate safely at 20% hydrogen blends [3] with very minor modifications. According to the ENA Gas Goes Green report, a blend of 20% hydrogen could result in a decrease in emissions of 6 million tonnes of CO_2-equivalent per year, equal to around 2.5 million cars off the road [4]. Hence, hydrogen blending is seen as an important steppingstone to the target of net-zero by 2050, allowing much-needed time to develop 100% hydrogen compatible appliances, and the government is set to release its blending policy in 2023.

This presents an urgent need to keep track of blending levels in order to fairly price gas supplies- 3 out of the 5 billing options presented by the Future Billing Methodology report require installation of new Calorific Value Determination Devices (CVDDs), up to a maximum of 44,000 devices across the UK [5]. It is also widely acknowledged by the authors of the report, that the other 2 options will also require "several 100s" of additional measurement points. These additional measurement points will enable gas networks to model the CV of the gas consumers receive, ensuring that they are billed fairly on the energy content of their gas. Currently, the recommendation is not to install these additional measurement points due to the high initial cost and vent requirements [5]. The real-time natural gas and hydrogen sensor which has formed the basis of this project is both inexpensive and zero emissions, and so has the potential to fill this gap in the market - helping to protect consumers from inaccurate pricing by enabling many more measurement points on which to base models.

Looking forward, the Hy4Heat reports have recommended that as a long-term fuel, a hydrogen purity of 98% is a satisfactory compromise between cost of production and effects on boilers [6]. Hence there will continue to be a market for low-cost and fast hydrogen purity analysis to enable a fair gas distribution system, with purity from 96-99+% still being discussed as viable solutions globally

According to the FBM, 'Large industrial loads connected to the LDZ network may be sensitive to sudden changes in the CV of gas being delivered at the meter, depending upon the type of equipment or process which is consuming the gas.' [5] This makes fuel switching an inherent risk for these businesses and creates an incentive for them to install their own analysis tools to aid the transition. However, current analysis solutions require a significant investment and have an unsuitable response time, hindering this process. The Bohr sensor technology may provide a solution for these industrial users looking for an analysis solution to independently monitor usage for billing purposes, or to optimise equipment in the face of changing gas quality. Fundamentally, despite the fact that many users can operate on a blended product (or a future 96+% product), the variations in the supply will have significant impacts in quality, efficiency and safety and this will impact commercial/industrial users in a much larger way than domestic users. This requires a dedicated focus, and a solution is required to allow fuel switching to become a viable strategy.

[1] *BEIS, "UK Hydrogen Strategy," 2021.*

[2] *BEIS, "UK government launches plan for a world-leading hydrogen economy," 2021.*

[3] *T. Isaac, "HyDeploy: The UK's First Hydrogen Blending Deployment Project," Clean Energy, vol. 3, no. 2, p. 114–125, June 2019.*

[4] *Energy Networks Association, "Gas Goes Green: Britain's Hydrogen Blending Delivery Plan," 2021.*

[5] *Cadent, "Future Billing Methodology: Recommendations," 2022.*

[6] *BEIS, "WP2: Hydrogen Purity," 2019.*

3 Sensor Development & Testing

There were 2 main aspects to the testing performed as part of this project:

1. Sensor assessment and selection (performed by TNO)
2. 3rd party testing (performed by NPL)

The combination of the 2 test elements was aimed at raising the TRL level of the sensing technology from TRL 4 & 5 (for the different analytes in question) to a consistent TRL 5.

3.1 Initial Assessments

Prior to starting the feasibility study, the following is a summary of the project team's understanding and expectations:

- Trace Methane – minimal testing had previously been completed for low level Methane as the sensing elements for methane were originally developed for Natural Gas and LNG and therefore all focus to date had been at the 70-100% Methane range. However, the ranges of Methane in question would be 100ppm up to 2%.
- Trace H_2S – some testing had been completed previously as part of early trials aimed at supporting the biogas industry. It had been established that the base PCB was relatively resilient to the H_2S at the concentrations in question. However, it is widely known that H_2S will relatively easily chemisorb onto a substrate, but desorption would be very difficult. In addition, other compounds in Natural Gas such as moisture would have a large impact on H_2S.
- Trace moisture – as with H_2S, some previous testing had been completed and demonstrated that the sensing chips could demonstrate good response to changes in trace moisture. However, the challenge was similar to H_2S in that it would be difficult to achieve the dry-down measurement. Additionally, previous experiments had shown a relatively slow response time, which may not be suitable for use in Hydrogen application. An alternative for the moisture, which would have significant benefit for the other readings, would be to utilise the moisture measurement as a way of correcting the other readings, which would all have some minor response to moisture.
- Oxygen – As stated in the original application, The measurement of Oxygen using this type of technology is not possible, however, alternative technologies that can be implemented at similar size/cost could potentially be integrated into a finished product alongside the other sensors. A desktop exercise would be performed to further understand this potential.

3.1.1 Sensor Assessment and Selection

A summary of the results from the TNO initial assessment and selection is included below:

3.1.1.1 Trace Methane

The assessment carried out by TNO demonstrated a linear response to changes in Methane concentration with a potential to measure accurately in the 0.05 to 2% range, which would be suitable for Industrial Fuel applications. At the lower end, as per the assumptions, the interference from moisture is expected to be significant, however, the initial assessment on moisture (see below) would allow the reading to be corrected. Due to the testing completed at TNO and in-house at Bohr, this technology is at TRL5. This TRL5 status can be reinforced by testing at NPL (see below).

3.1.1.2 H_2S

This measurement proved to be extremely challenging. There was a number of coatings generated and trialled and the results can broadly be allocated into 3 groups:

1. No measurable response to H_2S
2. Response, but poor reversibility
3. Response and reversibility

Of these 3 groups, only coatings included in group 3 are viable for progression. The main challenge with sensors in this group is the relatively low magnitude of response to the changes and a small element of losing accuracy over time (due to the reversibility). This would indicate that the sensors, as per their original development, would be more suitable to higher concentrations of H_2S, where the magnitude of the response is level-relevant. The best performing sensors were included for NPL testing. It is believed that the sensors could be further improved by the utilisation of an intermediate stage, for example heating the sensing surface after analysis, to support the reversibility. However, this would move the sensor away from our target market (ultra-low cost and remote power) and make it comparable to existing technologies.

3.1.1.3 Moisture

The moisture sensor had previously been developed as part of the development for an LNG market solution. Further desktop studies were carried out by TNO and a sensor element with high response to moisture has been selected for future use. As noted above, the relatively slow response time of the sensor will likely exclude it from some optimisation solutions, however it may still be suitable for use at the outlet of an electrolyser where there is little opportunity for real time adjustments, but overall performance is important and gas driers can be added/removed to optimise the process. Also as noted, the inclusion of a moisture sensor to be used as a correction for all the other sensors has significant merit due to the low cost of production and the significant improvement it can offer.

3.1.1.4 Oxygen

A desktop study was performed to understand the potential to include Oxygen in the suite of sensors included in the final product assembly. Very positive results were obtained by utilising an LED light as part of the sample process. As a standalone Oxygen sensor, this is extremely positive and is worth pursuing. However, as part of a low-cost sensor for Industrial Fuel switching, this solution does not currently fit with the potential product.

3.1.1.5 Overall

Based on the initial selection and trials at TNO, combined with work completed by Bohr (outside of the IFS trial but at the same time, looking at the response of the sensors at elevated temperature which indicates a way to optimise the sensors based on exposure to high temperatures during the production process), all of the sensing elements can be considered to be at TRL 5. However, the H_2S and Oxygen sensors do not appear to be suitable for the ultra-low cost finished product as per the target of this trial. These sensors have a significant commercial opportunity, but would unlikely form part of a product aimed at supporting the industrial fuel switch in the short term.

3.1.2 3RD Party Testing

The testing performed by NPL was to provide additional data to support the initial trials performed by TNO and Bohr. This testing was conducted on the trace Methane and trace H_2S sensors as selected by TNO. This stage of the testing was aimed at understanding the quantitative accuracy of the sensing elements and therefore included substantial effort producing and evaluating the test gases used (in contrast to the TNO testing which was looking to see the capacitance change in the sensors at different concentrations as a qualitative solution).

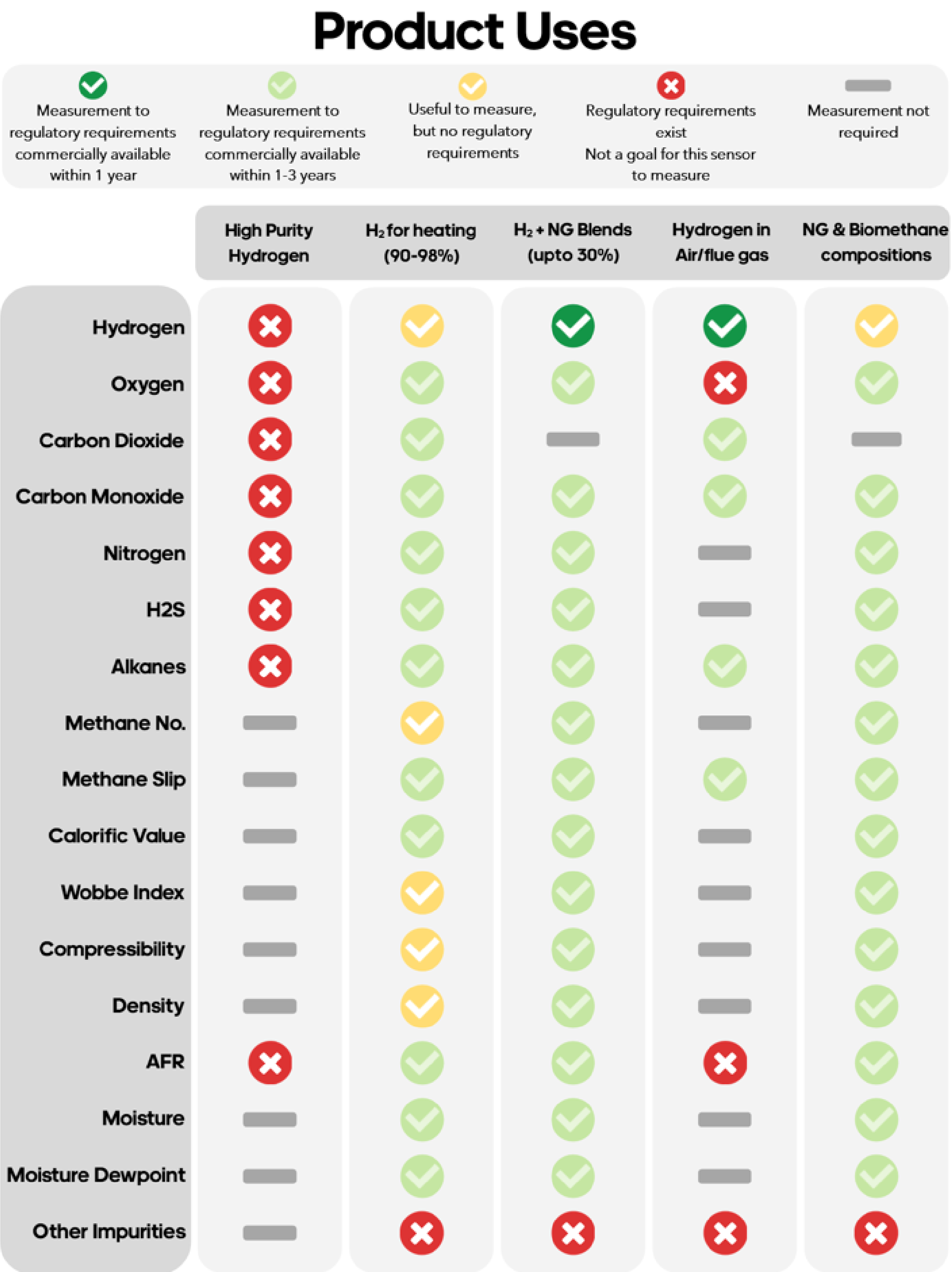
As part testing a gas delivery system containing two Methane sensors and two hydrogen sulphide sensors was calibrated and provided by Bohr Ltd, along with a data aggregation system. The sensors were for use with NPL primary reference materials containing nominally 500, 1000 and 5000 µmol mol-1 Methane in H2 and 10 and 100 µmol mol-1 H_2S in H_2. The test programme was complete as planned, but the results are proprietary and therefore, should not form part of the published report.

4 Sensor Functional Specification

There are a number of different aspects that should be considered while investigating the requirements for analysis as part of the transition to Hydrogen as an industrial fuel, including:

- Measuring impurities in 100% Hydrogen (High-Purity for PEM/Fuel Cell)
- Measuring impurities in 100% Hydrogen for Heat (>96% Hydrogen with high ppm to % Level Contamination)
- Measuring composition of hydrogen and natural gas blends
- Measuring Hydrogen in air blends
- Natural gas and biomethane compositions

The sensor's current capabilities, long term goals, and uses are summarised as follows:



4.1 Hydrogen for Heat Specifications

Measurement	Accuracy*	Detection Limits*	Regulatory Requirement (Proposed)[1]	Notes
Hydrogen	≤ 0.1 %	95 – 100%	98%	
Carbon monoxide	No current requirement	No current requirement	20ppm	
H2S	± 0.1 mg m^{-3}	0 – 6	≤ 5 mg m^{-3}	
Sulphur	± 1 mg m^{-3}	0 – 60	≤ 50 mg m^{-3}	
Oxygen	±0.01 mole%	0 – 0.25	≤ 0.2 %	
Hydrocarbon Dewpoint	± 2 °C	-60 – 20	-2 °C	Measurement not a target for the analyser
Water Dewpoint	± 2 °C	-30 - +10	-10 °C	
Carbon Dioxide	≤ 0.5 %	0 – 50 %	Sum of methane, CO_2, and total hydrocarbons ≤ 1 %	
Total Hydrocarbons	No current requirement	No current requirement		
Methane	≤ 1 %	20 – 100 %		
Total inert	± 0.1 mole%	1 – 10 mole%	≤ 2 %	
Wobbe No	± 0.1 MJ/SCM	45 – 55	42 – 46 MJ m^{-3}	
Other impurities (solid or liquid material)	Not available	Not Available	Shall not contain material that may interfere with operation	Measurement not a target for the analyser
Moisture	No current requirement	No current requirement	N/A	
Methane No	No current requirement	No current requirement	N/A	
CV	± 0.1 MJ/SCM	35 - 44	N/A	
Compressibility	No current requirement	No current requirement	N/A	
Relative Density	± 0.01	0.5 – 0.	N/A	
AFR	No current requirement	No current requirement	N/A	

*Taken as a guide from a sample grid entry agreement[4], so subject to change.

4.2 H_2 and Natural Gas Blend Specifications:

Measurement	Accuracy*	Detection Limits*	Regulatory Requirement**	Notes
Hydrogen	≤ 0.1 %	No current requirement	No current requirement	
Oxygen	± 0.01 mole%	0 – 0.25	≤ 0.2%	
Carbon dioxide	4% of measurement	0 – 5	No current requirement	
Hydrocarbons	No current requirement	No current requirement	No current requirement	
Nitrogen	4% of measurement	0 – 10	No current requirement	
H2S	± 0.01 mg/CM	0 – 6	≤ 5 mg/m^3	
CV	± 0.1 MJ/SCM	35 – 44	No current requirement	
Wobbe Index	± 0.1 MJ/SCM	45 – 55	47.20 ≤ WN ≥ 51.41	
Compressibility	No current requirement	No current requirement	No current requirement	
Relative Density	± 0.1	0.5 – 0.8	No current requirement	
AFR	No current requirement	No current requirement	No current requirement	
Moisture	No current requirement	Low level ppm**	No current requirement	
Methane No	No current requirement	No current requirement	No current requirement	
ICF	± 0.02	-3 – 2	≤ 0.48	Measurement not a target for the analyser
SI	± 0.02	0 – 1	≤ 0.60	Measurement not a target for the analyser
Moisture Dewpoint	± 2 °C	-30 – 10	Shall not interfere with pipes or appliances	

*Taken as a guide from a sample grid entry agreement[4], so subject to change.

** Based on current GS(M)R regulation[2], as no blending-specific standards are currently available.

4.3 Natural Gas/ Biomethane Specifications:

Measurement	Accuracy*	Detection Limits*	Regulatory Requirement[2]	Notes
Hydrogen	≤ 0.1 %	0 – 20 %	≤ 0.1 %	
Oxygen	± 0.01 mole%	0 – 0.25	≤ 0.2 %	
Carbon dioxide	4% of measurement	0 – 5	N/A	
Hydrocarbons	No current regulation	No current regulation	N/A	
Nitrogen	4% of measurement	0 – 10	N/A	
H2S	± 0.01 mg/CM	0 – 6	≤ 5 mg/m^3	
CV	± 0.1 MJ/SCM	35 – 44	N/A	
Wobbe Index	± 0.1 MJ/SCM	45 – 55	47.20 ≤ WN ≥ 51.41	
Density	± 0.1	0.5 – 0.8	N/A	
Moisture	No current regulation	Low level ppm**	N/A	
ICF	± 0.02	-3 – 2	≤ 0.48	Measurement not a target for the analyser
SI	± 0.02	0 – 1	≤ 0.60	Measurement not a target for the analyser
Moisture/ Hydrocarbon Dewpoint	± 2 °C	-30 – 10	Shall not interfere with pipes or appliances	
Other impurities (solid or liquid material)	± 0.01 mole%	0 – 0.25	Shall not contain material that may interfere with operation	Measurement not a target for the analyser

*Taken as a guide from a sample grid entry agreement[4], so subject to contextual specificities.

4.4 Flue Gas Specifications:

Measurement of waste gas from stationary sources is governed by many standards subject to the application, including EN15267-3. Aside from this, industrial users have an interest in measuring flue gases for several reasons:

- Monitor and control emission components to meet government requirements, local/international standards, business/operational targets, incentives and fines, including EU ETS.
- Increase efficiency and/or safety by dynamically changing the level of excess air injected, in order to keep the composition below the safety limits determined by the LEL (lower explosive limit) of the individual gases or maximise uptime of the process.

Example requirements for flue gas applications relating to a potential fuel switch could include:

Measurement	Accuracy[4]	Detection Limits[4]	LEL
Hydrogen	≤ 0.1 %	0 – 20 %	4%
Oxygen	± 0.01 mole%	0 – 0.25	N/A
Carbon dioxide	<0.5%	0 – 50 %	N/A
Carbon monoxide	No current requirement	No current requirement	12%
H2S	± 0.01 mg/CM	0 – 6	4.3%
Moisture	No current regulation	Low level ppm**	N/A

5 Customer Engagement & Engineering Design

As part of this project, Bohr planned to identify 4-6 sites which would be interested in supporting Phase 2 of IFS, the demonstration phase. Through various formal and informal discussions with customers across the industrial market (both UK and international), there were a significant number of interested parties. **ALL** industrial users indicated a desire to have real time knowledge of the gas and expressed a concern regarding the future gas matrix. They had a concern relating to the CV and WI of the future gas (Natural Gas + up to 20% H_2 and 100% H_2 which could be 96% with various amounts of Methane and inert gases). There was much less concern amongst industrial users regarding the trace components within the gas, as the general assumption was that the producers and gas networks would perform that analysis and ensure that all contaminants were within defined limits in advance of it reaching them and the contaminants would be similar to those found in the current Natural Gas supply. The exception to this was whether or not Methane (and other Hydrocarbons) present in “100%” H_2 would be classed as contamination – however, the concern here was related to the impact on the CV and WI, not the fouling potential or safety implication of the contaminant.

There was a general consensus that even in today’s gas network, insufficient knowledge existed regarding the CV of the gas and significant potential existed to optimise efficiency (for example, a large industrial user in Humberside identified that they run all their boilers with a minimum 10% excess air. With real time knowledge of the CV, this could be substantially reduced leading to £millions per year savings and significantly reducing environmental footprint).

In contrast, producers of the Hydrogen showed relatively little interest in having new, low-cost measurement technology. There was a general desire to have lower cost technology, but this was seen as “business as usual” aim to reduce operating expense, not a blocker to the deployment of their solutions. Their focus was much more on the big picture roll out of their technology, not the relatively small cost savings. However, this cost saving is significant if you consider a national transition to Hydrogen. For example, a major European electrolyser manufacturer utilise both an Oxygen and a moisture analyser in their current solution. This package costs them ~£21k to install in equipment worth on average £4.2million for current projects. Being able to install this equipment for £18k less is appealing, but it isn’t going to result in additional sales.

For the above reasons, the main focus for phase 2 was decided to be on the industrial users of the gas (and the gas networks) as the solution would enable the transition, instead of the producers of the gas who would likely be a customer for the product once developed, but didn’t have this development as a critical path.

The sites/users chosen for the Phase 2 demonstrations were:

Site ID	Details
001	A major European project aimed at developing offshore renewables, with an offshore electrolyser to blend Hydrogen into the European Gas Transmission (High Pressure) network.
002	An existing Biogas/Biomethane facility. Despite the fact that Hydrogen is generated during the acetogenesis phase of the AD process, if a plant is running correctly, it should then be converted to Methane during the methanogenesis phase. For this reason, the measurement of Hydrogen is risk assessed out of the gas quality measurements performed. The trial at serves many purposes including: Confirms the absence of Hydrogen; Proves the suitability of the technology for Biomethane (likely to be an increasing percentage of the future gas network)
003	A research organisation supporting aerospace, ceramics, energy, bio, etc. The site for the trials would be the customer's own research facility that can run on blends up to 100% hydrogen. This will allow demonstration of the technology, integration with a control system and more importantly, allow widespread user knowledge of a potential solution
004	A global testing and inspection facility. The customer has recently built a Hydrogen production (via steam methane reformation) plant at their facility. Utilising Bohr's technology will give the customer and their global customer base knowledge of the live gas matrix and an understanding of the impact of changing CV/WI and other contaminants in the gas.
005	A large non-UK based utility and Gas Distribution company. Because of the current lack of UK gas blending trials.
006	A Novel Hydrogen Production Facility are developing a potentially transforming technology for Hydrogen production

The above is a brief summary of each site. The full site survey and engineering design of the phase 2 installation is proprietary and is therefore, not available in the published report.

The site surveys identified several aspects, all of which are covered in the engineering design:

1. Physical location and constraints for a solution
2. Measurement required (1 or more per site, for example, a site might have 1 measurement location to analyse moisture, Methane, Hydrogen and gas properties. Alternatively, a site might only require CV to be measured, but it might be in several locations at a site, or alternatively, a site may have a requirement to measure 1 or more analyte across multiple locations on the site)
3. Means of validating the measurement. As this is a novel technology, validation of the accuracy and response will be required for the trials. Some sites might already have measurement solutions (albeit significantly more expensive than the proposed solution) to allow a comparison, other sites might not have a solution and so a technology will need to be installed, or a means to validate the results included
4. How the data will be used. This may simply be analysing the gas and recording the data for offline assessment, however, there may be an opportunity to build the live data into the site operating controls to deliver immediate benefits for the end user.

6 Project Development Plans for Phase 2

The original plan, as detailed in the Phase 1 application, is both vitally important and required by the industrial market to support Industrial Fuel Switching. The economic and environmental viability of Hydrogen fuel switching is entirely dependent on being able to accurately measure. Whether it is Hydrogen fuel quality (i.e. 96-100% Hydrogen) and the impact that will have on gas infrastructure, cost to produce, emissions, useability, etc.; or the overall emissions and efficiency of production; or the safety of use. All of these aspects require analytical technologies and a significant reduction in the cost and complexity of these technologies will be a direct enabler of the transition to Hydrogen. Further, by making these new technologies zero emissions and plug and play, will have a substantial direct impact on the carbon footprint of future projects.

6.1 Phase 2 – Plan

6.1.1 Project Summary

The plan for Phase 2 is to install the sensors at the sites detailed and allow them to operate alongside current Best Available Technology to prove that the low cost and simple alternative is suitable for the market. Current Hydrogen blending projects have analytical solutions that cost in the region of £100,000+ per site which is a major impact on the overall CAPEX cost of the project. In addition, each installation has significant ongoing (often daily) operating requirements, and the equipment continually vents gas to the atmosphere, in the region of 1-2NL/min per site (24hrs a day). The anticipated solution to be available by the end of Phase 2 will have zero emissions, zero ongoing costs and can be installed for <£5,000.

To achieve this, the sensor cells will need to undergo final design and development, develop a calibration process, build and certify the units. These units will then be installed as part of a site-specific project including utilising the data for control functionality where possible.

Alongside this, work will progress the overall design and build of the sensor to significantly reduce costs and improve repeatability ready for global commercialisation at the end of the project.

6.1.2 Product installations

Phase 2 (the demonstration phase) will involve the installation of the sensor at 6 locations in the Hydrogen chain.

The basis of the demonstration is to install 3 sensors (for redundancy/comparison) at each measurement point on each site/application to give a broad data set to show repeatability and durability for each application. The solution for each install location will vary slightly as each industrial user will have differing requirements for the data as detailed in the engineering design packs.

To provide a comparison/validation of the technology, we will design and install a Best Available solution which meets or exceeds global ISO standards and is acceptable to the wider industry for quality analysis. This will allow us to monitor the gas properties in each monitoring application in practically real-time and validate the novel technology meets or exceeds Best Available while eliminating emissions and at a fraction of the cost, improved response time and minimum maintenance. This will prove the technology can enable the nationwide fuel switching plan. It is planned to allow each installation to operate for approximately 9-12 months as this will allow the technology to be proven during different fuel loads (seasonal variations, consumption changes, ambient conditions, etc.). As detailed in the engineering design section of this report, some of the sites have existing, very high quality solutions in place which will allow the comparison/validation and therefore reduces the Phase 2 costs for those sites.

The demonstration will show that the novel technology provides results which meet, or exceed, Best Available Technologies and can therefore be accepted by industry and certified to various standards and codes, globally. The physical, real-world demonstration with customers can be used as prior experience when discussing the technology with new customers (a pre-requisite for many companies in this industry).

We have experience working with many of the technology providers, transmission/distribution companies and end users and we are familiar with the vendor list requirements (ISO 9001, supplier audits, H&S requirements, qualifications and experience, site certification and induction, etc.). Bohr will carry all the required certifications and qualifications to be able to design, build, install, operate and decommission the systems which could introduce significant project risk for other companies.

The main barrier to commercialisation is competition from multi-nationals that wish to maintain the status quo with technology they provide, achieved by controlling the writing/adoption of standards/codes, contracts and by providing preferential delivery and pricing to customers that use their products exclusively. The Bohr team has experience of commercialisation of related technologies and through this experience we are key contributors to many relevant international standards to ensure a level playing field; are recognised by the global community and regularly present at conferences; are regular contributors and technical experts to support major projects for oil and gas, industrial gas and OEM majors; have a broad contact list with established partners/reps; are already engaged with key stakeholders within the industry that are leading the way to a decarbonised gas network and have actively been involved in previous industrial fuel switching projects in the UK.

6.1.3 Commercialisation and Product Development

During the application for phase 1, we anticipated that the next step in commercialisation, after phase-2, would be final "productisation", which would include a final design for the sensor housing, packaged interface electronics, proposed solutions for ancillary equipment (such as remote telemetry), final certification and branding. However, due to the market interest and demand for this product range, the plan would now involve completing the productisation alongside the phase 2 project, which would allow immediate commercial sales at the end of the project.

The entire process of finalising the product will now be complete to coincide with completing the phase 2 demonstration. The next steps, which will vary by customer/country, will be ongoing sales effort, including training reps and technical presentations to customers. First sales are expected immediately based on early discussions with customers and global sales to 5+ countries expected within 12 months on completion of phase 2.

A key aspect of phase 2 will be transitioning the build from a very labour-intensive process, performed by certain individuals to something that can be mass produced.

7 Costing

Following a comprehensive costing exercise, the estimated costs for Phase 2 is **£1,971,710.53**. The breakdown of these costs is proprietary and therefore, is not available in the published report.

8 Commercialisation & Roll Out Plan

8.1 Introduction

The Bohr sensor has been developed to enable and facilitate the decarbonisation of gas in gas networks and industry. Multiple prospective users and applications (some existing, some emerging) have been identified where the sensor can accelerate fuel switching and decarbonisation programmes.

To maximise the value of the work completed under this project, the sensor must be fully industrialised and commercialised and available to the open (global) market for purchase, at a reasonable price point and within an appropriate timeframe with regards to legislated and industry-led targets and commitments.

8.2 Requirements

For the rollout of the sensor to be successful, a number of requirements must be clarified and agreed with stake holders, and incorporated into the design and rollout plan. A summary of the different types of requirements are outlined in this section.

8.2.1 Safety

For the instrument to be adopted by gas networks and industry, the device must meet some minimum safety requirements, as required by the Health and Safety Executive (HSE) and legislative regulations, such as UKEx (the certification for equipment to be used in hazardous areas).

Furthermore, installations should be designed to conform to these and other regulations and standards governed by the gas networks and the Institution for Gas Engineers and Managers (IGEM).

Finally, the rollout and installation of devices on the gas networks and at industrial facilities must be done in accordance with site specific requirements and have appropriate permits, risks assessments and method statements in place (as required) prior to works being completed. Bohr has significant experience in both design and installation of such equipment and systems in these environments and is fully aware of general requirements and able to meet site-specific safety requirements, in addition to its own practices and policies of safe working, under which all employees operate.

8.2.2 Performance

The performance requirements of the sensor will differ depending on the application and the requirements of the specific user / stake holders. In general, fast and low-cost gas quality data is desperately sought. Stake holder engagement is repeatedly cited as an important element of the commercialisation and rollout of this technology, since it is capable to be deployed in unprecedented numbers and applications.

8.2.3 Total cost of ownership (TCO)

The total cost of ownership (TCO) of the sensor is an important success factor in widespread rollout of the device and benefits to the industry and consumers alike. Failure to provide a commercialised instrument that is not only a suitable unit cost, but can be effective to install, operate and maintain, will inhibit the success and benefits. The TCO is made up of a number of costs that are not always appropriately assessed and compared when evaluating instruments to be used on the gas network or in industry. TCO includes, but is not limited to:

- Capital expenditure (CAPEX)
    - Unit cost
    - Ancillary equipment costs (with conventional gas analysers, this can be multiples higher than the actual unit cost)
    - Installation cost, including labour and consumable materials
    - Commissioning costs, including specialty gases, skilled labour
- Operational expenditure (OPEX)
    - Utilities
    - Consumables (with conventional analysers, expensive calibration and carrier gases are continuously consumed and then vented to atmosphere)
    - Maintenance costs
        - Labour for routine and ad-hoc servicing requirements
        - Spare parts
        - Specialty gases (if required by the instrument or the appropriate authority)
- End of life costs
    - Replacement costs
    - Decommissioning
    - Uninstallation
    - Disposal or recycling
- Miscellaneous costs
    - Engineering and administrative costs associated with installation/uninstallation (not always covered in other costs above)
    - Training of resource in the operation of the instrument
    - Environmental costs/benefits of carbon footprint/reduction

The Bohr sensor has been designed to offer significant improvement in all aspects of the TCO, with a huge TCO saving overall. Not included in the above, are additional cost benefits to the user, such as:

- Fuel consumption reduction (fuel bill)
- Combustion efficiency improvement (better use of energy / reduce wasted energy)
- Emissions reduction (emissions / carbon accounting)
- Less product contamination / wastage from unknowingly using poor or variable quality gas

The environmental benefit of Bohr's zero emission technology is significant, although today there are no direct costs / penalties associated with the continuous venting of sample gas, carrier gas or calibration gas from analysis equipment to atmosphere (as is the norm with the vast majority of gas analysis equipment available today).

8.2.4 Other Requirements

Other requirements that have been taken into consideration include lifetime costs, availability and reliability, but the details of which are proprietary and are therefore, not available in the published report.

8.3 Risks

The following risks and risk mitigations associated with commercial rollout of the sensor have been identified:

Risk	Risk Mitigation
Insufficient funding to progress development	Robust application for IFS phase 2 funding. Continue revenue-generating business activities to safeguard business continuity.
Unknown or shifting requirements – decoupled from design and rollout programme	Timely stake holder engagement and regular communication
Alternative analyser technology selection/deployment	Market vigilance and continued development at pace, to maintain first-mover, BAT advantage
Operational rollout issues – access, site owner labour constraints, logistical issues	Early engagement with site custodians and detailed implementation planning
Government policy or legislation changes to inhibit or prohibit decarbonisation of gas	Keep abreast of communications and advise Government on opportunities for gas.

8.4 Summary

The sensor technology has a huge opportunity to enable industrial fuel switching projects, through gas analysis in multiple applications.

In order to achieve its potential benefit to industry and society, the sensor must achieve the following steps:

- Demonstration of the technology capability (note: a funded demonstration opportunity such as IFS2 is absolutely critical to achieve this, and a key enabler to subsequent phases)
- Stake holder engagement and requirements agreement
- Design developments and certification
- Supporting analytical studies and beta testing of commercialised instruments
- Ramp up of sales and manufacturing activities to support the breadth of industry throughout the energy transition, starting as soon as possible with improved efficiency and costs of distribution and consumption of existing grid gas.

9 Job Creation & Social Value

To support the ongoing development of the sensor to which this funded project relates, Bohr employed a full-time data analyst with a Mathematics degree, who's role is to interpret data gathered from instrumentation into a meaningful outcome, through data aggregation, processing, trending, comparison and interpretation. This person is expected to play an important role in the ongoing development of new and extended capability, through lab and field data analysis, should the development of the sensor technology continue as hoped.

Through delivery of this feasibility study, Bohr has directly and indirectly engaged a large number of critical energy infrastructure and industrial companies. This has raised significant awareness of the rising challenges surrounded variable gas quality and the pending obstacles to decarbonisation of gas. In turn, this has raised the visibility, profile and value of the work Bohr is doing for the global gas industry and industry in general; and generated interest in further work that Bohr hope to complete as part of IFS phase 2.

Phase 2 of the IFS funding represents a critical steppingstone for Bohr: moving status from an informed and innovative theoretical consultant with some novel technology in development, to an agile deliverer of solutions and value to industry. It is this profile upgrade that is a key enabler to customer confidence and engagement for the next steps of development of the core sensor technology and the Bohr business plan in general. Without this investment and direction, Bohr will be obliged to seek funding (at the cost of significant share ownership of the business) or to continue development as a "nice to have" on the side of the revenue generating parts of the business, which cannot survive if focusing on sensor development alone.

Upon successful award of the Phase 2 Demonstrator, there will be a further 7 full-time positions created from design through to build and installation/commissioning. There will also be a requirement to build an assembly and test facility with the creation of 3-4 full-time high specification technician roles. Beyond this, there will be a need for broader team reinforcement, including sales, engineering, commissioning and technical support, ensuring the UK is the centre of excellence for hydrogen purity, hydrogen blending and other sampling, analysis and measurement disciplines. The team will support the global market with sales, technical support, training and engineering.

Building up this team and the capabilities of the technology on offer will provide significant export opportunities too. The technology is something that will be required on gas networks and industrial applications all over the world and therefore, once proven through the industrial fuel switching programme, opportunity for export is expected to grow significantly. The testing that we are also doing as part of the A4I programme, extending the temperature range of the sensor to -40C to +70C (ambient & process temperature) will also mean that it will be suitable for deployment anywhere in the world, with no ancillary heating/cooling. The team at Bohr also already has valuable experience in export, having worked in previously roles supplying products and solutions around the globe, which minimises any potential risks.

Bohr has a fair and comprehensive recruitment strategy, which will provide equal opportunity for all candidates, including those that have previously faced employment barriers. As explained above, we anticipate to be recruiting for a range of different roles, requiring a variety of skills and assets. Some of the roles required will be specialist to the products and industry Bohr operate in, but we will fully support new employees with all the necessary training, courses and qualifications required for the role. Near enough all of the roles will be in a high growth sector and the skills will be transferable, as the UK transitions to low carbon energy. Bohr will actively look to offer work experience and internships to engineering students looking to further develop their skills and knowledge during degree level courses, and this is something that the team at Bohr have already successfully done in previous roles. Every member of the team will have a skills and training matrix, identifying project-specific required competencies, employee competency and any shortfalls that need fulfilling. From this we will identify the required training and courses to address the skill gaps. To further support employee development, Bohr will ensure all staff are encouraged to join industry specific webinars, conferences and register with relevant affiliations, for example IGEM. Longer terms prospects include apprenticeships, traineeships and T Level industry placement opportunities, with clear progression paths and opportunities to succeed.

10 Carbon Benefit Analysis

There are three keys ways in which the technology presented in this project provides a significant reduction in carbon emissions. Firstly, technology such as this must be implemented to enable the industrial acceptance of largescale hydrogen/biomethane/alternative fuels in the gas network and to also ensure accurate billing to consumers and ensuring a safe gas blend is entering people's homes and for use by large industrial users. It is widely estimated that a switch of only 20% hydrogen in the natural gas blend will offer a saving of 6 million tonnes of CO2 emissions per year. Currently the opportunity to transition to this low carbon fuel is restrained due to the inability to correctly monitor/control the fuel they are using.

Secondly, in addition to the indirect savings that will be delivered by enabling the fuel switch is the direct savings by eliminating gas venting during analysis. Current Best Available Technology (such as chromatography) require the gas used for analysis to be vented, typically ~0.5L/min to atmosphere, and based on current installations, eliminating this will result in savings from 2,800-30,000tonnes of CO2 per year. Furthermore, based on the projections in Future Billing Methodology where 5-44,000 installations are potentially required (many of which would also be necessary for widescale industrial fuel switching), this relates to a saving of 1.3 to 11million cubic meters of natural gas/hydrogen being vented to atmosphere each year.

Finally, the technology has the ability to positively and immediately impact the UK carbon emissions, even prior to the adoption of Hydrogen. Based on HM Governments "The Industrial Decarbonisation Strategy", 16% (72 Mt CO2e) of UK emissions are from Industry. Based on previous studies performed by industry experts on behalf of Bohr, we have seen an opportunity to reduce fuel consumption by 9% for typical industrial process using Natural Gas as a fuel (glass and paper manufacturing, metals, ceramics, etc.). This is possible by having live, real time knowledge of the gas quality being used by the process and allowing efficiencies to be obtained by optimising air-fuel ratio. Typical examples of this are highlighted by 2 discussions that took place during Phase 1 customer engagement (and actually indicate real-world optimisation to far exceed the 9% from our studies):

1. Chemical facility – burning a minimum 10% excess air and running burners at 80% of output as a safety factor, which results in 10% additional air being heated and failing to achieve maximum efficiency of the burner
2. Small gas-electricity facility in Teeside operating at a maximum 78% output, despite the massive demand for electricity due to engine knocking and trips as a result of varying gas quality. The engines were only able to operate for 80% of the day and at reduced output.

By achieving a reduction in fuel of 9% and taking a very broad assumption that 40% of the 72MT CO2e come from Natural Gas as the fuel source (BEIS UK Greenhouse Emissions 2020) there would be immediate savings for the UK of 2.59Mt CO2e, and this can be implemented in advance of an industrial fuel switch.

In addition, this improvement would not only apply to Industry as mentioned above, but would directly impact energy production and many other areas of the UK's current emissions so the CO2e savings would be far greater.

11 Dissemination Plans

Throughout the duration of the project, Bohr have been conducting various dissemination activities to support the efforts in unlocking barriers to a decarbonised industry. Since the conception of the project, Bohr have attended the GAS 2022 symposium in Paris, the World Gas Conference in South Korea, Gastech 2022 in Milan, Hydrogen & Fuel Cells in Birmingham, IGEM North East Section Innovation Event in Harrogate, Innovate UKs GBIP Industrial Clean Growth in Israel, Innovate UKs GBIP Hydrogen in South Korea and other events, where Bohr have either presented to industry experts or discussed via the exhibition hall the industry challenges and the objectives of Bohr's contribution to the Industrial Fuel Switching Programme.

In parallel, Bohr have had a continued involvement in a number of UK, European and Global standards, including BSI, ISO, GPA, ISA, IGEM and CEN standards. Representatives from Bohr have continued to support these committees, presenting the project for the Industrial Fuel Switching programme as part of that, in order to support to keep the industry up to date with the latest technological advancements on the path to Net Zero.

Another significant activity Bohr delivered during the project included hosting a working group for all of the gas networks and other key industry representatives to demonstrate the sensor development on the HyDeploy 2 project at Winlaton, in the North east. Even though this installation did not directly form part of the project, it was an ideal platform to discuss the technology, the Industrial Fuel Switching programme and future analytical requirements with a group of experts.

Moving forward Bohr already have several conferences lined up to present this technology and the Industrial Fuel Switching programme, this includes the Green Gas Day 22 in Birmingham, the Energy Networks Innovation Conference in Glasgow and much more in 2023. Bohr will also continue to support the various committees and working groups stated above, presenting the findings from the project and the feasibility of a sensor such as this one to enable the fuel switch.

Further to this, Bohr are also active on social media, primarily LinkedIn, and will therefore, be posting press releases and reports on the platform for the industry to see and digest. Finally, Bohr are exploring the possibility of producing a co-authored journal with TNO for publication on the internet on sites such as Science Direct.

A summary of the dissemination activities performed to date is as follows;

Activity	Title	Status	Comments
Press Release	Press Release	Complete	Press release on contract award
Press Release	Press Release	Planned	Press release on completion of project
Conference Paper	World Gas Conference	Complete	3 off Technical papers presented
Conference Paper	Gas Analysis Symposium	Complete	1 off Technical paper presented
Exhibition	IGEM NE&Y	Complete	Discussions with many industry experts
Exhibition	Hydrogen & Fuel Cells	Complete	Discussions with many industry experts
Stakeholder Engagement	Stakeholder Engagement	Complete	20+ customers discussed with
Working Group - HyDeploy	Stakeholder Engagement	Complete	10 key industry companies
Working Group	GBIP Israel	Complete	Full week, back-to-back meetings discussing clean energy
Working Group	GBIP Korea	Complete	Full week, back-to-back meetings discussing hydrogen
Exhibition	Green Gas Day	Planned	Discussions with many industry experts
Exhibition	Energy Networks Innovation Conference	Planned	Discussions with many industry experts
Standards / Committees	Standards / Committees	Ongoing	Standards / Committees

12 Conclusion

The key aims and objectives of the project were to conduct an initial assessment into the feasibility of low-level measurements of trace contaminants to support Industrial Fuel Switching, conduct laboratory testing on the Methane and Hydrogen sulphide sensors (helping to ensure the sensors are at a TRL5 by the end of the project), desktop studies into the feasibility of Oxygen and moisture sensors, engage with customers with regards demonstrating the technology as part phase 2 of IFS, engineering design for 6 sites interested in being involved in phase 2, cost a phase 2 application, develop and detail a commercialisation roll-out plan and discuss job creation and carbon benefit of the project.

The sensor technology will be a direct enabler for the Hydrogen/Natural Gas/Biomethane blend that is anticipated for the next 10+ years. The additional trace measurement sensors would have a significant cost and complexity reduction for blending projects, however, their main benefit, should the sensors all reach a future TRL 9+, would be immediate direct and indirect emissions benefits and significant CAPEX reduction, for the future 100% Hydrogen networks – all aspects of the technology will have substantial impact on enabling the industrial fuel switch.

The initial assessment into the sensors was carried out by TNO, who are responsible for the original development of the core sensor technology. TNO developed, investigated and tested various sensor chip coatings for Methane, Oxygen, moisture and Hydrogen sulphide. Based on the initial selection and trials at TNO, combined with work completed by Bohr (outside of the IFS trial but at the same time, looking at the response of the sensors at elevated temperature which indicates a way to optimise the sensors based on exposure to high temperatures during the production process), all of the sensing elements can be considered to be at TRL 5. However, the H2S and Oxygen sensors do not appear to be suitable for the ultra-low cost finished product as per the target of this trial. These sensors have a significant commercial opportunity, but would unlikely form part of a product aimed at supporting the industrial fuel switch in the short term.

The laboratory testing, simulating a relevant environment, was conducted by NPL in Teddington, UK. The best performing Methane and Hydrogen sulphide sensors were selected, based on the initial assessment process and supplied to NPL along with a sample delivery system and a data aggregation system.

The customer engagement part of the project was enormously successful. Bohr reached out to 20+ customers throughout the duration of the study and they all indicated a desire to have real-time knowledge of the gas quality and demonstrated a concern regarding the future gas matrix. These positive discussions demonstrated the importance of this project and the requirement for technology such as this. Six of the customers were carefully selected to cover a range of different applications throughout the industry, including gas transmission, gas fired furnaces, biomethane facilities, testing facilities and hydrogen production. Bohr completed a site survey on each of the sites, produced a site survey report detailing the installation requirements and produced an engineering design pack. It was found that on a number of the sites, there is no existing analysis technologies at all and therefore, as part of the Phase 2 costing, Bohr have included some proven technologies, which can be used for a data comparison/validation. It is worth noting that the proven technologies are not cost-effective and are labour-intensive for installation and ongoing operation and therefore, will never be a feasible solution for mass deployment.

Following the customer engagement, the Phase 2 costings were generated. These were based on the requirements for each site, as dictated in the engineering design pack, supplier quotes, Bohr's experience for project delivery for something of the scope and other key commercial factors. Based on this comprehensive exercise, the expected costs for Phase 2 are £1,971,794.74 (>£100,000 lower than initially forecast).

have gained a substantial amount of valuable information which will feed into the next stages of development for the sensor. The project also provided valuable insight into what the industry requires.