Hydrogen for the Ceramics Sector

Industrial Fuel Switching Phase 1

Final Report

BRITISH ceramic CONFEDERATION

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British Ceramic Confederation

Executive Summary

The British Ceramic Confederation has led a project to investigate the feasibility of using hydrogen in the ceramics industry, with 12 BCC members involved covering most sub-sectors and products in the sector.

The project has successfully run trials on a modified rig at Glass Futures' Brinsworth site, with three sets of firings carried out for different product groups (heavy clay, whitewares and refractories). Each set carried out a firing on 100% methane and 100% hydrogen.

The trials demonstrated the potential of firing ceramics using 100% hydrogen, with the test results indicating comparability to 100% methane-fired products, with many products within technical specifications. However, as largely expected there are lessons to take forward to Phase 2. This, along with other projects being carried out elsewhere, reflects the demonstrators investigated.

The project developed and investigated plans for three on-site demonstrators (one in detail), through work led by Otto Simon Ltd. An off-site demonstrator has also been developed given the variety of products and firing cycles in the sector.

In addition, the project has considered other hydrogen projects in the UK and further afield and conducted economic modelling to assess the financial viability of switching to hydrogen for a selection of member sites in the project group.

The project has engaged, and will continue to afterwards, with BCC members who were not in the project, along with wider publicity and dissemination.

As a result, BCC will apply for Phase 2 Industrial Fuel Switching funding for demonstrator projects.

BCC would like to acknowledge the support and contributions it has received throughout the duration of the project, particularly from project group members, Glass Futures (who supported the development of the project, application and project work) and the funding organisation — the Department for Business, Energy & Industrial Strategy (BEIS).

HYDROGEN PROJECT

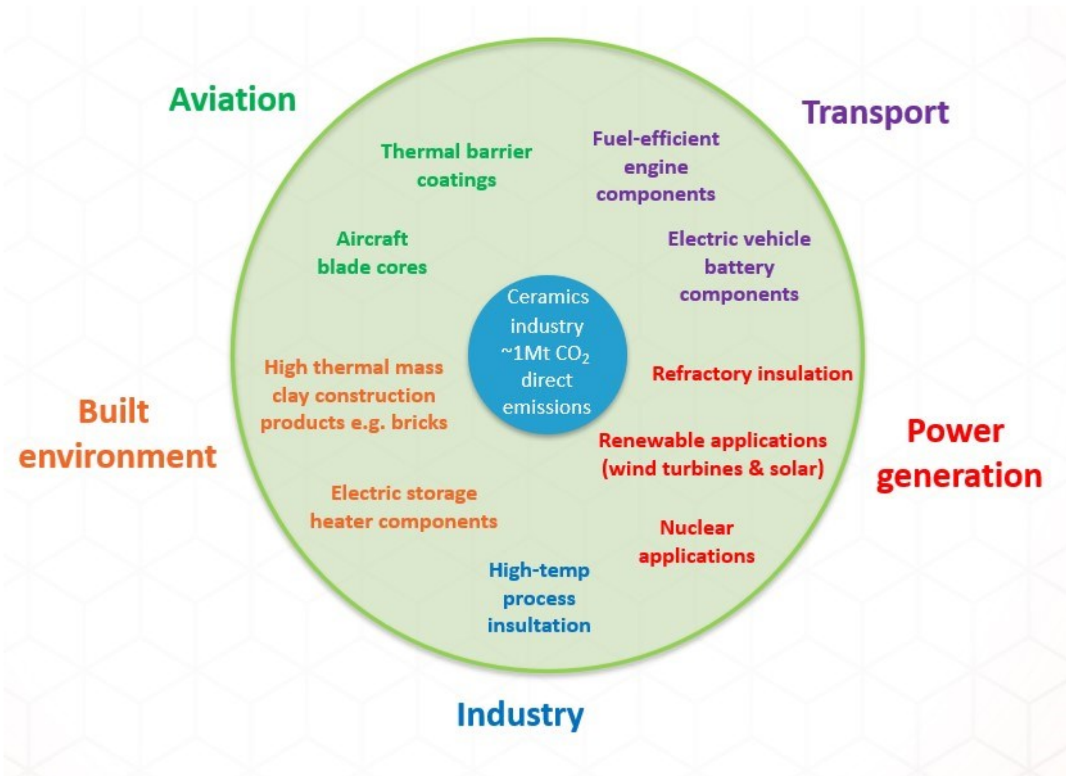
Background to the Ceramics Industry

The British Ceramic Confederation (BCC) is the trade association for ceramic manufacturers in the UK and represents the collective interests of all ceramic sectors. BCC safeguards the industry's prosperity, acting on its behalf in discussions and negotiations with Government and public authorities.

The UK ceramics industry is diverse and includes manufacturers of:

- Bricks
- Gift and Tableware
- Refractories
- Clay Roof Tiles
- Floor and Wall Tiles
- Industrial Ceramics
- Clay Drainage Pipes
- Sanitaryware
- Suppliers to the industry

Ceramics help to meet the net zero carbon emissions challenge, supplying a variety of products to the UK economy. Their recognised thermal insulating properties, durability, long service life and inertness underpin a host of societal applications and are integral to solving real-world challenges in the future net zero economy.



BCC represents around 90% of the industry's UK manufacturing capacity. British Ceramic Confederation member statistics are:

From an energy perspective, the sector's consumption is split as approximately 85% gas and 15% electricity. Thus, hydrogen is therefore seen as a key decarbonisation route for most parts of the ceramic sector.

Introduction to the Project

In late 2019, BCC's Energy and Emissions Group set up a Low Carbon Working Group (LCWG). The aim was to investigate the feasibility of using low carbon technologies in the ceramics industry. This was to be achieved by practical development and demonstration of the various technologies. With the resources of the group, it was decided to focus on hydrogen initially.

This led to the submission of an application to the BEIS Industrial Fuel Switching competition for a hydrogen project in autumn 2021. All members of LCWG were offered the chance to join the project application, of which 12 members did.

The project group members are: Wienerberger (including chair of project group), Churchill China, DSF Refractories & Minerals, Hinton Perry Davenhill, Forterra, Michelmersh, Johnson Tiles, Ibstock, Marley, Naylor Drainage, Ideal Standard and Wavin.

The project group selected Glass Futures to work with, who helped to initially develop the project, the application process, then as part of the project run trials and provide other support.

Aims

The aims of the project were:

- Undertake preliminary hydrogen combustion trials (at various blends of natural gas/hydrogen) for representative ceramic body firing cycles.
- Review current work being undertaken and build links with other groups, across the globe, working on the use of hydrogen within the ceramics sector.
- Scope out and design a flexible pilot-scale kiln/s capable of assessing hydrogen firing (if suitable equipment not identified in the initial review exercise).
- Develop an economic model to assess the costs of switching industrial ceramics sites to hydrogen.
- Detailed scoping, planning and design for industrial-scale hydrogen trials at ceramics manufacturing sites.

The aims were delivered through seven work packages (WP):

- **WP 1:** Develop comprehensive understanding of product mixes, firing cycles and economics of existing ceramics sector, producing a database of firing cycles and kiln conditions that will need to be assessed to de-risk a switch for the whole ceramics sector to hydrogen.
- **WP 2:** Review of current work into hydrogen-firing for ceramics, building links with other groups working in this area across the global ceramics sector, plus other industry sectors who could partner with the ceramics sector.
- **WP 3**: Undertake preliminary hydrogen combustion trials using industrial-scale (350kW) burners, assessing a range of fuel scenarios (e.g. 100% hydrogen firing and hydrogen:natural gas blends), for a selection of representative ceramic body firing cycles to benchmark performance against natural gas.
- **WP 4:** Results from WP 1, 2, 3 will be used to scope out and design pilot-scale kiln/s capable of assessing hydrogen firing (if not identified in WP 1).
- **WP 5:** Development of an economic model (through modifying tool developed for the glass sector) to assess the costs of switching ceramics sites to hydrogen.
- **WP 6:** Detailed planning and scoping for hydrogen trials at a range of industrial-scale ceramics manufacturing facilities.
- **WP 7:** Project management and dissemination

Work Package 1: Kiln Scenarios Review / Work Package 2: Review into H2 firing for ceramics and burner review

For Work Packages 1 and 2, a questionnaire was distributed to the project group members and two non-project group members from the un-represented technical ceramics sub-sector.

Thirteen responses from 12 companies were received. This included one non-project group member company who provided two responses.

Some members provided supporting information beyond the questionnaire (diagrams, graphs, maps etc).

A lot of the information provided by members is confidential and site-specific and thus for many questions only a high-level summary or no information can be provided.

Questions and Responses, Section 1

Q1. Please state your company?

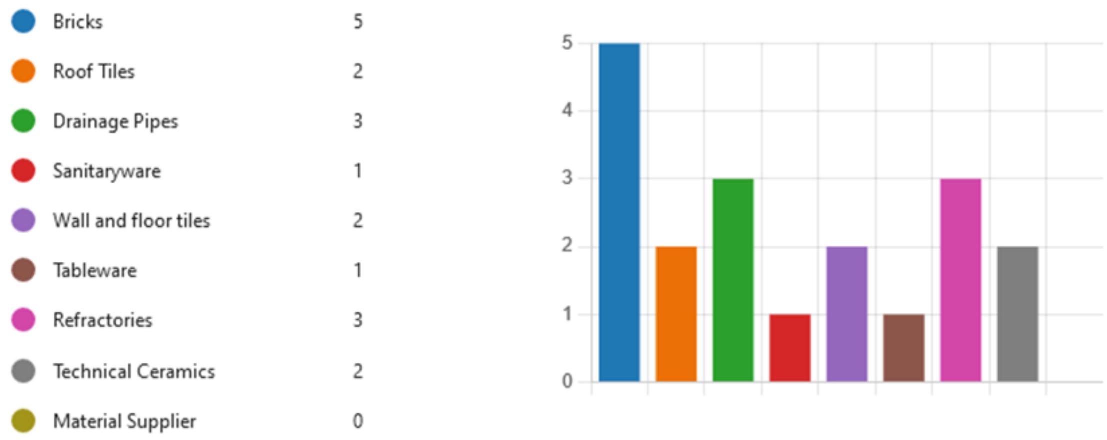
The questionnaire received 13 responses from 12 companies:

Churchill China
DSF Refractories & Minerals
Forterra
Hinton Perry & Davenhill
Ibstock Brick
Ideal Standard
Johnson Tiles
Michelmersh Brick Holdings
Morgan Advanced Materials (technical ceramics, non-project group member, two responses)
Naylor Drainage
Wavin (Hazlehead)
Wienerberger

Q2. What type of products does your company manufacture (select all that apply)?

- Technical Ceramics: 2 companies
- Drainage Pipes: 3 companies
- Refractories: 3 companies
- Roof Tiles: 2 companies
- Wall and floor tiles: 2 companies
- Bricks: 5 companies
- Sanitaryware: 1 company

Summarised in graph below:



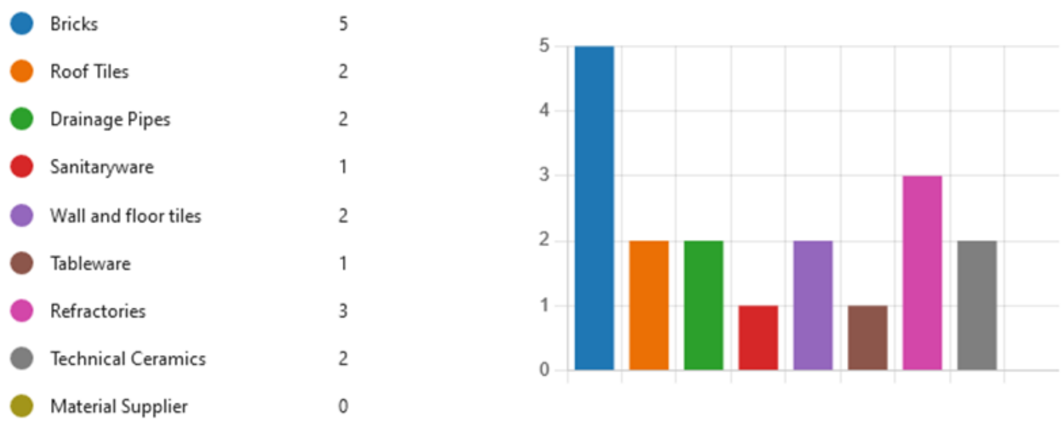
This largely reflects the membership of the project group and the additional companies it was sent to.

Q3. What type of products would you be interested in firing with hydrogen?

- Technical Ceramics: 2 companies
- Drainage Pipes: 2 companies
- Refractories: 3 companies
- Roof Tiles: 2 companies
- Wall and floor tiles: 2 companies
- Bricks: 5 companies
- Sanitaryware: 1 company

This largely reflects the membership of the project group and also the additional companies it was sent to. A difference in response from question 2 with one company manufacturing drainage pipes, but not interested in testing them.

Summarised in graph below:



Q4. Please describe the type of products in further detail? For example, the raw materials used, the dimensions or other relevant parameters.

The answers to this question reflect the wide variety of inorganic and non-metallic materials made by the sector and alluded to in questions 2 and 3. Compositions used by the project group span both traditional clay-based ceramics (e.g. clay, shale, mudstone, earthenware, stoneware etc) which are used to produce essential daily-use items, and engineering ceramics (metal oxides in the case of the project group) where specialised material properties are utilised in numerous cutting-edge applications. Products may be either glazed or unglazed and vary in size from millimetre to metre scale.

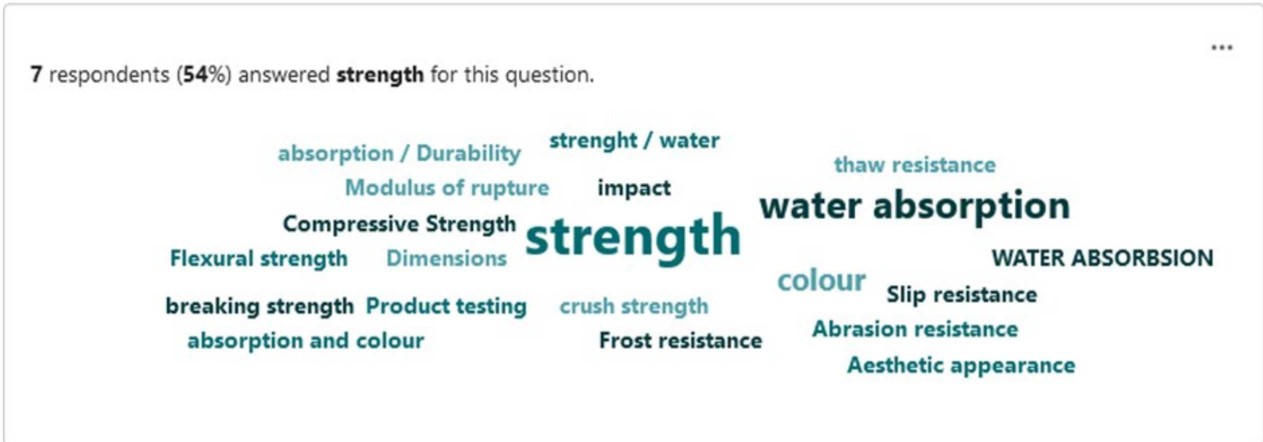
The basic manufacturing process consists of preparation of raw materials, forming, drying, firing, finishing processes (which may include further steps of coating and firing or machining), inspection and packing. The specific processes used in each step vary between and within the sub-sectors according to the scale of production, the product and the raw materials used. All products have the common element of firing to a temperature (which varies in the project group from ~ 1050^{o}C to over 1,600 °C) to start the required chemical and physical changes to develop the final properties, including bonding to form a rigid ceramic matrix.

One product-related concern associated with hydrogen firing is that it will not be possible to achieve product colourations and visual effects that are currently obtained through fuel-rich / oxygen poor 'reduction' firing conditions whereby metallic oxides in the product are converted to their reduced or more metallic form.

Q5. Please provide details of product testing that is required to determine the impact of hydrogen firing on product properties.

The box provided below is an automatic summary by the form. It identifies strength as being the most frequent answer, in fact strength is more widely represented given the variety of terms used.

Similarly other important areas identified were water absorption, durability / frost resistance and modulus of rupture / breaking strength / crush strength.



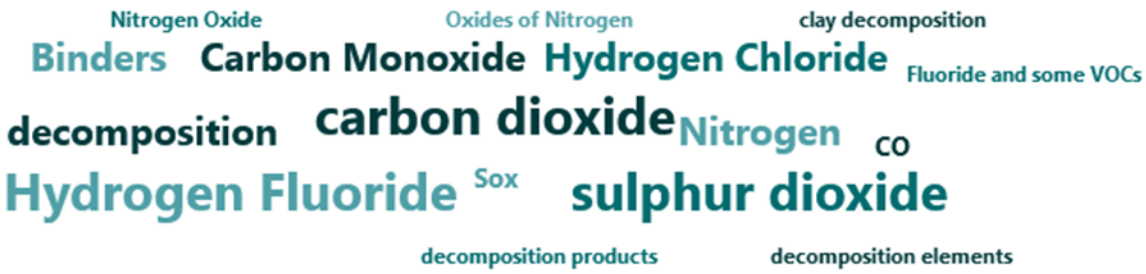
Q6. Please provide any details on body additives (e.g. deflocculants, dispersants) and body colourants that are used.

The box provided below is an automatic summary by the form. It identifies a number of additives and binders used, which could be relevant to the design of a trial, particularly if an independent or separate new kiln is being considered for a trial.

Q7. Please provide any details of emissions that might be released during the firing cycle.

The main emissions noted are oxides of nitrogen (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), carbon dioxide (CO_2), water (H_2O), hydrogen fluoride (HF), chloride compounds, particulate matter (PM_{10}), formaldehyde and total volatile organic compounds (VOCs).

Also, binders in the form of the base chemicals or decomposition products.



Q8. Do you have any site(s) or kiln(s) you would be willing to put forward for an industrial-scale hydrogen trial? *Branch point, if no, sent to final question. If may be or yes, on to next question and section.*

The majority of respondents were interested in putting forward a site or kiln for an industrial scale trial. Note the number below refers to responses, some companies offered multiple kilns or sites.

Questions and Responses, Section 2

From this point on only responses which were a yes or maybe to offering a site / kiln for a trial were asked to provide a response.

Q9. Please provide the following details for each site and or kiln/s you'd be willing to consider for a hydrogen trial (site / kiln 1)?

This question is split into two for each site / kiln to aid information provision and repeated for up to 3 sites / kilns.

- Fuel / natural gas used, annual and time profile of consumption
- Atmosphere conditions for product made
- Is kiln manually operated or automatic?
- Kiln temperature profile (ramp up, dwell, rapid cool, slow cool etc)
- Pre-heater combustion air
- Clay type, ware or raw materials information (including approximate recipe / formulation)
  Refractory, insultation and linings.

Q10. Please provide the following details for each of the sites or kilns you'd be willing to consider in undertaking a hydrogen trial (site / kiln 1).

- Kiln information, such as make, model, dimensions, age and condition
- Burners:
  - ◊ List of burner types / designs
  - ◊ Number of each type / design
  - ◊ Configuration of burners in kiln
  - ◊ Power (of each burner and total power)
  - ◊ Supplier / manufacturer

The age of the kilns considered for the trials ranged from being commissioned in the early 1980s to early 2010s. It is typical for a kiln to last at least 40 years (or typically longer), albeit with maintenance and refurbishment.

The burner manufacturers (or suppliers) used are: Bricesco, Ceric / Cleia, Eclipse, Esa / Pyronics, Hauck, Honeywell Eclipse, Instalat, KromSchroder, Lingl, Nu-Way, Sacmi, Steimer and Weisshaupt.

The power of burners ranged from low ~ 20 kW to higher capabilities around 2000 kW, a typical figure is 200 kW. A number of different types of burners are used including duct add heat, lance / injector and nozzle mix.

Q11 to Q14: Questions repeated for site / kiln 2 and 3 (optional)

Q15. What kiln firing cycles would you like to investigate in a hydrogen trial? Please list in order of priority.

The information provided contributed to the firing cycles prepared and used in work package 3, which give an idea of the firing cycles the sector (using gas for firing) is likely to need.

Q16. Please describe the locations and as appropriate provide any diagrams of the kiln locations.

Member responses included descriptions, overhead and Google Maps links and schematic drawings.

Q17. Please outline the space available for hydrogen delivery and fuel skids and access to kiln from the delivery area. For example, the following would be needed: 3 metre exclusion zone around delivery area, access route details and tie-in point for hydrogen supply, further details in the Otto Simon slides from March meeting.

Member responses provided indications of where space could be available for hydrogen delivery and the use of a fuel skid, although with space varying from site to site.

Q18. Please describe the area beyond the boundary of the site(s) e.g. rural, housing etc.

The responses can be split into three, i. rural location with little else around, ii. sites with housing close by and iii. sites with industrial units nearby (or ii and iii combined).

Q19. What H&S measures or challenges do you perceive would have to be addressed if there was an industrial trial at your site(s)?

A number of H&S challenges were identified:

- Potentially COMAH
- Storage, gas pipe leakage and pipework to kilns
- Comprehensive safe systems of work
- Assessment of site conditions for storage and safe use by competent personnel
- Installation requirements
- Site induction, risk assessment and expertise on gas safety

Q20. Please provide details of engineering and support services you could provide for Phase 2 (the trials)? Note the grant would cover some of the costs for this resource.

The project group members were mostly able to provide engineering and support services for any trial.

Q21. Please confirm your energy and production data has been provided to the BCC database to end of 2021?

Most of the project group had fulfilled their membership requirement to provide energy and production data to BCC's energy and production database.

Q22. For the sites under consideration, what are the CO_2 emissions, for combustion and process?

The majority of the sites said their site CO_2 emissions were in the low 10,000s tonnes per year.

Q23. For the sites under consideration what percentage of your site CO_2 emissions are from the kilns?

Most of the sites said their kilns, when excluding electricity use, generate 90% of the CO2 emissions from their site. Where the figure was lower it was usually because electricity use had been included.

Q24. Of the sites listed for possible trials would you be willing for other BCC members to visit? Please provide details, for example, it may be yes but only if a different sub-sector, or yes but access to only specific parts of a site.

A range of answers were provided with most companies willing to accept some form of access to other project group members, albeit with visits focusing on the trial area. A few were happy with full access. The specific company answers slightly depend on the number of competitor companies within a sub-sector.

Q25. What is the availability for the kilns? For example, is it in commercial use, are there shutdowns planned, or is it not being used.

A range of answers were provided from batch kilns with specific runs, to dedicated production runs of several weeks and continuous operation with only scheduled shutdowns planned.

Q26. Do you have any liquid fuel back-up systems?

No sites had liquid fuel back up, although one member noted they do occasionally use some oil-fired kilns.

Q27. Please provide information of any other details the project team should be aware of, e.g. trial success criteria or any other issues.

The responses noted project group members wished to find out if the necessary high temperatures can be achieved with hydrogen, continuing to achieve product quality, durability and colours.

In addition, no significant increase in operational hazards and no detrimental effect on the kiln structure or emissions. It was also important for an on-site trial to fit around commercial activity.

Q28. If you have any further comments or questions, please write them here.

Selecting Test Kilns and Sites

The project group agreed to focus on selecting a continuous kiln for the full planning for scale up report (work package 6), with two lighter reports for batch kilns.

The following criteria were used to assess options for test kilns and sites:

- Age and condition
- On-site setting or restrictions
- Off-site setting
- Variety of products that could be fired and / or maximum temperature of kiln / maximum temperature rating of refractories.
- Availability of kiln and facility (enthusiasm)
- Access by other members
- Suitable space/footprint to house hydrogen fuel skid
- Distance from where hydrogen fuel skid would go to kiln for trial
- Kiln size/power
- Approximate dimensions of load that could be fired - length (m) by breadth (m) x height (m)
- Engineering / support services
- Describe how load is placed / removed from kiln (front door slides open, front door hinges open, top lifts off)
- Existing availability of access ports for thermocouples, firing atmosphere analysis
- Existing availability of motorised dampers to help control speed of kiln cooling
- Height of kiln floor above surrounding floor (access - some kilns require steps to access, some don't)
- Photos showing inside, outside and items of interest

Tunnel kiln site selected:

- **Wavin (Hazelhead)**

Batch kiln sites selected:

- **Churchill China**
- **DSF Refractories**

Please see Work Package 6 section of report for further details.

Work Package 2 (cont.): Summary of Other Research

UK

Lucideon

Provided by Lucideon:

"Since April 2022 Lucideon is operating a blended hydrogen/natural gas research kiln, capable of up to 1650 Deg C with both oxidising and reducing internal atmosphere control. The kiln can operate in 100% natural gas mode or in a blended mode with a range of hydrogen/natural gas mixes. The kiln is designed to provide a universal platform for traditional, technical and advanced ceramics product manufacturers who are looking to understand the impacts of a hydrogen combustion environment on a wide range of ceramic materials. Initial work has been in support of the UK's HyDeploy programme to assess a range of safety critical ceramic products for product conformance variations when comparing both 100% natural gas and blended 80/20% natural gas and hydrogen.

This project is due to report to the client in September 2022 with subsequent public dissemination. The kiln specification utilises industry standard burners, with modified safety controls, hydrogen is supplied via cylinder packs fitted with an auto change over system providing continuous supply of hydrogen for extended firing schedules."

From LinkedIn a video available.

Also photos available:

Michelmersh

Michelmersh was also awarded funding in Phase 1 of the Industrial Fuel Switching competition, their public description is: "Michelmersh Brick Holdings PLC will trial the feasibility of replacing natural gas with hydrogen for firing in brick production, with the ultimate aim of demonstrating a potential decarbonisation route for clay brick manufacturing. The project will investigate the feasibility of retrofitting gas burners used for brick firing, trialling 100% green hydrogen in a test kiln at Michelmersh's site in Sussex. In parallel, project partner Limpsfield Combustion will develop and conduct laboratory testing of burners and investigate their energy efficiency. Other partners/contractors in the project include the University of Brighton, Greater South East Net Zero Hub, Net Zero Associates and Geopura."

Forterra

In a recent stock market announcement Forterra stated about a hydrogen project (20% hydrogen): "We continue to prepare for our previously publicised hydrogen trial where we will gain an understanding of how firing bricks with hydrogen impacts both the product and our kilns, unfortunately the global supply chain challenges have delayed this important step as we seek to source the necessary equipment, although we expect these trials to commence in the second half of the year."

Hydex / Keele University

Keele University were involved with the HyDeploy project. This part of the project was a pilot trial between 2019 and 2021 and demonstrated the injection and use of up to 20% (by volume) of hydrogen into the university's natural gas network to 100 homes and 30 faculty buildings. This network was selected as it is private and separate to the national or distribution networks.

The trial has focused on the generation and supply of a blend of hydrogen to a network, followed by use in a controlled domestic and small business environment, but not for use in manufacturing. The project is now in a larger second phase in Gateshead.

Keele University is leading the Hydex programme in the Midlands to accelerate innovation in hydrogen, build markets and the supply chain, and support the skills needed to establish the Midlands as UK lead in hydrogen transport and heating with business clusters and industrial sectors.

This project provides wider context and also Keele University has the infrastructure in place to generate hydrogen via an electrolyser, but limited capacity to test its use in manufacturing conditions.

In addition, the British Ceramic Confederation's 'Delivering Net Zero for British Ceramics' conference took place at Keele University on 29th November, 2022.

Spain

Orange BAT

An international consortium of 40 organisations from Spain, Germany, Switzerland, Italy and Greece, led by the technological company ETRA, has launched ORANGE.BAT, to incorporate green hydrogen into the ceramics industry in Spain. The project includes 100MW electrolyser and was presented in January 2021 to the Green Deal call requesting the support of the European Commission.

There will also be an emphasis on getting value from by-products, such as the oxygen obtained from the separation of hydrogen from water, which will be used in ceramic frit kilns, and the waste heat will be used in residential and industrial heating.

It seems the focus is on developing a 100MW electrolyser rather than testing end product use, although there is an aim to eventually use the hydrogen in the ceramics industry, it's likely to be mostly the wall and floor tile production cluster in Castellón, Spain. It is planned to start operating in early 2024.

Institute of Ceramic Technology

The Institute of Ceramic Technology (ITC-AICE) has achieved hydrogen combustion in a ceramic kiln using conventional burners with mixes of up to 20% hydrogen. The research was carried out in a specially designed combustion chamber.

According to the study team, controlled combustion was achieved with conventional burners with mixes of up to 20% hydrogen in these early experiments. It should be noted that work is being done on the design and development of burners specifically adapted for use in the ceramic industry, so that they allow the controlled combustion of natural gas and hydrogen mixtures at the temperatures required in the ceramic process, with the goal of achieving 100 per cent hydrogen combustion at the project's next milestone, scheduled for the second half of 2022.

South Korea Hydrogen Webinar

Building a hydrogen bridge with South Korea Webinar

Organised by the Energy Research Accelerator, University of Nottingham, and Chungnam Province, South Korea, the aim of the event was to introduce the hydrogen capabilities both in the Midlands and in Chungnam Province and demonstrate the advanced technologies in both countries.

From a South Korea perspective, an update on their hydrogen projects from production to end uses, although nothing ceramics specific. From a UK Midlands perspective, the view is as per the description above.

Germany

A paper by Thomas Lansdorf considers the production of hydrogen through a variety of different techniques, the possible options for storage and fuel cells to re-convert hydrogen to electricity.

There is then consideration of use of hydrogen in industrial processes and challenges such as calorific value and heat transfer, flame temperature, impact on furnace materials, increase water vapour and emissions. It doesn't review or conduct any testing or demonstration of equipment.

Netherlands

In the Netherlands DNV GL is focusing on developing burner control technology to deal with variations of hydrogen for a number of sectors.

DNV GL has launched an international industry consortium in collaboration with Dutch glass production expert company Celsian to develop the technology required for a gradual transition from natural gas to hydrogen as a *fuel in energy-intensive industrial production processes. The programme provides an important building block for the successful rollout of the sustainable hydrogen value chain.*

"Existing burner and burner control technology to decarbonize industrial production processes are not yet market-ready, despite great interest and the advantages of hydrogen as a low carbon fuel in high-temperature industries. Our programme aims to have new burner concepts available within two years," said Sander Gersen, project leader, DNV GL – Oil & Gas.

The two-year programme is a unique collaboration in the introduction of hydrogen as a fuel for industrial use, aiming to contribute fundamental improvements to existing industrial heating processes to make the gradual transition from natural gas to hydrogen fast and cost-efficiently.

In addition, Gasunie (an energy network operator in the Netherlands) has produced a hydrogen outlook report for the Dutch ceramic industry. The report considers a wide range of topics including targets and policies, technical challenges, economics and network and infrastructure challenges. It's not concerned with any specific trials.

Italy

In Italy similarly the focus seems to be on the production of hydrogen via photovolatics, gas storage and an electrolyser, with equipment designed to run on 100% hydrogen, but potentially still some time to operation.

"The Iris Ceramica Group and Snam have signed a memorandum of understanding for an industrial project involving the study and development of the world's first ceramics factory powered by green hydrogen. The new Iris Ceramica Group production site, which will be completed in Castellarano (RE), will, by 2022, be equipped with native technologies allowing the use of green hydrogen as an energy source.

The solution developed by the Iris Ceramica Group with the support of Snam will allow the production site in Castellarano (Reggio Emilia, Italy) to immediately produce ceramic surfaces born from a blend of green hydrogen, produced from solar energy, and natural gas. A photovoltaic plant (with 2.5 MW power output) will be installed on the roof of the factory, combined with an electrolyser and a storage system for the renewable hydrogen produced on site. The solution using a blend of green hydrogen and natural gas will immediately lead to a reduction in CO_2 emissions and, in the long term, will pave the way for the exclusive use of renewable energy for zero-emissions production, as the plant is designed to run on 100% hydrogen."

Work Package 3: Hydrogen Combustion Trials

Introduction

In Work Package 3 the project conducted a series of trials at Glass Futures' combustion test bed (CTB) in Brinsworth, South Yorkshire.

The trials tested samples for the following sub-sectors and products:

- Heavy clay construction products: bricks, roof tiles, drainage pipes and flowerpots
- Whitewares: unglazed plates, glazed wall tiles and glazed sinks
- Refractories: blocks

Combustion Test Bed for the Trials

The tests were undertaken on the Glass Futures Ltd Combustion Test Bed (CTB) that was adapted to simulate a scaled down ceramic kiln.

The original design of the combustion chamber consists of a scalable replica of an end-fired regenerative glass furnace in which the flame entry is located on one side of the back wall and the exhaust port is located on the other side of said wall. The thermal load of a glass melt is simulated by ten water-cooled pins which were not used for this set of trials. As such, the ceramic products were located on the left-hand side of the chamber to avoid flame impingement (i.e. the flame directly touching the products) as agreed by the project partners, see Figure 1.

The major components of the CTB (see Figure 2), which form the basis of the control strategy, are:

A. Water-cooled hearth pins and cooling system (not used)
B. Exhaust gas system
C. Electric combustion air pre-heating system (not used)
D. Burner and fuel system
E. Combustion chamber

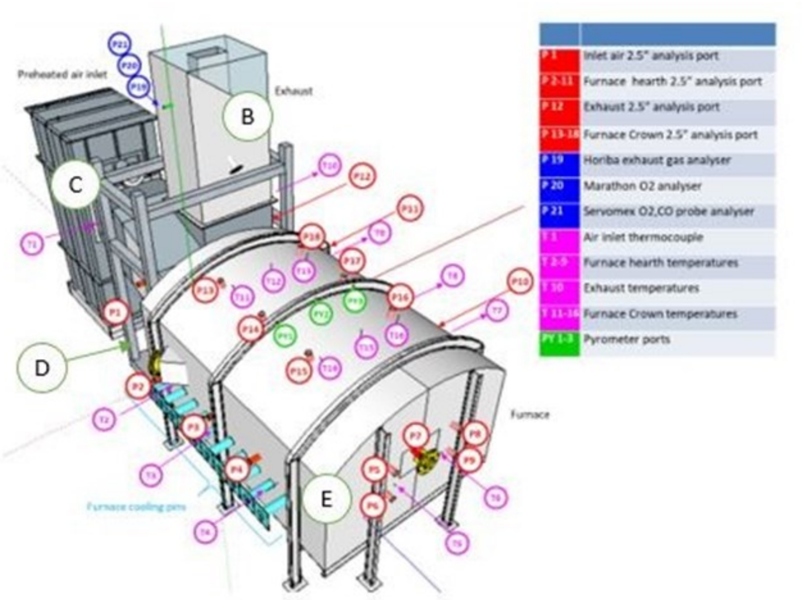
The furnace is equipped with several access ports along the side, end walls and furnace crown to allow the flames, internal furnace temperatures and firing atmospheres to be monitored during the tests. A schematic of the system showing the access points for measurements can be seen in Figure 3.

The general appearance of the exterior and interior of the CTB can be seen in the photographs of Figure 1 (interior) and Figure 2 (exterior views).

Figure 1 – ***Interior of CTB combustion chamber loaded with heavy clay products prior to firing***

Figure 2 - ***Exterior of combustion test bed (original design with water-cooled pins)***

Figure 3 - ***Schematic of CTB with measuring ports***

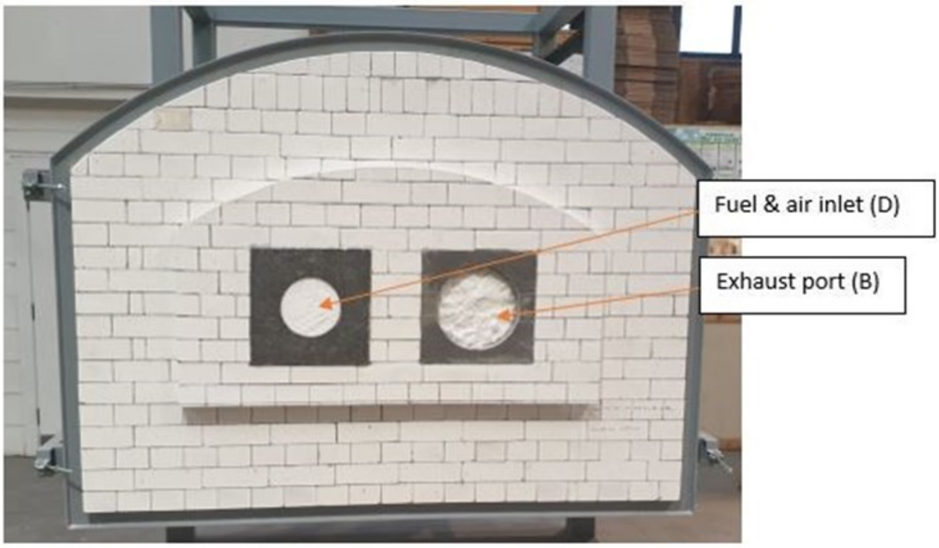


The CTB back wall consists of an exhaust port (through which the exhaust gases are extracted) located alongside the burner port, into which the burner is inserted (Figure 4) simulating the firing arrangement of a ceramic kiln in a horizontal plane.

The furnace exhausts directly to a flue gas collector hood via a furnace pressure damper at the exit of the furnace flue duct, with assistance of a venturi inductor to guarantee that all exhaust gases enter the flue hood.

For the ceramics firing trials, the CTB rig and control system were upgraded such that the incoming combustion air was drawn into the burner at ambient temperature and the burners were ignited at ambient temperatures in order to replicate the types of burner typically used throughout the ceramic sector.

Figure 4 - ***CTB back wall showing burner port (D) and exhaust flue entry (B)***



The CTB was fired by a single Global Combustion Systems gas burner similar to a ceramic burner configuration in a ceramic kiln.

Firing Cycles

Firing is the process by which raw materials are thermally transformed from a friable blank into a robust, rigid product. This process may also be referred to as sintering or densification. Firing is the dominant energy and emissions-intensive step in ceramics processing. Conventional firing is accomplished by heating the dried ceramic to approximately two-thirds of the melting point of the material and holding at this temperature for a sufficient time for chemical and physical changes to develop the final properties of the product.

In ceramics, the firing temperatures and cycle times vary enormously depending on the raw material composition (with firing temperatures in fossil fuel-fired kilns ranging from 1,000 to 1,750 °C) and the size and thickness of the product (with cold-to-cold cycle times varying from 30 minutes to up to one week).

The project group agreed a set of firing cycles for three different sub-sectors / groups of products: heavy clay (bricks, roof tiles drainage pipes and flowerpots), whitewares (wall and floor tiles, sanitaryware and tableware) and refractories. For each product group, the cycles agreed represented a compromise position between the different consortium members making such products, rather than set to conditions mirroring a specific member or their products. Consequently, this resulted in some products within a particular product group being underfired, with others being overfired.

Table 1: ***The sets of firing cycles carried out for each group of products, i. heavy clay, ii. whitewares and iii. refractories***

	Heavy Clay	Whitewares	Refractories
Product	Etruria Marl brick Weald / Alluvial roof tile Drainage pipe / flower pot	Ball day based cups / plates Ball day based sanitaryware Ball day based wall tiles	Refractory bricks - various compositions
Initial ramp up	24 hrs to 1,110°C (45°C / hr)	25.5 hrs to 1,175°C (45.3°C / hr)	30 hrs to 1,500°C (49.3°C / hr)
Dwell	2 hrs at 1,110°C	2 hrs at 1,175°C	5 hrs at 1,500°C
First phase cool	4.5 hrs to 650°C (-100°C / hr)	5.25 hrs to 650°C (-100°C / hr)	5.3 hrs to 1,100°C (-75°C / hr)
Second phase cool	5 hrs to 500°C (-30°C / hr)	5 hrs to 500°C (-30°C / hr)	6 hrs to 500°C (-100°C / hr)
Off	Cool as quickly as possible	Cool as quickly as possible	Cool as quickly as possible
Cold to 500oC cycle time	35.5 hrs (plus cooling from 500oC)	37.75 hrs (plus cooling from 500oC)	46.3 hrs (plus cooling from 500oC)

For each product group, two firings were conducted - a firing with 100% methane (as a control) and a firing with 100% hydrogen (as the test). This approach was taken to enable a direct comparison between products fired in methane and those fired in hydrogen, whilst removing any kiln variations associated with comparing test samples fired in the combustion rig, with standard products fired in production kilns.

Temperature Profiles of Firings

Figure 5: ***Temperature profile of firing cycle for heavy clay, natural gas***

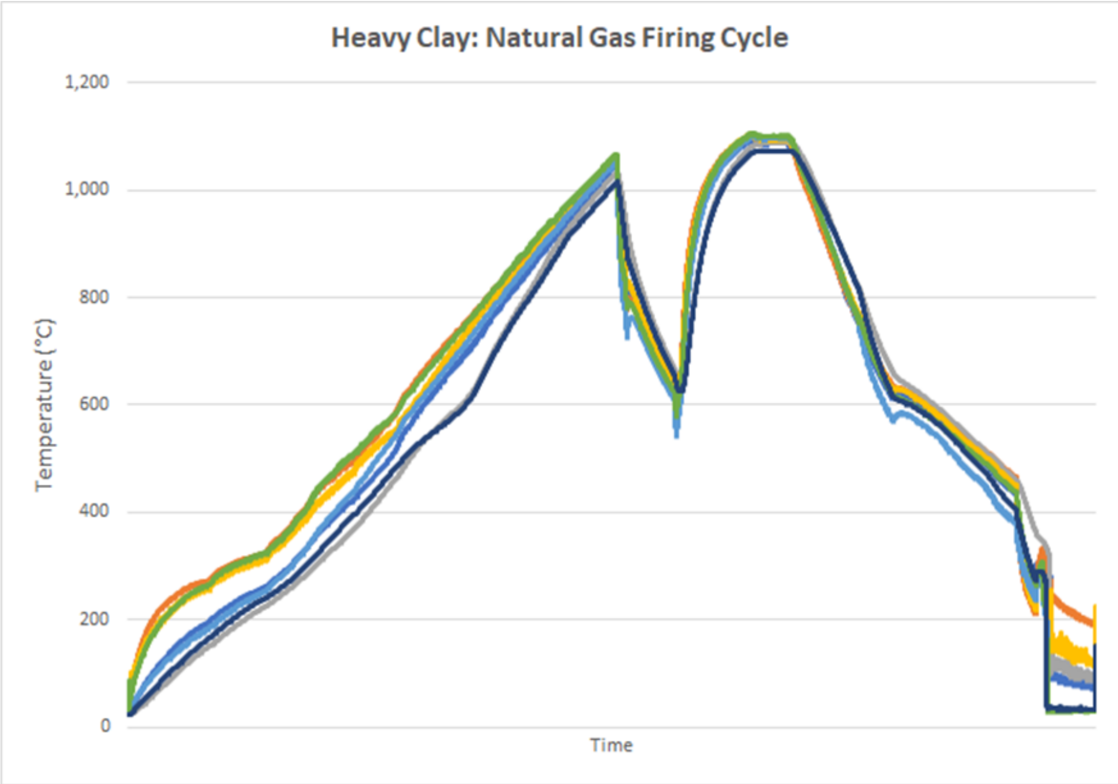


Figure 6: ***Temperature profile of firing cycle for heavy clay, hydrogen***

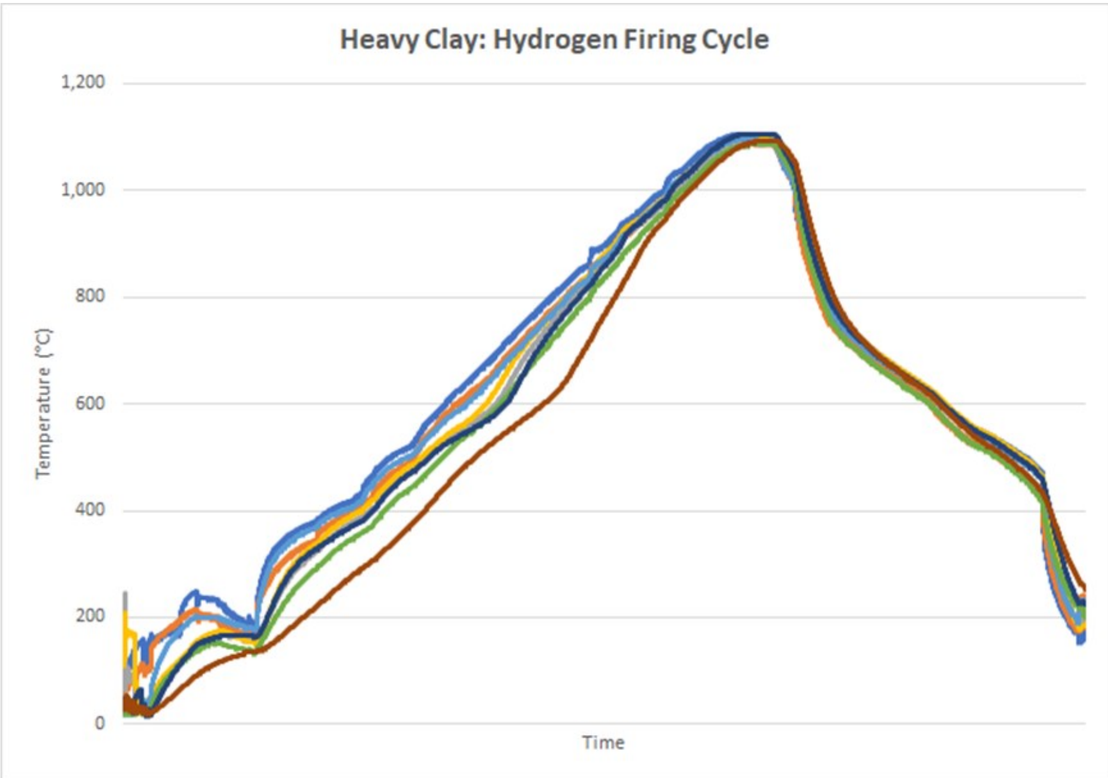


Figure 7: ***Temperature profile of firing cycle for whitewares, natural gas***

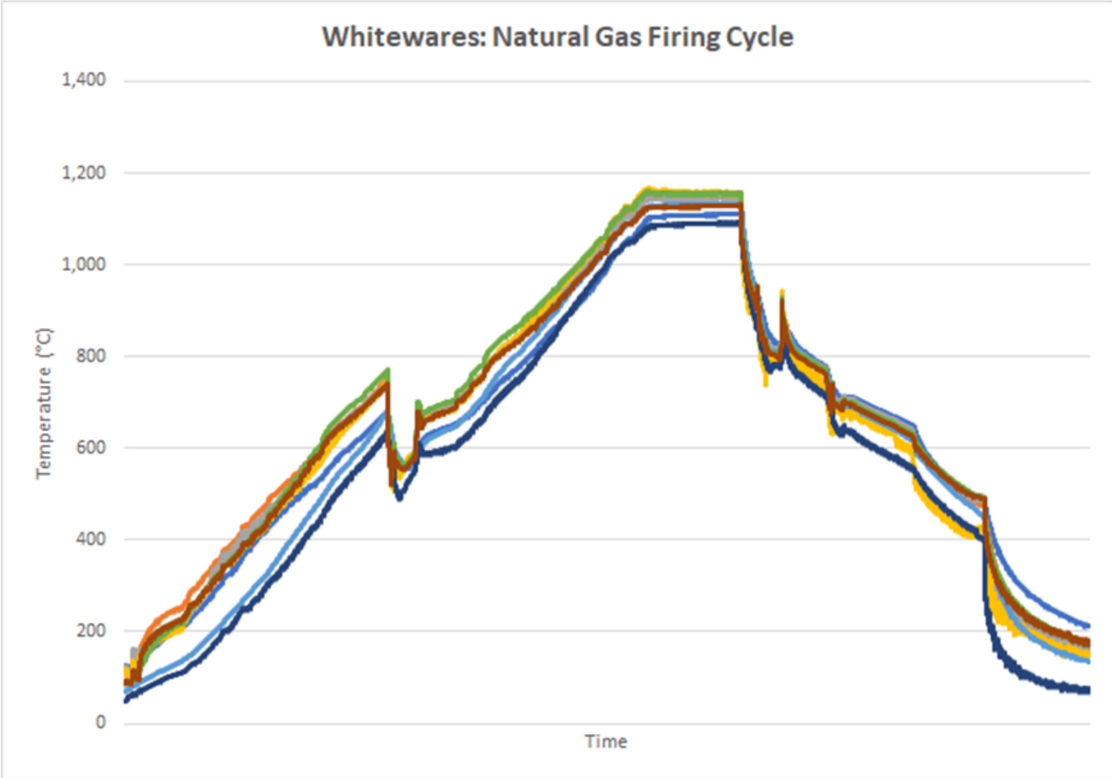


Figure 8: ***Temperature profile of firing cycle for whitewares, hydrogen***

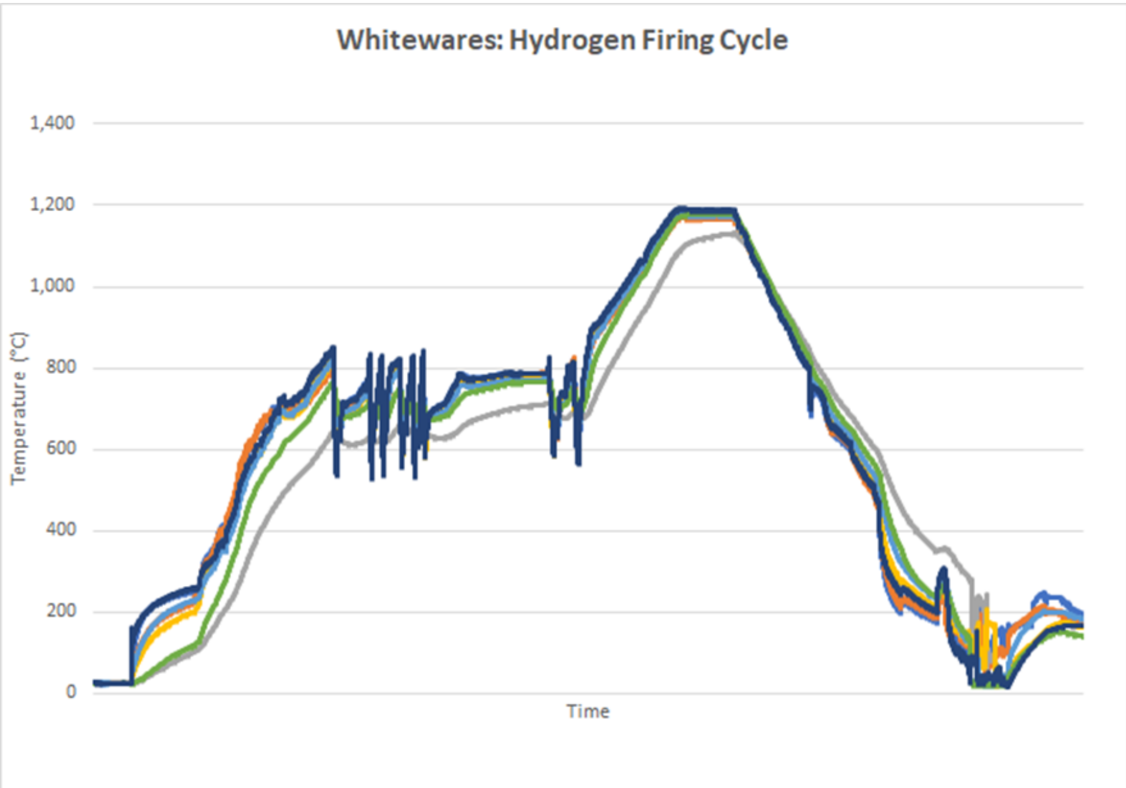


Figure 9: ***Temperature profile of firing cycle for refractories, natural gas***

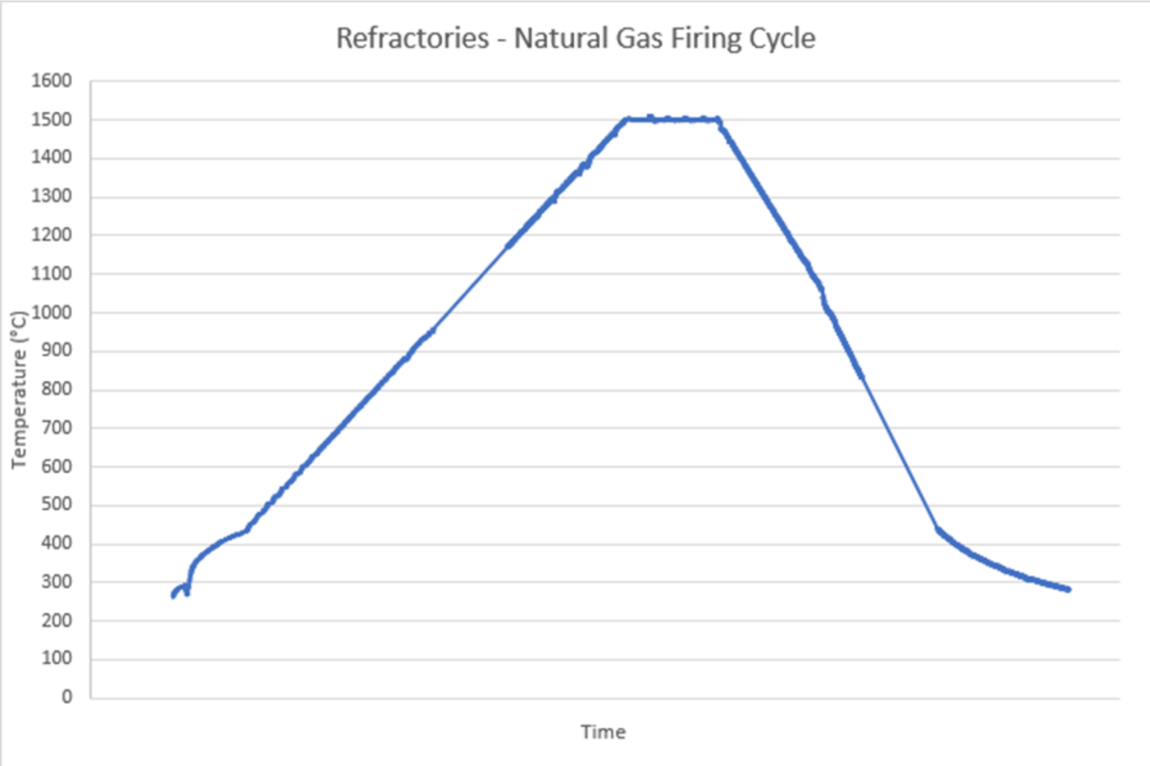
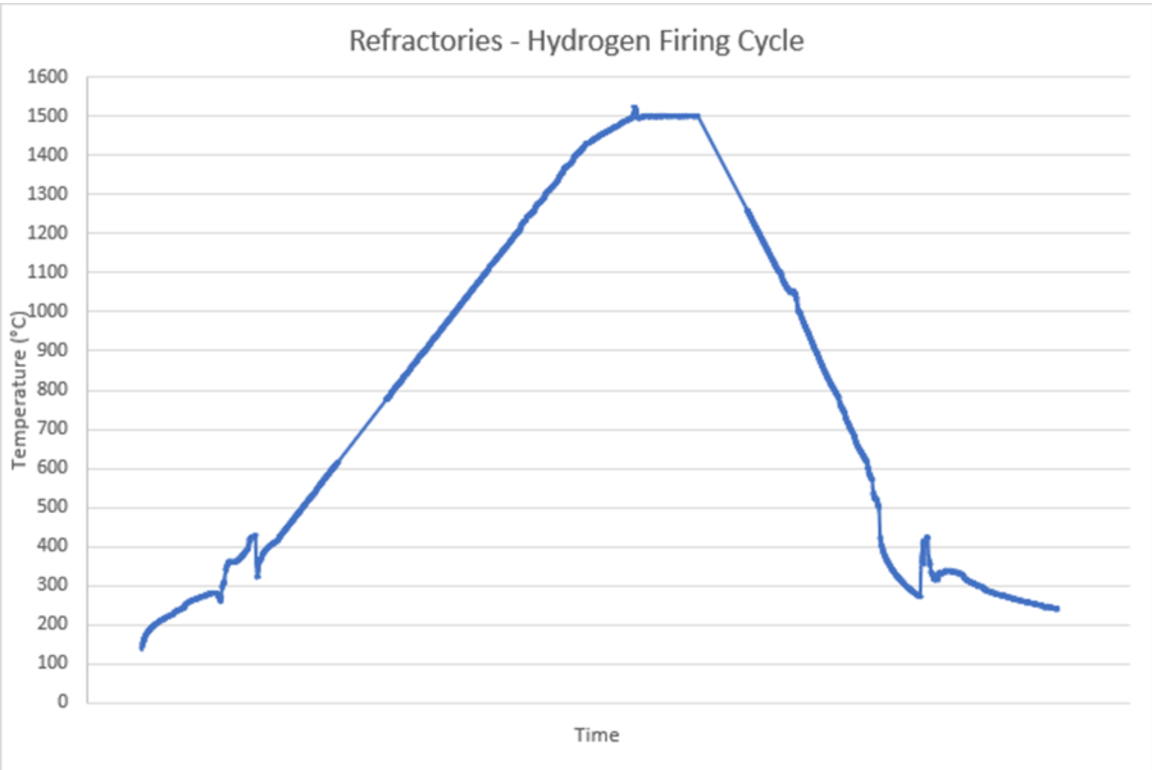


Figure 10: ***Temperature profile of firing cycle for refractories, hydrogen***



Testing of Products

Following the trials, the project group members tested the products according to their normal production procedures, which is typically a mix of internal testing and the use of external testing houses. A summary by each grouping of firings is below.

Heavy Clay

For the heavy clay firings, testing results were received from: Hinton Perry Davenhill (HPD), Michelmersh, Wavin and Wienerberger. This included bricks, roof tiles and drainage pipes.

The outcome of the heavy clay firings was very encouraging, with the results indicating similar or little discernible difference in fired colour, aesthetics or product properties (physical dimensions, density, water absorption and compressive strength) between the two sets of products. If anything, the technical properties of the hydrogen-fired products may be marginally more developed (i.e. a lower water absorption, smaller product dimensions etc.), but the limited number of firings (one pair) mean this cannot be stated conclusively. One member provided side-by-side photos to show colour consistency between the methane and hydrogen fired bricks (Figure 11).

One member reported a more pronounced variation in colour for their products, across both firings, with the darker products exhibiting a slightly lower water absorption, suggesting a variation in temperature across the kiln. Visible 'rings', corresponding with the perforations on the underlying refractory supports were also evident on some of these products, suggesting kiln atmosphere or a contaminant may also be playing a role.

A recurrent theme was that both sets of products were often underfired or overfired when compared with the manufacturer's standard production, which thus impacted colour, technical performance and conformance to specification for both sets. However, this is reflective of the compromise nature of the firing selected – overfired for some and underfired for others.

Whitewares

The project demonstrated a range of glazed and unglazed whitewares could be successfully fired using 100% hydrogen.

Visually the body and glazed surfaces of both the natural gas and hydrogen fired products were essentially the same. No detrimental effects on shade or surface between the two firings were noted, although all had a small amount of contamination on the glaze surface, probably due to a combination of marking from sample handling and contamination blowing around the kiln. The surface of both sets of wall tiles was also more pitted due to the compromise nature of firing schedule, where a slower ramp up would be required to enable the underlying body to degas before the glaze started to seal.

Technical properties of both sets of products (hydrogen and methane-fired) were found to be similar, again possibly with the properties being slightly more developed for hydrogen-fired products, but this could be caused by small inconsistencies between the firings and so cannot be stated conclusively.

Again, individual members found that their products were underfired (tableware) or overfired (tiles), thus impacting technical performance and conformance to specification for both sets. However, this is reflective of the compromise nature of the firing selected, overfired for some and underfired for others.

Refractories

The project also demonstrated that refractories blocks could successfully be fired using 100% hydrogen. For this product group, there was only one member company in the project consortium, meaning the firing curve investigated was closer to their production schedules (as opposed to a compromise between multiple producers in the other two product groups).

The visual appearance and block dimensions of both sets of products were similar and within specification. The company intends to carry out further testing including mineral phase identification to check phase conversion and some high temperature properties.

Conclusions

In conclusion, the initial firing trials have demonstrated the potential of firing ceramics using 100% hydrogen, with the test results indicating comparability to 100% methane-fired products. Many of the products were within the required technical specifications, with deviations occurring for both methane and hydrogen-fired samples depending on the extent of divergence between the test firing cycle and routine production firing curves – with the compromises selected naturally resulting in overfiring for some and underfiring for others.

However, as largely expected, there are lessons to take forward to Phase 2. Using a kiln specifically designed for ceramics will enable a wider range of compositions, products and firing atmospheres to be more closely evaluated. In addition, on-site demonstrators will give an understanding about using hydrogen in an industrial environment and using real world kilns.

Photos

Figure 11: ***Visual comparison of natural gas and hydrogen-fired bricks***

Figure 12: ***Whitewares items loaded in the combustion rig (unglazed plates, glazed sink, glazed wall tiles)***

Figure 13: ***Heavy clay items loaded in the combustion rig (bricks, roof tiles, drainage pipes and flowerpots)***

Figure 14: ***Sanitaryware items (plates, sink and wall and floor tiles) after firing***

Figure 15: ***Refractory blocks in the combustion rig***

Figure 16: ***Bricks after firing***

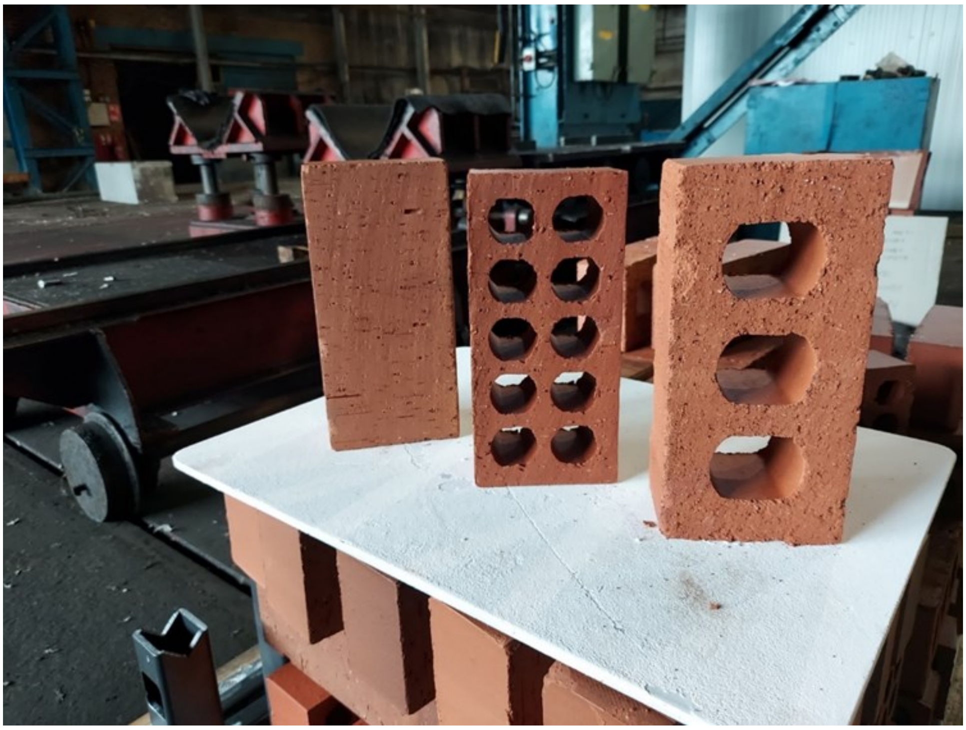


Figure 17: ***Refractory blocks after firing***

Work Package 4: Design of Hydrogen Pilot Kiln

The aim of Work Package 4 was to develop a pilot kiln for the ceramics sector to be able to test their products and firing cycles. As the project progressed it was clear the priority site in Work Package 6 (on-site demonstrator) would be a roller hearth kiln, which could only fire a specific product. The other two batch kilns would have less development in Phase 1, but would have greater flexibility over what could be fired. However, it would be unlikely to provide suitable conditions and trials for all members of the project group.

This led to developing the idea for an independent kiln, hosted and with trials run at a third-party site in this work package. This would enable the firing cycles and conditions to be controlled, as needed and appropriate, to the different products made by members of the project group.

To develop and prepare for a Phase 2 application, a request was sent to potential kiln suppliers, extract below. The aim was not to select a company at this stage, but to establish the likely cost and budget needed for Phase 2.

Extract from invitation to quote for a batch kiln to run hydrogen trials in Phase 2

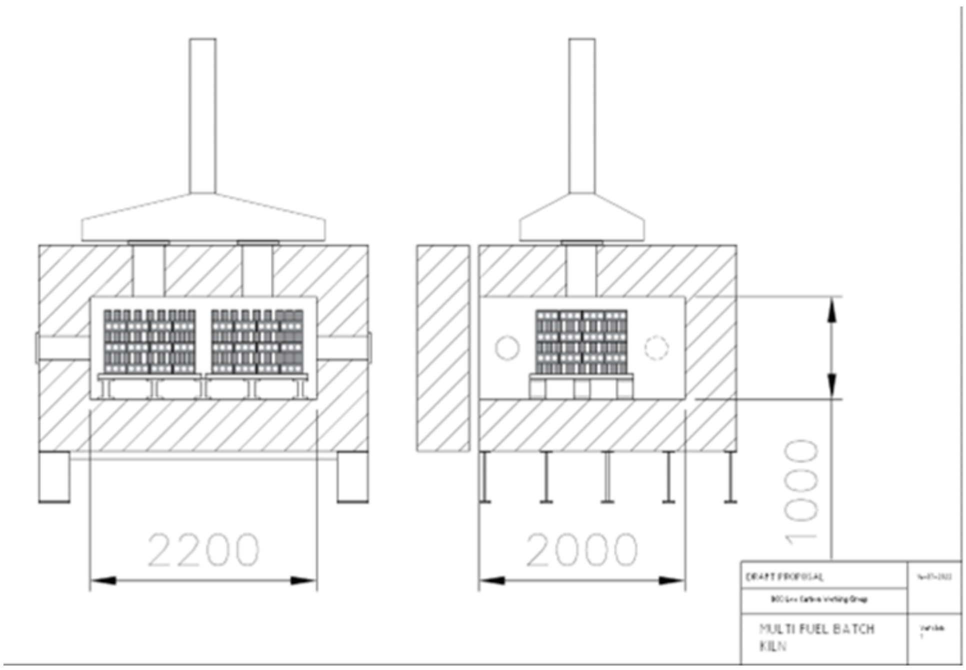
"In Work Package 4 we are considering the possibility of a batch kiln which would be based at a third party / independent site. This will allow all project group members to test their products in controlled conditions.

We are separately considering the exact location of this kiln, but it would be in the UK. The site would operate the kiln and trials.

We would like a kiln to have the following characteristics:

- The ability to fire, as broad categories:
  - ◊ Refractories
  - ◊ Technical Ceramics
  - ◊ Drainage Pipes
  - ◊ Bricks
  - ◊ Roof Tiles
  - ◊ Wall and Floor Tiles
  - ◊ Sanitaryware
  - ◊ Tableware
- The approximate kiln dimensions are 2.2 metres * 2 metres * 1 metre (internal) equal to $4m^3$
- It should have a remote stacking ability
- Loading pattern: see schematic
- Maximum firing temperature: the ability to reach peak temperatures, ideally to a maximum of 1,500^{o}C
- The ability to fire solely on methane or hydrogen, and blends thereof
- Cooling facilities: there should be pressure control and please include design aspects of exhaust
- Control zone of the burner(s): up to 2
- Type of door opening:
  - ◊ If vertical, manual, see picture as example
  - ◊ Door at one end
- Loading method: single bogey, electric or refractory plate.

- Fixed or moving hearth: truck or fork loading design (see photo for an example)
- Burners: ability to accommodate more than one type of burner
- Heat exchanger to give ability to preheat combustion air
- For each product:
    - ◊ Ability to fire a variety of cycles
    - ◊ Ability to consider a variety of atmospheres, oxidative / reductive / flashing (noting it's a challenging area for hydrogen)
- The ability to conduct temperature analysis and accommodate thermocouples.
- Gas meters for methane and hydrogen
- Electricity meter
- Lambda combustion control
- PLC control (PID loop) and supervision with process data recording facility (temperatures, pressure, atmosphere - O_2 / CO / CO_2 / NO_x / SO_2 / H_2O, λ, energy consumption)
- Air combustion with noise suppression enclosure
- Inspection hole (for camera)
- Stainless steel casing
- Refractories: the ability to change to accommodate different products and temperatures.
- To note and accommodate the emissions and their analysis, which when firing with methane are typically:
    - ◊ The main emissions are oxides of nitrogen (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), carbon dioxide (CO_2), water (H_2O), hydrogen fluoride (HF), chloride compounds, particular matter (PM_{10}), formaldehyde and total volatile organic compounds (VOCs)
    - ◊ Also binders in the form of the base chemicals or decomposition products
- Technical assistance, commissioning, and training for the kiln
- Schematic: see schematic with example of bricks



In addition, the kiln will need a third party location and organisation to host and run the trials, thus a request was made to appropriate organisations. The aim was not to select a company at this stage, but to establish the likely cost and budget needed for Phase 2."

Extract from invitation to quote for hosting and running trials for the above kiln

(specification also supplied)

"In Work Package 4, the project is developing proposals for a demonstrator kiln at a third-party site. This request relates to hosting a kiln and conducting trials with member samples firing them with methane and hydrogen.

Please provide information on:

- Your ability to host a kiln at a location in the United Kingdom.
- Your ability to run firing trials with methane and hydrogen and ceramic materials in the kiln. The main focus is likely to be on 100% methane and 100% hydrogen, but ideally the option for blends should be available.
- The kiln specification request is included with the covering email, which has been sent out to potential suppliers in parallel to this request. The specification includes technical assistance, commissioning and training for the kiln.
- The site and kiln would have to be accessible to all members of the project group.
- Please provide any one-off costs you would associate with hosting such a kiln.
- Please provide a per hour cost to run trials with methane, hydrogen and blends and any start-up costs with each particular trial.
- Please advise of other details such as kiln would be located, personnel involved with the work, experience of operating such a kiln (particularly with hydrogen) and ceramic materials and company information."

Anticipated Firing Cycles

It is anticipated the firing cycles will accommodate the following variations in conditions:

- 100% methane, 100% hydrogen and blends of methane and hydrogen.
- Different products or groups of products across the Phase 2 project members, such as different temperatures (peak and holding) and length of firings as appropriate.
- Different atmospheres such as reducing and oxidising atmospheres.

Work Package 5: Economic Modelling of Hydrogen Fired Kilns

Background to Model

The G-FUSE (Glass FUel Switching Economics) model was developed by Glass Futures and Element Energy for the BEIS-funded Industrial Fuel Switching Phase 3 project led by Glass Futures. The purpose of the model was to improve the understanding of the impact of fuel switching on manufacturers' operations and investment cycles. It aimed to allow sites to compare possible scenarios for fuel switching with regards to their economic impact, as a function of choice of low carbon fuel, year of fuel switching, and whether furnace replacement or retrofitting is targeted. The model takes into account a range of site-specific factors, such as: number of furnaces; number of production lines; energy consumption; maintenance schedules; equipment age, etc. For the Phase 1 BCC H_{-2} project, the input parameters have been adjusted to zero for any parameters which do not apply to ceramics manufacturers. In the interests of time, the model has been simplified to focus on the kiln as the primary source of emissions.

Chosen Sites for Modelling

For the economic modelling two project group member sites were chosen and they provided data for the assessment and report. With the nature of the information provided and outputs the sites are not identified.

Modelling Approach

The model calculates the cashflow for a kiln/furnace or full site over a multi-year period, both for the counterfactual case (where natural gas continues to be used) and the fuel-switching case (where hydrogen becomes the primary fuel). The cashflows from both cases are then compared. From this, the two key output metrics are:

- **Net Present Value (NPV)** – The sum of the discounted net savings of fuel switching compared to the counterfactual:

Where c_i is the costs and s_i the savings (in £) for each year, i, and d is the discount factor.

- **Levelised Cost Of Abatement (LCOA)** – The sum of the discounted net costs (in £) divided by the discounted abatement (in tCO_2):

Where n_i is the net costs (in £) in year i excluding carbon cost savings, and a_i is the abatement (in tCO_2).

The NPV indicates whether switching to hydrogen makes economic sense compared with remaining with natural gas. A positive NPV indicates that fuel switching will save money compared to the counterfactual over the whole assessment period, whilst a negative NPV suggests the opposite. The LCOA values allow the cost of the CO_2 abatement to be assessed in terms of projected technology and fuel costs, without considering policy measures such as carbon pricing.

For this exercise, only retrofitting of kilns to fire on hydrogen has been considered, rather than replacement of existing kilns with new, hydrogen-fired kilns. It is unlikely that a manufacturer would replace a kiln that isn't at end-of-life, given the significant capital and time costs of replacement. It is also assumed that retrofitting a kiln to hydrogen-firing will not significantly impact the maintenance and repair schedules. For each model, the year of fuel switching was varied from 2022 to 2050, and the NPV and LCOA assessment periods ran from 2022 to 2100.

It is assumed for all models that switching to hydrogen firing has no impact on maintenance schedules, fuel efficiency, production rate, yields/scrap rates, product prices, etc. However, it is likely that there may be some effect on many of these variables, but the data aren't currently available to assess this.

An objective of Phase 2 studies will be to begin to develop this understanding.

The model uses projections for the fuel prices, carbon prices and fuel carbon intensities. Projections produced by BEIS were used for natural gas prices (2020, high estimate), natural gas carbon intensity (2020) and carbon costs (2021, high estimate). Hydrogen was assumed to be green, with the price projection produced by the Climate Change Committee in their sixth UK Carbon Budget used (medium estimate). The carbon intensity for green H_2 assumed renewables as the source of electricity, and the carbon intensity projection used was produced by BEIS (2021). It should be noted that these price projections were all published before the highly volatile prices of the last two years, rendering the absolute values in these models subject to a significant amount of uncertainty. However, benchmark projections must be used, and the costs of natural gas, electricity and hydrogen are coupled, so the relative values can still be compared.

For site 1, the modelling was focused on one kiln. As this kiln runs in campaigns, any downtime associated with retrofitting to hydrogen firing can be subsumed within normal planned downtime. A sensitivity analysis on the retrofitting costs was performed for this site as this is likely to be one of the key factors affecting the economic viability of the switch to hydrogen firing. Retrofitting costs of £500k, £1m, £2m, £3m and £5m were modelled.

For site 2, data were provided for four kilns: two kilns with high firing temperatures; and two kilns with low firing temperatures. Each kiln varies in output (average number of tonnes of product per day), energy consumption (GJ per tonne), refit frequency, and refit cost. An estimate of £200k per kiln for the costs of retrofitting to hydrogen firing was provided and used in the model.

Results

Site 1

Figures 18 and 19 show the NPV and LCOA, respectively, as a function of the year in which the switch to hydrogen firing takes place for site 1. In general, the NPV is negative before 2030, suggesting that switching to hydrogen may not be economically feasible here without changes to the commercial environment. The NPV then becomes positive in the early 2030s, reaching a maximum in the early 2040s, before dropping back down slightly.

The cost of retrofitting the kiln to hydrogen has a clear impact on both the NPV and the LCOA. As might be expected, when the retrofitting cost increases, the NPV values decrease for all years of fuel switching, with greater decreases seen for earlier years of fuel switching, gradually decreasing as the year of fuel switching moves later. One key change is that the year in which the NPV first becomes positive, i.e. the first year in which fuel switching is economically beneficial, moves later with increasing retrofitting cost (Table 2). In addition, when the year-by-year cashflows are considered, the break-even point also moves back in time. Table 2 gives these years for two example fuel switching cases, 2030 and 3035.

Figure 18: ***Net Present Value (NPV) as a function of year of fuel switching for site 1.***

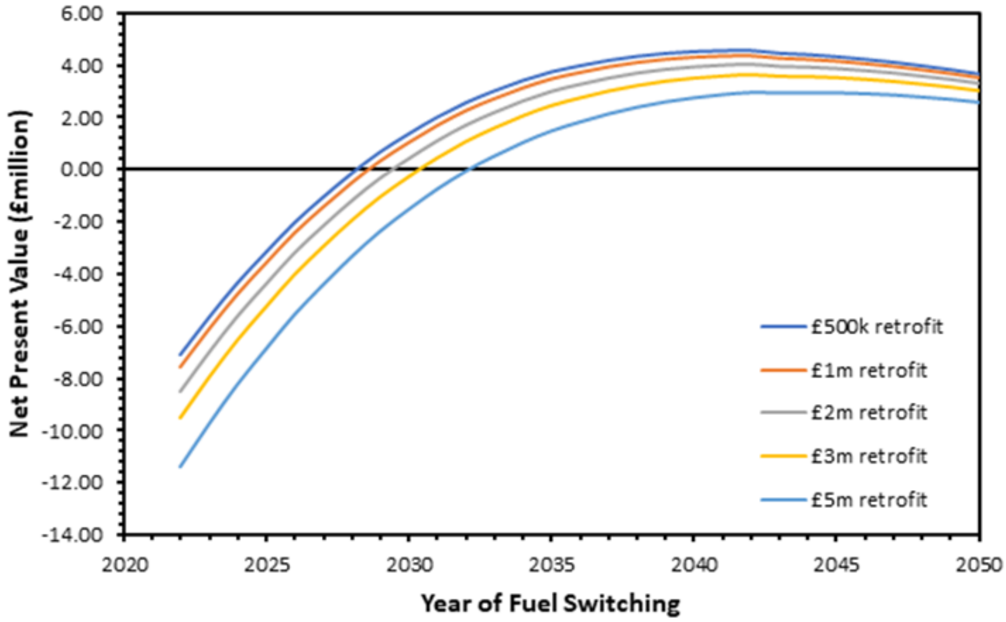


Figure 19: ***Levelised Cost Of Abatement (LCOA) as a function of year of fuel switching for site 1***

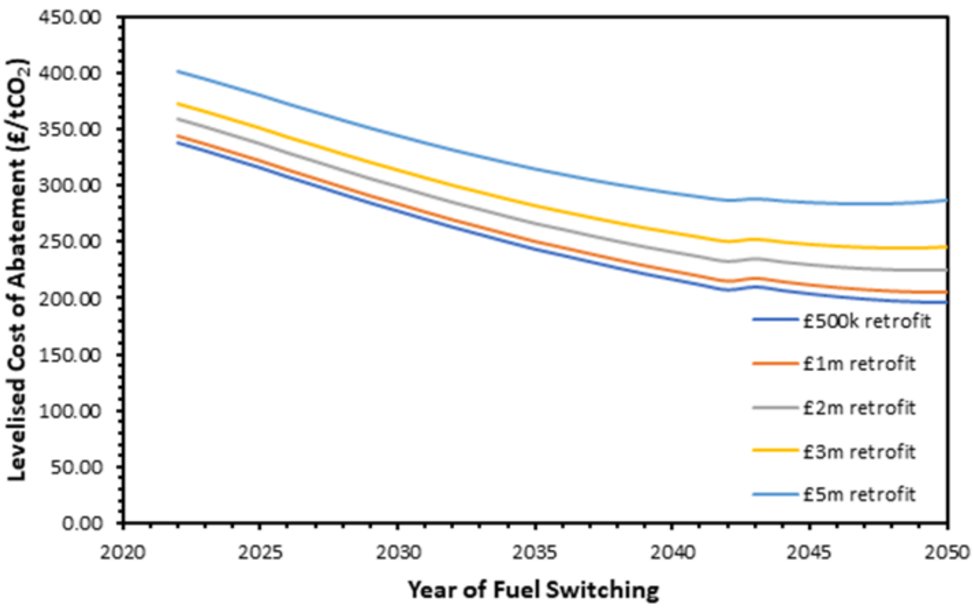


Table 2: ***Year of first positive NPV and cashflow break-even year if switching in 2030 or 2035, as a function of retrofitting cost.***

Retrofitting Cost	First Positive NPV	Break-even year for fuel switching in 2030	Break-even year for fuel switching in 2035
£500k	2029	2062	2050
£1m	2029	2064	2051
£2m	2030	2068	2054
£3m	2031	2072	2056
£5m	2033	2084	2061

The general trend for the LCOA values is approximately inverse to the NPV, i.e. the cost of abatement tends to decrease as switching to hydrogen occurs further away in time. In addition, increasing cost of retrofitting significantly increases the LCOA. LCOA values range from £195 – 340 per tonne CO_2 for a £500k retrofit, to £280 - £400 per tonne CO_2 for a £5m retrofit.

Site 2

Figure 20 shows the Net Present value as a function of year of fuel-switching for each of the four kilns modelled at site 2. The trends vary significantly between each kiln and also show the effect of the company potentially being forced into the ETS. If the ETS regime stays as it is now ('No ETS'), the NPV for all kilns, for all years of fuel-switching, are negative, implying that switching to hydrogen firing at any point under this scenario would result in a net loss for the company. The effect is greatest for kiln 4 and least for kiln 1, with kiln 2 and kiln 3 having almost identical trends. These trends follow the average energy usage per year for each kiln; the higher the rate of energy usage, the more negative the NPV. If it is assumed that the company is forced into the ETS ('ETS from 2030'), generally, the NPV starts negative and then moves to positive in the late 2020s before peaking around 2040, because of the effect of the costs of being in the ETS. The gradient of the increase in NPV increases as kiln 4 > kiln 3 = kiln 2 > kiln 1. Again, this is in order of the rate of energy usage, from high to low.

For the Levelised Cost Of Abatement (LCOA, Figure 21), there is no difference between 'No ETS' and 'ETS from 2030' as the LCOA value does not take into account carbon costs/savings. The trends for each kiln are very similar. Kiln 4 has the lowest LCOA across all years of fuel-switching, followed by kilns 2 and 3, and then kiln 1 had the highest LCOA.

Figure 20: ***Net Present Value (NPV) as a function of year of fuel switching for four kilns at site 2***

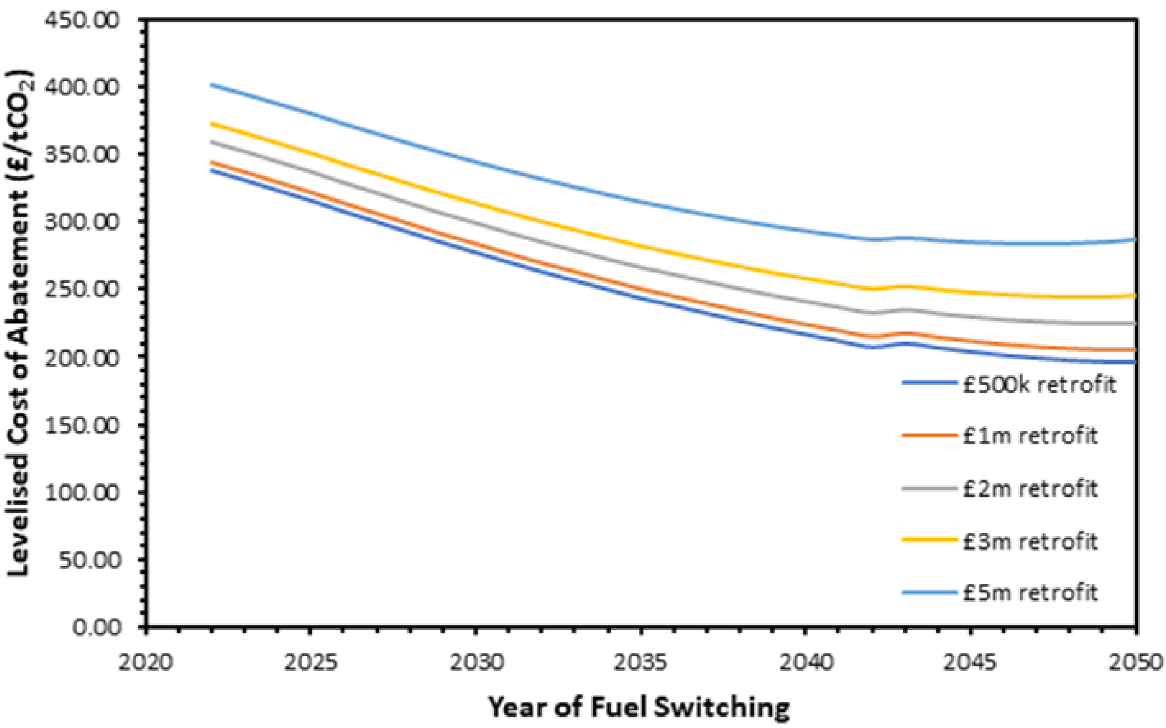
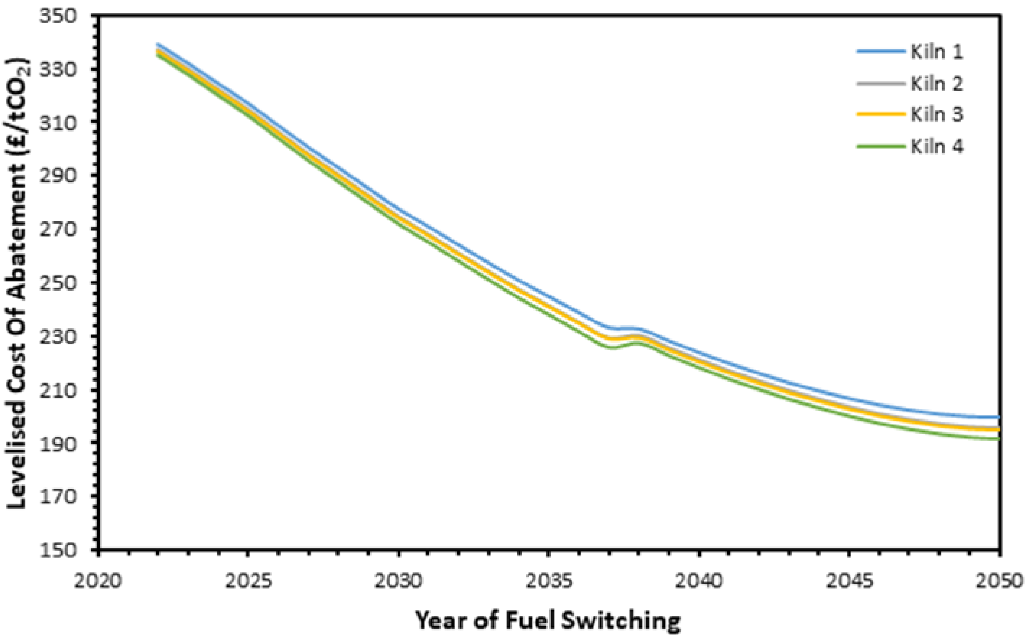


Figure 21: ***Levelised Cost Of Abatement (LCOA) as a function of year of fuel switching for the four kilns at site 2***



Discussion

The modelling results for site 1 are effectively a balance between the increased projected costs of using hydrogen, and the projected savings from reduced CO_2 emissions and hence reduced costs under the ETS programme. The simple model here, with its many assumptions and its dependency on the costs of retrofitting the kiln to hydrogen firing, indicates that it might become economically feasible to switch to hydrogen firing by the 2030s. However, even if this is true in terms of NPV, the ROI values for the switch are potentially in the order of 15 – 30 years. This suggests that, given the assumptions built in, and without other factors (which are currently not considered in this model) impacting these figures, a switch to hydrogen may be unlikely to be in time to fully impact the Net Zero 2050 target. Examples of factors which may play a role in tipping the balance towards earlier fuel switching are:

- Government Policy – e.g. subsidies on fuel costs, increased carbon taxes
- Supply Chain Development – e.g. Advances in hydrogen generation, increase in market competitiveness
- Industry Development – e.g. hydrogen firing increases fuel efficiency, reduces maintenance requirements

As site 2 does not currently fall within the ETS, the modelling of four of the kilns on site focused both on the parameters of the individual kilns, and also considered the impact of the site potentially coming under the scope of ETS. There are three key takeaways from this: 1) The costs of decarbonisation using hydrogen are high and cannot easily be met by the company without support in the form of subsidies or grants; 2) If the site were to come into ETS, there could appear to be an economic driver for switching from natural gas to hydrogen, but this would only be to reduce the extra cost of carbon imposed by the ETS scheme and the extra costs and burden of ETS could mean the company would be unable to continue to operate; 3) In the scenario where the site comes under the ETS, the greatest benefits would be found in switching the kilns with the highest energy consumption rate.

It is extremely important to reiterate that the data do not suggest that ceramics sites must come under the ETS so that switching to hydrogen firing becomes economically feasible, as very small units are rightly recognised as too small to bear the compliance burdens of the scheme, especially given many compliance costs are fixed irrespective of installation size. Instead, it highlights that there must be other factors to balance out the costs of switching to hydrogen firing to make it attractive to manufacturers. As described above, these could be in the form of government subsidies to increase the attractiveness of low carbon technology, or increases in firing efficiency, etc.

Future Work

The key next step recommended is to develop a bespoke model, tailored to the ceramics industry. This would enable more detailed simulations to be performed which more accurately reflect the nature and range of the kilns and production scenarios used by ceramics manufacturers. However, this is a significant piece of work which will require investment of time and resources. In response to this, this work will be incorporated into a bid being submitted to the IFS Phase 2 funding call.

Further work to understand the costs and benefits surrounding switching from natural gas to hydrogen is also required. Examples of such costs/benefits are:

- Cost of retrofitting kilns to hydrogen firing as a function of kiln type, use and size
- Impact of hydrogen firing on fuel efficiency, yield/scrap rates, etc.
- Impact of hydrogen firing on maintenance schedules/requirements/costs/abatement

Social Value

The UK ceramics sector employs 17,500 people directly, with £1.6bn turnover, of which over £600m is exports. There are approximately 150 manufacturing sites across the BCC's membership, collectively emitting 1.2Mt CO_2 per year. With 85% of the sector's energy consumption being from gas, the use of hydrogen as an alternative is seen as a key route to decarbonisation.

In addition, it is anticipated there will be an increased demand for 'green' or 'zero-carbon' ceramic products, especially within the construction sector but also for white goods; if so then early adoption of hydrogen technologies across UK ceramics manufacturers could lead to significant growth across the UK ceramics sector due to the competitive advantage this provides over overseas competitors only able to sell products manufactured using fossil fuels.

The project has engaged with 12 BCC members as project group members, two main contractors (Glass Futures and Otto Simon), kiln suppliers (UK and abroad) and organisations interested in hosting and running trials for the independent kilns. It has generated interest in non-project group members in BCC, with four members expressing interest in joining Phase 2.

With the project demonstrating the potential opportunity to use 100% hydrogen in ceramics manufacturing, it is delivering social value to support the manufacture of low carbon ceramics in the UK. Thus, the project has contributed to the journey of enabling hydrogen as a decarbonisation option.

Work Package 6: Planning for Up-scale

Work Package 6 was designed to carry out detailed planning and scoping for hydrogen trials at a range of industrial-scale ceramic manufacturing facilities. The sites assessed were selected through the information gathered from the questionnaire in Work Packages 1 and 2.

The aim was to carry out or consider the following to enable a FEED study to commence in phase 2:

- Site visit and inspection reports
- Process flow diagrams
- Equipment listings
- Layout drawings with supporting calculations
- Capital cost estimates
- Detailed designs and installation programmes
- Project risk assessments
- Review of site safety concerns

Otto Simon Ltd (OSL) were chosen by the project group to conduct the work. The project group agreed to focus on the Wavin site with a roller hearth kiln as the main candidate for a demonstrator, given the development of an independent batch kiln for off-site trials. Thus, there was a lower level of investigations for the two sites with batch kilns.

A summary of the reports from Otto Simon Ltd are shown below for each of the three sites selected:

- Wavin (Hazlehead, near Sheffield, manufacturing drainage pipes)
- Churchill China (Stoke-on-Trent, manufacturing tableware)
- DSF Refractories (Near Buxton, manufacturing refractories)

Wavin

This report describes the work undertaken by Otto Simon Ltd for the British Ceramic Confederation in connection with the Industrial Fuel Switching project for the Wavin Clay Pipe Manufacturing Facility located at Hazlehead, South Yorkshire. The phase of work now competed has been the conceptual design definition and estimating phase and it is the hope that this work will lead to a Phase 2 FEED study and eventually the execution phase, expected to commence in Spring 2023.

The Site

BCC chose the Wavin site in South Yorkshire as one location for a trial with hydrogen as a fuel. During this initial study, OSL made two visits to the site (4 August and 8 September 2022) to study the logistics of designing and installing suitable trial demonstration equipment, with the following general conclusions drawn:

1. The site is large and there is a considerable area alongside the proposed kiln building for locating a hydrogen supply. This is not always the case and simplifies several design considerations.
2. But the kiln chosen (Roller Kiln #4) is old and it is unlikely that support from equipment suppliers would be available regarding the switch to hydrogen. Also, Wavin (in its earlier guise as Hepworth) acted as the central design entity for the design and build of the kiln when originally installed, implying that there is no system designer or integrator other than Wavin to approach for further assistance.
3. There is no desire to trial using a natural gas and hydrogen blend. This is a simplifying factor for the design of the trial equipment.
4. There is great enthusiasm and support for the trial from the site personnel and this will be important during all subsequent project phases.

The Hazlehead site is approximately 180 acres, although a significant part of the site is now owned by a wood recycling firm and has been used for clay pipe manufacturing since the 1800s. The site is self-contained with a large area of outdoor space and several large structures. It is a COMAH lower tier operator. An aerial shot of the site is shown in Appendix D which illustrates this size and the separation of the proposed hydrogen trial facility from other site locations.

The manufacturing site operates on a 24/7 basis and the production lines operate in campaigns to meet product demand. The total number of personnel on site is around 80, predominantly operational and engineering staff. There are a small number of offices on site which house around 10 employees.

Existing Plant

At the Hazlehead site, Wavin produces a variety of clay pipes from locally sourced clay, the only raw materials used are quarried clay, water and small additions of dolomite, calcium magnesium carbonate.

The site uses butane gas to fuel a thermal process in which the clay is pre-calcined to remove impurities, however the location of the flammable gas storage is not expected to impact upon the design of the hydrogen trial equipment. But it is this butane gas and the quantity stored on-site that gives rise to the COMAH[1] lower tier operational status and Wavin will need to ensure that the appropriate COMAH procedures are followed in respect of the hydrogen addition. These are expected to be formalities only but must be followed.

The other kilns on the site are heated using natural gas from a site distribution system pressure of 40psi (2.75bar) which is reduced down in pressure locally to each plant area.

Roller Kiln ~4 (RK4) is one of three continuous kilns of a unique design which were all built in the 1980s. RK4 produces a single product, 150mm bore sewer pipe at 1.75m length. The clay and water mixture is extruded into pipe lengths and cut to size at the front end of the production line, it is then processed through a drier feeding into the kiln. The kiln feeds product at 175 pipes per hour and takes approximately two hours from the input through to the top temperature 1173°C to the final product temperature of 170°C.

Design and Trial Fundamentals

Process Description

The Process Description document (OSL document number 5004-PRS-002) describes a two-stage pressure let down from road going hydrogen tube trailer providing gaseous hydrogen at 228 bar to a delivery pressure to Roller Kiln #4 at a few hundred of millibar. Two hydrogen tube trailers, on a duty / standby basis, have been assessed as being required and will be parked in a new concrete enclosure to be constructed alongside the building that houses RK4.

The hydrogen pipework into the building will generally follow the route of the existing natural gas supply but once inside the building the precise interface points to the kiln will need to be defined and the pipe route established in detail, taking into account issues such as constructability, the avoidance of potential hydrogen leak points and consequential areas for hydrogen accumulation inside the building and the requirements for the trials themselves. The natural gas pipe arrangement to the kiln is complex and the new hydrogen pipework must be designed with this in mind.

Given the age of the equipment, it is OSL's expectation that there will not be any support from the suppliers of the burners for operation on hydrogen and the likelihood is that replacement burners, with supplier guarantee and support, will be required in the sections of the kiln to be fed with hydrogen. This might be with burners that can operate on both fuels or only with hydrogen and that are then replaced with burners for use with natural gas again.

The majority of the existing exhaust gases are simply discharged to atmosphere (a relatively small proportion is diverted for use in the dryer section of the kiln) and this approach would be retained for the hydrogen trials.

The hydrogen supply equipment includes for emergency manual shut-off via the manual isolation valve to the inlet of the stage 2 skid.

The Layout

Two hydrogen tube trailers will be parked in a new temporary walled enclosure to be constructed alongside the building. This area is currently used as a store of numerous completed products, and these will need to be relocated. The two pressure let-down skids and associated equipment will also be located within this enclosure which will become an exclusion zone whenever hydrogen is on site. The hydrogen supplier will commission its own equipment and then operate it whenever hydrogen is to be supplied.

The pipe route from the compound to the building is straightforward.

The compound will also need to include for the required hydrogen vents which will be positioned to avoid any hazardous area or hydrogen dispersion difficulties.

Quantity of Hydrogen / Design Capacity for the Trial

RK4 contains 13 zones of heating of which there are 7 zones containing burners, zones 7 to 13 (zones 1-6 utilise recirculated hot air). Each burner has an individual remotely controlled gas flowrate setting, within each zone the gas flowrates are the same. The proposal for the trial is to run 100% hydrogen as a direct replacement for natural gas supply on zones 7 and 12 in separate trials.

The proposed trial cycle has been discussed with Wavin personnel and this and other fundamental aspects for the hydrogen trials are recorded in the Trial Fundamentals (see OSL document number 5004-PMR-001). It is envisaged each trial would be run until the hydrogen in the tube trailer(s) is consumed, as this would minimise the impact of the reduced production campaign length for the trial.

A gap of one week is expected to be required between the two trials to set up the next zone, perform isolations, leak test and purging before re-introducing hydrogen.

Based upon our understanding of the gas flow rates, we calculate hydrogen requirements for the trials in Table 1 below. In summary for the trial in zone 7, one tube trailer would allow for around 40 hours of kiln production and in the zone 12 trial, two tube trailers would allow for 11 hours of kiln production. Should further production time be required in each trial additional trailers can be purchased to replace empty units.

Table 3: ***Hydrogen requirements for trial based on 250kg tube-trailers (TT)***

Zone 7 Hydrogen Requirement			
Stage & Basis	H_2, kg/h	Usage, kg	H_2 remaining, kg
Initial hydrogen 1 x TT (250kg)			250
Preheat – 2 x Zone 7 burners low fire (72h)	0.70	50.4	199.6
Dwell – Zone 7 low fire (12h)	3.84	46.1	153.5
Production – Zone 7 low fire (12h)	3.84	46.1	107.4
Remaining H_2 after 24h production	107.4kg		
Additional production available	27.9h		
Total Production time on 1 tube trailer	39.9h		
Total Production time on 2 tube trailers	104.9h		
Each additional full tube trailer will allow 65 hours of further production			
Zone 12 Hydrogen Requirement			
Stage & Basis	H_2, kg/h	Usage, kg	H_2 remaining, kg
Initial hydrogen 2 x TTs (500kg)			500
Preheat – 2 x Zone 12 burners low fire (72h)	2.3	165.6	334.4
Dwell – Zone 12 ave fire (12h)	14.6	175.2	159.2
Production – Zone 12 ave fire (12h)	14.6	175.2	-16
2 tube trailers would allow for 11 hours of production			
Each additional full tube trailer will allow 17 hours of further production			

Issues to Consider

Kiln Complexity

Roller Kiln #4 is a large unit that is split into 13 'zones', each zone being fed with a number of nozzles on either side of the kiln. The different zones are operated at different temperatures to suit the production process. The zones under consideration for the hydrogen trialling are zone #7 (which operates at ~750°C) and zone #12 (which operates at up to 1173°C). The trials would be for each zone in turn, there is no thought of supplying hydrogen to more than one zone at a time.

Hydrogen will need to be supplied to each zone chosen but the existing natural gas is fed to the zones in a single circuit and removing the natural gas supply to zone #7, as an example, also removes the natural gas supply to all subsequent zones. Hence, introducing a hydrogen supply also implies modifying the natural gas supply to all subsequent zones with a zone #7 by-pass in this example. It can be seen that the fuel supply pipework and control will quickly become complex and agreement to the exact zones that are to be fed with hydrogen must be achieved early in the next phase of design if rework and abortive costs are to be avoided.

Each zone has many nozzles and each will need a hydrogen supply. Each nozzle supply includes solenoid valves, a flow control valve and a flowmeter and all will require replacing with hydrogen ready components.

Designing the whole piping system will require careful thought, particularly given the number of potential leak points.

Equipment age

The Roller Kiln #4 was designed and installed in the 1980s and this project was managed by Wavin itself. These factors imply that support from equipment suppliers and designers is highly unlikely to exist. Of particular issue here will be the fuel burner nozzles and there will be no supplier guarantee available for use on hydrogen as a fuel. New fuel burner nozzles will be required for those sections of the kiln that are to be used for the trial, see Section 3.1 above, and the supplier must guarantee their use with hydrogen.

The kiln should also be subjected to a general overhaul and test before any hydrogen trial, it would not be conducive to a successful trial if breakdown of existing equipment was occurring.

Process Safety Aspects

In many ways the engineering considerations related to the use of hydrogen are very similar to those for natural gas, but important differences exist and must be considered.

Loss of Containment

Hydrogen is the smallest element that exists and consequently will readily leak from vessels and pipework where leak paths exist. Therefore, the design and construction will seek to minimise potential leak paths, the pipework will be pre-fabricated as welded sections to minimise flanged joints at site and leak testing after construction will use a helium and nitrogen mix as opposed to just nitrogen; helium being the next smallest element and therefore the most likely method of highlighting potential leaks.

Accumulation

Hydrogen is lighter than air and therefore will generally rise as soon as it escapes from the vessels and pipework. Therefore, the design should seek to avoid areas where escaped hydrogen might accumulate, typically in the apex of a building.

Detectability

Natural gas is odourless but has a Mercaptan stenching agent added so that it is detectable by smell. Hydrogen as available today, for use such as these trials, has not been modified in this manner and therefore is not detectable by smell. The addition of hydrogen detection equipment is often considered a sensible precaution.

Dispersion

Although probably less of a concern for the Wavin site due to its size and space between facilities, assessment of hydrogen dispersion is sometimes undertaken to aid in layout considerations, for example a hydrogen escape from a trailer parked close to a building might result in hydrogen entering the building through open windows. Dispersion modelling can be undertaken to predict dispersion patterns and thereby inform layout considerations.

Invisible Flame

Hydrogen burns with an invisible flame implying that loss of the flame inside equipment such as a kiln might go undetected. The loss of flame inside the kiln would lead to hydrogen accumulation and eventual fire and possible explosion and therefore, when designing for hydrogen use as a fuel alternative, methods of flame detection are used such as Infra-Red.

Escaping hydrogen that is burning might not be detected due to its invisible flame. Hazardous Area Considerations, ATEX specification and positioning of suitable flame detection devices need to be considered whenever designing with hydrogen.

Hydrogen availability

Hydrogen has been in use in industry for decades but tends to be used local to its production facility and very little distribution infrastructure exists beyond these locations. Hence the hydrogen that is distributed further than this is by facilities such as cylinders and road going trailers and quantities are not large. If hydrogen is to become a major component of UK Industries fuel mix this situation will need to change but this change will take many years.[2]

This fuel switching project is one of many such projects ongoing in the UK. The implication for this project is that, when the project is ready to receive hydrogen for the trials, it might be in competition with several others which might affect timing of the trials and quantity of hydrogen available. It is also worthwhile noting that a typical road going hydrogen trailer carries only 250kg of hydrogen. The project must think carefully about the quantity of hydrogen that is required to allow for a meaningful trial and engage with the hydrogen supply chain in sufficient time to gauge availability.

Costs and Sensitivity

Cost Estimate

Based upon our knowledge of the site and the fundamentals of the trial that is required, OSL has developed an indicative cost estimate by calling upon information available from several similar Industrial Fuel Switching projects (details of some of these projects can be found in the original proposal document that OSL submitted to BCC).

Cost Sensitivities

2022 has seen the return of double-digit inflation and many economists predict this to continue to rise and last well into 2023. The equipment and services included within the OSL estimate will not be immune to this issue.

Consequently, an allowance for inflation to costs included in the OSL estimate should be made and the preliminary programme described in Section 5 and included in Appendix C extends into 2024, i.e. almost two years from the estimate's date basis.

Supply chain issues are being seen across many sectors of the economy and many products and items are proving difficult to obtain without extended lead times. A common theme is anything containing computer chips, as there is a worldwide shortage. As a consequence of these issues, OSL is seeing an effect on suppliers and contractors with quotations being provided with very short validity periods, sometimes measured only in days, and with statements regarding cost increases that would be passed on to purchasers. An example statement from a quotation received for a control system fabrication for a current project is copied below:

"*Based upon our current workload, the anticipated manufacturing period will be 12 working weeks to be confirmed at formal proposal from receipt of full and final information, but based upon the current global chip shortages and difficult supply chain challenges we are experiencing we cannot guarantee a definite delivery date*."

We also have quotations for standard items of instrumentation with delivery periods quoted of more than a year.

The estimate is indicative only, based upon factoring from data for other projects, past and present, to this one. This suggests that BCC should allow for a contingency to cover potential scope growth that subsequent design and liaison with potential suppliers and contractors is likely to identify. As a guide an indicative estimate is usually considered to have an accuracy of +/-50% and OSL suggests that BCC considers a 25% contingency as a starting point.

It is important to note the exclusions that are identified along with the estimate presented in Appendix B. Wavin, as site hosts, will have costs that need to be established, BCC will need to use the hydrogen quantity requirements calculated in this report to assist in calculating likely hydrogen fuel supply costs and all other items listed as excluded will need to be considered. Some, such as ground remediation, are unlikely to be required but could be extensive if they are and it would be prudent to check such issues.

Schedule

A preliminary programme through to the completion of the hydrogen trials and decommissioning thereafter is included in Appendix C and allows for 20 months from start to finish, including an initial three-month FEED Study programme.

This programme is based upon OSL's experience from previous projects and would need to be reviewed and qualified after further design definition and approaches to the supply chain.

Conclusions

The initial work completed to date, coupled with OSL's experience from previous and concurrent projects, demonstrates that trialling hydrogen on Wavin's Roller Kiln #4 at the Hazlehead site is well within the capacities of the parties. Detailed design work will be required to establish the final configuration of the trial equipment and it will be important that Wavin and BCC, in its wider role, are in agreement with the design and trial objectives before this detailed design commences.

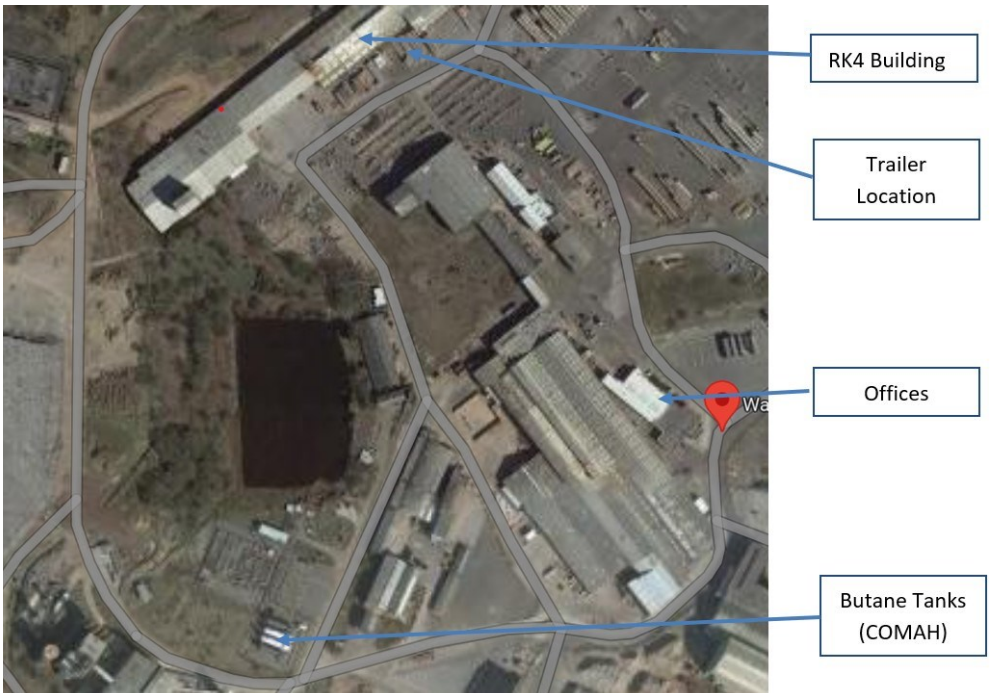
The Hazlehead site is eminently amenable to the proposal. The kiln will most likely need some upgrading, in particular to the burners, but this is not seen as insurmountable.

[1] Control of Major Accidents and Hazards Regulation (2015)

[2] Large scale hydrogen production and distribution programmes across the UK are now moving into execution phases but timescales often run into the 2030s and beyond.

Figure 22: ***Proposed trailer location***

Figure 23: ***Aerial view of the Wavin site***



**** Note numbering and references to Appendices may not be applicable due to this being a summary of the full report***.

Churchill China

The British Ceramic Confederation has asked Otto Simon Limited to make preliminary investigations into the feasibility of trialling hydrogen as a substitute fuel to natural gas at the Churchill China factory in Stoke-on-Trent. To this end Otto Simon Limited and the British Ceramic Confederation visited the Churchill China factory 14th September 2022 to meet and discuss the proposal with staff and to inspect the kiln proposed by Churchill China for these hydrogen trials. The preliminary conclusions from this visit are that the proposal is eminently achievable, and achievable in a controlled and safe manner, but there will be several technical issues to resolve before a successful project could be concluded.

The initial work completed to date, coupled with OSL's experience from previous and concurrent projects, demonstrates that trialling hydrogen on CC's kiln at the Stoke-on-Trent site is well within the capacities of the parties. Detailed design work will be required to establish the final configuration of the trial equipment and it will be important that CC and BCC in its wider role are in agreement with the design and trial objectives before this detailed design commences.

The CC site is amenable to the proposal but will require careful design and some reconfiguration of facilities, storage and personnel. The kiln will most likely need some upgrading, in particular to the burners, but this is not seen as insurmountable.

DSF Refractories

The Site

The site visit, held 16th September, came to the following general conclusions:

- The whole site is large but the production area is busy. However, the site is well isolated from other neighbouring facilities or dwellings and so, although challenges exist, there is a high degree of confidence that a trial could be arranged. For the siting of the required hydrogen tube trailers, we will recommend that specialist hydrogen dispersion modelling should be considered to provide confirmation. An area outside the building in which the chosen kiln is sited is one possible location, see Photographs 5 and 6 in Appendix C but, as the photographs clearly show, this area is heavily used already and would need to be cleared for the duration of the trial build, the trial, and subsequent decommissioning.

- The pipe route from the Photograph 5 and 6 location to the kiln is straightforward, it would follow the apex of the building roof as shown in Photograph 4 which is taken facing away from the kiln and the end wall of the building can be seen.
- The site is busy with many employees. Whenever hydrogen is on-site the trailer area will become an exclusion zone and this will need to be enforced by the site management.
- Whether the existing natural gas burners used on the chosen kiln could be used with hydrogen must be considered unlikely (OSL experience is that a burner manufacturer will need to be engaged for design and support for a hydrogen application).
- The kiln is used intermittently, making it a good choice for a trial.
- There is no desire to trial using a natural gas and hydrogen blend. This is a simplifying factor for the design of the trial equipment.
- There is great enthusiasm and support for the trial from the site personnel and this will be important during all subsequent project phases.

Design and trial fundamentals

Trial fundamentals

The OSL approach to all Industrial Fuel Switching projects is to agree the “Trial Fundamentals” with the project group. This ensures that all requirements for the trial, all constraints that pertain at the site and the general ‘shape’ of the trial to be designed for are identified early, in a simple format, and recorded.

For the trial at DSF, the following fundamentals are suggested:

- The hydrogen trials are to performed in the kiln closest to the building’s northwest wall. This kiln is located in a building alongside other kilns supplied from the same natural gas supply.
- The trial is to be performed on the firing of 100% hydrogen through a full kiln firing cycle. There are no hydrogen and natural gas blending requirements for the trial.
- The trial is to be undertaken on single product only, DSF Refractories to select.
- DSF Refractories’ quality checks are for product colour, shape, consistency and water absorption and can be undertaken for the trial by established testing procedures and techniques.
- The measurements required during the trial shall be:
    - ◊ Hydrogen flowrate (total & instantaneous)
    - ◊ Flue gas moisture content
- The hydrogen tube trailer and pressure let down skid shall be located outside the kiln building in a new temporary compound to be constructed.
- The hydrogen pipeline shall closely follow the apex of the building roof to reach the kiln. The internal route to the kiln shall be reviewed as the project progresses. The building is ventilated but shall be subject to ventilation assessment for hydrogen use.
- New burner nozzles suitable for 100% hydrogen are anticipated, there being no supplier guarantee or support for the existing nozzles for a hydrogen application. It is also possible that existing flame detection won’t be suitable for hydrogen and will need to be replaced.

- The equipment shall be subject to a full service prior to the hydrogen trial.
- There shall be no interruption to normal site operations for the duration of the hydrogen trial.
- All equipment must be safe to operate and failsafe.

<u>Process description</u>

OSL anticipates a two-stage pressure let down from road going hydrogen tube trailer providing gaseous hydrogen at 228 bar to a delivery pressure to the kiln at a few hundred of millibar. Two hydrogen tube trailers, on a duty / standby basis, have been assessed as being required and will be parked in a new concrete enclosure to be constructed close to the building that houses the kiln.

The hydrogen pipework into the building will generally follow the apex of the building roof and be supported from the roof (an assessment of the roof steels will be undertaken during detailed design) but once close to the kiln inside the building the precise interface points to the kiln pipework will need to be defined and the pipe route established in detail taking into account issues such as constructability, the avoidance of potential hydrogen leak points and consequential areas for hydrogen accumulation inside the building and the requirements for the trials themselves. The natural gas pipe arrangement to the kiln is complex and the new hydrogen pipework must be designed with this in mind. However, the piping arrangement that will be required is generally considered to be straightforward.

Given the age of the equipment it is OSL's expectation that there will not be any support from the suppliers of the burners for operation on hydrogen and the likelihood is that replacement burners, with supplier guarantee and support, will be required. This might be with burners that can operate on both fuels or only with hydrogen and that are then replaced with burners for use with natural gas again.

The existing exhaust gases are simply discharged to atmosphere via a larger system and this approach would be retained for the hydrogen trials.

The hydrogen supply equipment includes for emergency manual shut-off via the manual isolation valve to the inlet of the stage 2 skid.

<u>The Layout</u>

The two-hydrogen tube trailer will be parked in a new temporary walled enclosure to be constructed alongside the building, see Photographs 5 and 6. This area is currently used as a store of numerous completed products and these will need to be relocated. Access to some other site facilities will also need to be maintained and an early design task will be for OSL and DSF to agree the basic layout and traffic management arrangements. The two pressure let-down skids and associated equipment will also be located within this enclosure which will become an exclusion zone whenever hydrogen is on-site. The hydrogen supplier will commission its own equipment and then operate it whenever hydrogen is to be supplied.

The compound will also need to include the required hydrogen vents which will be positioned to avoid any hazardous area or hydrogen dispersion difficulties.

<u>Quantity of Hydrogen / Design Capacity for the Trial</u>

As a preliminary assessment OSL considers that two hydrogen trailers, on a duty / standby basis, should be considered for each trial. DSF needs to review how many trials it requires, at the moment the OSL assumption is that a single trial for a single product is required.

The proposed trial cycle needs to be discussed with DSF personnel and this and other fundamental aspects for the hydrogen trials then recorded in the Trial Fundamentals that is to be developed.

Issues to consider

Kiln complexity

The kiln uses several burners around the unit to provide the fuel to the chamber and the new hydrogen pipework will need to match this arrangement. The area is relatively clear, but the proposal would be to employ a laser scanning technique to create an electronic model that can be quickly imported to the OSL 3D Model which will allow for an accurate hydrogen pipework arrangement to be designed in a reasonable period.

The OSL hydrogen supply pipework would interface with the new burners, the natural gas supplies having been isolated beforehand but capable of easy reconnection.

Equipment age

New fuel burner nozzles will be required, and the supplier must guarantee their use with hydrogen.

The kiln should also be subjected to a general overhaul and test before any hydrogen trial, it would not be conducive to a successful trial if breakdown of existing equipment was occurring.

Process Safety Aspects

In many ways the engineering considerations related to the use of hydrogen are very similar to those for natural gas but important differences exist and must be considered.

Loss of Containment

Hydrogen is the smallest element that exists and consequently will readily leak from vessels and pipework where leak paths exist. Therefore, the design and construction will seek to minimise potential leak paths, the pipework will be pre-fabricated as welded sections to minimise flanged joints at site and leak testing after construction will use a helium and nitrogen mix as opposed to just nitrogen, helium being the next smallest element and therefore the most likely method of highlighting potential leaks.

Accumulation

Hydrogen is lighter than air and therefore will generally rise as soon as it escapes from the vessels and pipework. Therefore, the design should seek to avoid areas where escaped hydrogen might accumulate, typically in the apex of a building. Additional ventilation, forced and natural, will need to be considered for this application.

Detectability

Natural gas is odourless but has a Mercaptan stenching agent added so that it is detectable by smell. Hydrogen as available today for use such as these trials has not been modified in this manner and therefore is not detectable by smell. The addition of hydrogen detection equipment is often considered a sensible precaution.

Dispersion

Assessment of hydrogen dispersion is recommended for this application, for example a hydrogen escape from a trailer parked close to a building might result in hydrogen entering the building through open windows. Dispersion modelling can be undertaken to predict dispersion patterns and thereby inform layout considerations.

Invisible Flame

Hydrogen burns with an invisible flame implying that loss of the flame inside equipment such as a kiln might go undetected. The loss of flame inside the kiln would lead to hydrogen accumulation and eventual fire and possible explosion and therefore when designing for hydrogen use as a fuel alternative methods of flame detection are used such as Infra-Red.

Escaping hydrogen that is burning might not be detected due to its invisible flame. Hazardous Area Considerations, ATEX specification and positioning of suitable flame detection devices need to be considered whenever designing with hydrogen.

Building Congestion and Numbers of Personnel on Site

The building that the kiln is housed within is used for numerous operations with several other kilns and operations in place and product and material around, often in close proximity. The site also has a sizeable population and segregation from the hydrogen facilities will be important, although the chosen location for the hydrogen trailers does appear to be well away from many of the other site activities.

Once layout drawings and hazardous area considerations have been undertaken it is highly likely that OSL will be insisting on exclusion zones around the kiln and hydrogen pipe route to it.

Hydrogen Availability

Hydrogen has been in use in industry for decades but tends to be used local to its production facility and very little distribution infrastructure exists beyond these locations. Hence the hydrogen that is distributed further than this is by facilities such as cylinders and road going trailers and quantities are not large. If hydrogen is to become a major component of UK Industries fuel mix this situation will need to change but this change will take many years.[1]

This fuel switching project is one of many such projects ongoing in the UK. The implication for this project is that when the project is ready to receive hydrogen for the trials it might be in competition with several others which might affect timing of the trials and quantity of hydrogen available. It is also worthwhile noting that a typical road going hydrogen trailer carries only 250kg of hydrogen. The project must think carefully about the quantity of hydrogen that is required to allow for a meaningful trial and engage with the hydrogen supply chain in sufficient time to gauge availability.

Costs and sensitivity

Cost Estimate

Based upon our knowledge of the site and the fundamentals of the trial that is required, OSL has developed an indicative cost estimate by calling upon information available from several similar Industrial Fuel Switching projects (details of some of these projects can be found in the original proposal document that OSL submitted to BCC). The estimate is included in Appendix A.

Cost Sensitivities

2022 has seen the return of double-digit inflation and many economists predict this to continue to rise and last well into 2023. The equipment and services included within the OSL estimate will not be immune to this issue.

Consequently, an allowance for inflation to costs included for in the OSL estimate should be made and the preliminary programme described in Section 5 and included in Appendix B extends into 2024, i.e. almost two years from the estimate's date basis.

Supply chain issues are being seen across many sectors of the economy and many products and items are proving difficult to obtain without extended lead times. A common theme is anything containing computer chips as there is a worldwide shortage. As a consequence of these issues, OSL is seeing an effect on suppliers and contractors with quotations being provided with very short validity periods, sometime measured only in days, and with statements regarding cost increases that would be passed on to purchasers. An example statement from a quotation received for a control system fabrication for a current project is copied below:

"Based upon our current workload, the anticipated manufacturing period will be 12 working weeks to be confirmed at formal proposal from receipt of full and final information, but based upon the current global chip shortages and difficult supply chain challenges we are experiencing we cannot guarantee a definite delivery date."

We also have quotations for standard items of instrumentation with delivery periods quoted of more than a year.

The estimate is indicative only, based upon factoring from data for other projects, past and present, to this one. This suggests that BCC should allow for a contingency to cover potential scope growth that subsequent design and liaison with potential suppliers and contractors is likely to identify. As a guide an indicative estimate is usually considered to have an accuracy of +/-50% and OSL suggests that BCC considers a 25% contingency as a starting point.

It is important to note the exclusions that are identified along with the estimate presented in Appendix A. DSF, as site hosts, will have costs that need to be established, BCC will need to use the hydrogen quantity requirements calculated in this report to assist in calculating likely hydrogen fuel supply costs and all other items listed as excluded will need to be considered. Some, such as ground remediation, are unlikely to be required but could be extensive if they are and it would be prudent to check such issues.

Schedule

A preliminary programme through to the completion of the hydrogen trials and decommissioning thereafter is included in Appendix B and allows for 20 months from start to finish including an initial three-month FEED Study programme.

This programme is based upon OSL's experience from previous projects and would need to be reviewed and qualified after further design definition and approaches to the supply chain.

Conclusions

The initial work completed to date, coupled with OSL's experience from previous and concurrent projects, demonstrates that trialling hydrogen on DSF's kiln at the Friden site is well within the capacities of the parties. Detailed design work will be required to establish the final configuration of the trial equipment and it will be important that DSF and BCC in its wider role are in agreement with the design and trial objectives before this detailed design commences.

The DSF site is amenable to the proposal but will require careful design and some reconfiguration of facilities, storage and personnel. The kiln will most likely need some upgrading, in particular to the burners, but this is not seen as insurmountable.

[1] Large scale hydrogen production and distribution programmes across the UK are now moving into execution phases but timescales often run into the 2030s and beyond.

**** Note numbering and references to Appendices may not be applicable due to this being a summary of the full report.***

Figure 24: ***Rear of the building, possible trailer location***

Work Package 7: Project Management and Dissemination

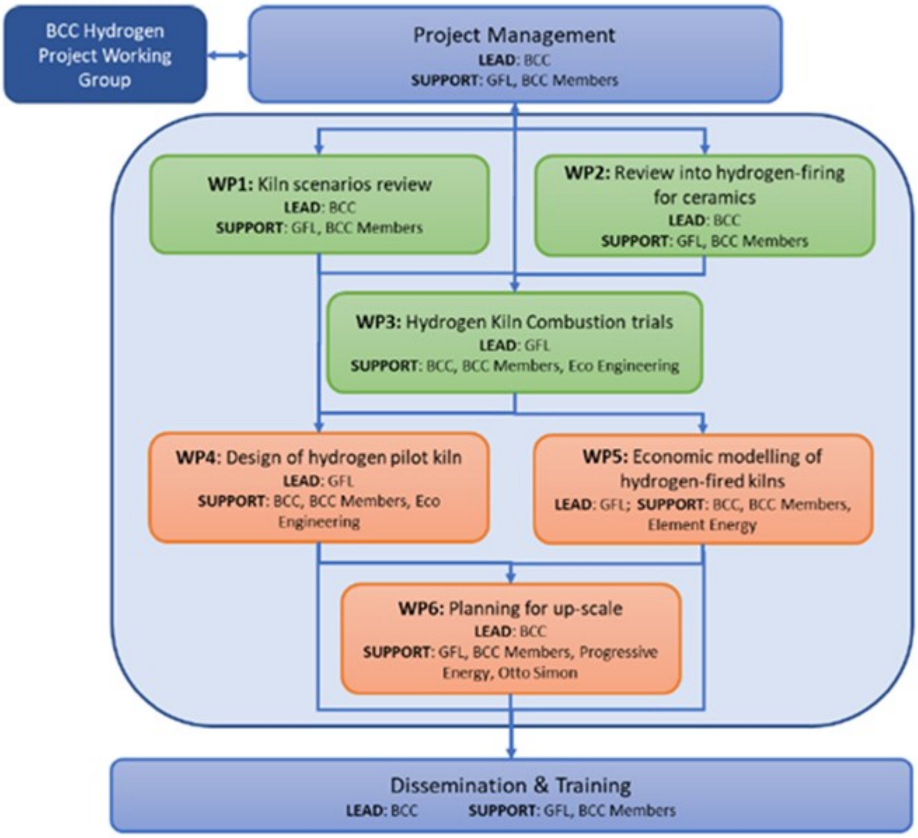
Project Management

The lead for the project was BCC. The main contractor has been Glass Futures who worked on the application and across all the work packages, with Otto Simon a contractor for work package 6.

The chair of the Low Carbon Working Group and the Project Group is Stephane Vissiere, Head of Energy and Major Projects at Wienerberger.

Twelve BCC members were involved in the project: Wienerberger, Churchill China, DSF Refractories and Minerals, Forterra, Hinton Perry Davenhill, Ibstock, Ideal Standard, Johnson Tiles, Marley, Michelmersh, Naylor Drainage, and Wavin. Thus, it has been a project which has worked across the different sub-sectors and products in the ceramic sector.

The project group members supported the application process and costs and provided in-kind support.



The project group held meetings at least once a month to ensure appropriate progress with all the work packages. In addition, weekly project meetings were held between BCC, Glass Futures and the project group chair.

Dissemination

The project has conducted a variety of communications with members and other stakeholders through a variety of channels, including member specific communication, LinkedIn and Twitter.

Hydrogen Project

Trials are now well under way to study the feasibility of using hydrogen as a fuel for the ceramics sector. We have been working closely with not-for-profit research and technology organisation Glass Futures, who produced this video which puts the spotlight on the work.

Tests have included the firing of ceramic products using 100% hydrogen, such as bricks, roof tiles, floor/wall tiles, sanitaryware, refractories, drainage pipes, and tableware.

Thanks to BCC members Churchill China (UK) Ltd, DSF Refractories & Minerals Ltd, Ideal Standard, Johnson Tiles, Ketley Brick, Michelmersh, Naylor Industries, Wavin UK and Wienerberger UK for supplying samples for the project.

We are working with 12 member companies from the BCC's Hydrogen Project Working Group, representing key areas of the ceramics sector.

Click image above to play video

HYDROGEN PROJECT

LinkedIn Posts

British Ceramic Confederation
1,230 followers
3mo •

We are delighted to announce that £300,000 of Department for Business, Energy and Industrial Strategy (BEIS) funding has been awarded for a project to study the feasibility of using hydrogen as a fuel for the ceramics sector as the industry pushes to work towards net zero targets.

The BCC will work on the project with 12 member companies from the BCC's Hydrogen Project Working Group, representing key areas of the ceramics sector (bricks, roof tiles, floor/wall tiles, sanitaryware, refractories, drainage pipes and tableware).

Further support will be provided by not-for-profit research and technology organisation Glass Futures

BCC Energy & Innovation Manager Jon Flitney said: "BCC is delighted to be leading this hydrogen project. We look forward to assessing the feasibility of hydrogen for the ceramics sector and developing proposals for demonstrator projects as part of Phase 2."

Read more https://lnkd.in/eMGuEgY2

Congratulations also to our member Michelmersh Brick Holdings PLC for its successful bid to fund its Deep Decarbonisation of Brick Manufacturing project.

#ceramics #hydrogen #netzero #funding #energy

British Ceramic Confederation
1,416 followers
5mo •

Trials to study the feasibility of hydrogen as a fuel for the ceramics sector are now well under way as part of a £300,000 project funded by the Department for Business, Energy and Industrial Strategy (BEIS)

We have been working closely with not-for-profit research and technology organisation Glass Futures, who are carrying out the trials for the project group. Thanks to Glass Futures also for producing such a great video which puts the spotlight on the work that is under way. https://lnkd.in/e34DBTXJ

Tests have included the firing of ceramic products using 100% hydrogen, such as bricks, roof tiles, floor/wall tiles, sanitaryware, refractories, drainage pipes, and tableware with thanks to BCC members CHURCHILL CHINA (UK) LIMITED, DSF Refractories & Minerals Ltd, Ideal Standard International NV, Johnson Tiles, Ketley Brick Staffordshire Clay Building Products, Michelmersh Brick Holdings PLC, Naylor Industries Plc, Wavin UK, Wienerberger UK and for supplying products for the project.

We are working with 12 member companies from the BCC's Hydrogen Project Working Group, representing key areas of the ceramics sector.

#ceramics #hydrogen #project #technology #industry #manufacturing

Click image above to play video

Twitter Posts

British Ceramic Confederation @ceramfed · May 31
THREAD: We are delighted to announce that £300,000 of @beisgovuk funding has been awarded for a #project to study the feasibility of using #hydrogen as a fuel for the #ceramics sector working with 12 BCC members and @GlassFutures Read more: bit.ly/3PTWmpo 1 / 2

1 3 5

British Ceramic Confederation @ceramfed · May 31
2/2 Congratulations also to our member @mbhplc for its successful bid to fund its Deep #Decarbonisation of Brick Manufacturing project #ceramics

British Ceramic Confederation @ceramfed · Aug 9

THREAD 1/2 Our hydrogen trials are well under way with ceramic products now test fired with 100% hydrogen, working closely with @GlassFutures who are doing the trials and produced this video. youtu.be/xysnD6VXVLw

1 7 10

British Ceramic Confederation @ceramfed · Aug 9

2 / 2 Thanks to @churchill1795 DSF Refractories & Minerals Ltd @IdealStandardUK @JohnsonTiles @KetleyBrick @mbhplc @Naylor_Ind @WavinUK @wienerbergeruk for supplying products as we work with 12 member companies on the #Hydrogen Project.
#ceramics #industry

2 6

British Ceramic Confederation Website Article ***https://www.ceramfed.co.uk/funding-helps-fuel-hydrogen-project-in-push-for-net-zero/***

FUNDING HELPS FUEL HYDROGEN PROJECT IN PUSH FOR NET ZERO

The British Ceramic Confederation (BCC) is delighted to announce that £300,000 of Government funding has been awarded for a project to study the feasibility of using hydrogen as a fuel for the ceramics sector as the industry pushes to work towards net zero targets.

The funding has been awarded by the Department of Business, Energy & Industrial Strategy (BEIS) from the Net Zero Innovation Portfolio (NZIP) which provides funding for low-carbon technologies and systems. The funding is aimed to decrease the costs of decarbonisation, the Portfolio is enabling the UK to end its contribution to climate change.

The BCC will work on the project with 12 member companies from the BCC's Hydrogen Project Working Group, representing key areas of the ceramics sector (bricks, roof tiles, floor/wall tiles, sanitaryware, refractories, drainage pipes and tableware). Further support will be provided by not-for-profit research and technology organisation, Glass Futures.

The 'Hydrogen for the ceramics sector' project will review the feasibility of converting the UK ceramics sector from natural gas fired kilns, to kilns that can be fired with hydrogen fuels (up to 100%), laying the groundwork for industrial-scale hydrogen trials in a Phase 2 follow-on project.

BCC Energy & Innovation Manager Jon Flitney said: "BCC is delighted to be leading this hydrogen project. We look forward to assessing the feasibility of hydrogen for the ceramics sector and developing proposals for demonstrator projects as part of Phase 2."

The project will provide a comprehensive assessment of the feasibility to switch the ceramics sector to hydrogen through:

- A review into current work being undertaken across the globe into hydrogen technologies for the ceramics sector, building links with other groups working in this field
- Undertaking combustion trials to benchmark a range of hydrogen fuel scenarios (up to 100%) against natural gas, assessing the impact o ceramics bodies being fired under such conditions
- Undertaking an economic modelling exercise to assess the costs of switching industrial ceramics sites to hydrogen
- Scoping out and planning industrial-scale hydrogen trials at a range of ceramics manufacturing sites

Hydrogen Project Working Group chair Stephane Vissiere, from Wienerberger, said: "This project will be a step forward to help answer questions about the feasibility of hydrogen in the ceramics sector."

"It is gratifying to see the sector come together in this way, as we all acknowledge the importance of this work as we push to confirm viable routes towards net zero in order to meet 2050 decarbonisation targets."

The group will also look to engage with other industrial sectors and ceramics research groups including outside the UK.

The BCC members involved are Wienerberger, Churchill China, DSF Refractories, Forterra, Hinton Perry & Davenhill, Ibstock, Ideal Standard, Johnson Tiles, Marley, Michelmersh, Naylor and Wavin.

In addition, BCC discussed the project with its Management Committee and Energy and Emission contacts in relevant meetings throughout the project.

BCC provided project group members with specific information and text to use for their own publicity.

The dissemination about the project findings and Phase 2 will continue following the end of the project.

Non-Project Group Member Workshops

BCC held two workshops for members which are not in the project group.

The first was held as a hybrid meeting with in-person attendees at ITM Power, with a tour after the meeting of their green hydrogen electrolysers. There were eight non-project group members in attendance.

The second was held as a hybrid meeting with in-person attendees at Wavin (Hazlehead), one of the sites being considered for a demonstrator in Phase 2. There were four non-project group members in attendance.

Figure 25: ***Photo at Wavin during the non-project group member workshop***

Phase 2 Plans

As a result of the success of the phase 1 feasibility study it is intended to make an application for phase 2 of the Industrial Fuel Switching programme. This would focus on:

- **On-site demonstrator(s):**
    - ◊ At least one of the three sites (Wavin, Churchill China, DSF Refractories) considered for scale up will be taken forward to an on-site demonstrator. As detailed in work package 6, the most likely site to progress to a demonstrator is Wavin and focusing on a trial with 100% hydrogen.
    - ◊ The aim of an on-site trial is to demonstrate the practicalities of using hydrogen in a real-world manufacturing environment.
    - ◊ Please see Work Package 6 for further details.

- **Off-site demonstrator:**
    - ◊ The purchase of a batch / intermittent kiln by a Phase 2 project to be hosted and trials run at a third party location using both blends of methane / hydrogen and 100% hydrogen.
    - ◊ The reason for this kiln is an individual site is designed for a process to make the site's particular product. As detailed in other parts of this report the ceramics sector includes a wide variety of products, firing temperatures and other process conditions, for example the atmosphere in the kiln. It means even with several on-site demonstrators the whole project group may not be adequately represented.
    - ◊ This means an independent kiln run by the project group and hosted and run at a third party site will give maximum opportunity to run trials suitable to all project group members and allow tailoring of the firing conditions.
    - ◊ Please see Work Package 4 for further details.

Conclusions

It is concluded the firing trials have demonstrated the potential of firing ceramics using 100% hydrogen, with the test results indicating comparability to 100% methane-fired products. Many of the products were within the required technical specifications, with deviations occurring for both methane and hydrogen-fired samples depending on the extent of divergence between the test firing cycle and routine production firing curves, with the compromises selected naturally resulting in overfiring for some and underfiring for others.

However, as largely expected there are lessons to take forward to Phase 2. Using a kiln specifically designed for ceramics will enable a wider range of compositions, products and firing atmospheres to be more closely evaluated. In addition, on-site demonstrators will give an understanding about using hydrogen in an industrial environment and using real world kilns.

The project has developed three potential on-site demonstrators (one in detail), through work led by Otto Simon. An off-site demonstrator has also been developed given the variety of products and firing cycles in the sector.

In addition, the project has considered other hydrogen projects in the UK and further afield which has helped guide future work. It conducted economic modelling to assess the financial viability of switching to hydrogen for a selection of member sites in the project group, which demonstrated when hydrogen could be financially beneficial (early 2030s) and also when it could be the most financially optimal time (early 2040s) to switch to hydrogen.

The project has also engaged, and will continue to afterwards, with BCC members who were not in the project, along with wider publicity and dissemination.

As a result, BCC will apply for Phase 2 Industrial Fuel Switching funding for a demonstrator project to take forward the information and knowledge learned from this feasibility study into the use of hydrogen in the ceramics sector.

Assessment of Whether Aims were Achieved

1. Undertaking preliminary hydrogen combustion trials (at various blends of natural gas/hydrogen) for representative ceramic body firing cycles. **Complete, three sets of firings conducted with 100% methane and 100% hydrogen.**
2. Reviewing current work being undertaken by and building links with other groups, across the globe, working on the use of hydrogen within the ceramics sector. **Complete, has also informed Phase 2 work.**
3. Scope out and design a flexible pilot-scale kiln/s capable of assessing hydrogen firing (if suitable equipment not identified in the initial review exercise). **Complete, slightly different direction with procurement of independent batch kiln being proposed.**
4. Develop an economic model to assess the costs of switching industrial ceramics sites to hydrogen. **Complete, to build upon in Phase 2.**
5. Detailed scoping, planning and design for industrial-scale hydrogen trials at ceramics manufacturing sites. **Complete, focus on one site with roller hearth kiln, with less detailed work on two batch kiln sites.**

TRL Assessment

It was considered the use of hydrogen was TRL 4, defined as technology validated in a laboratory, prior to this project starting. With the completion of the project, it is considered to have progressed to TRL 5 (technology demonstrated in a relevant environment), although noting the environment was an adapted rig with generic firing cycles rather than necessarily specific conditions for any individual product. It was also focused on 100% hydrogen.

It is viewed the plans for Phase 2 could move the technology to TRL 6 (technology demonstrated in relevant environment) via the independent kiln demonstrator and to TRL 7 (system prototype demonstration in operational environment) through the on-site demonstrators.

Acknowledgements

The British Ceramic Confederation would like to acknowledge and express gratitude for the support and contributions it has received throughout the duration of the project.

We would like to note the contributions from the following organisations:

BEIS (Department for Business, Energy & Industrial Strategy)
Churchill China
DSF Refractories & Minerals
Eco Engineering
Forterra
Glass Futures
Hinton Perry Davenhill
Ibstock
Ideal Standard
Johnson Tiles
Marley
Michelmersh
Mott MacDonald
Naylor Drainage
Otto Simon Ltd
Wavin
Wienerberger