BEIS Energy Innovation Programme

Alternatives to Natural Gas for High Calcium Lime
Manufacturing: Hydrogen

FS4243

Final Report
July 2022

Executive Summary

Lime production is an essential UK industry that supports civil society and manufacturing. Fuel switching from natural gas to hydrogen offers a means to decarbonise production and support the transition to a net zero economy. This full-scale demonstration project aimed to understand the issues associated with such a switch.

The project examined all potential regulatory constraints and found that Environmental Permitting Regulations in England were relevant to the demonstration project. Based on the experience of this project, early engagement with the environmental regulator is desirable as they are likely to require changes to permits, even for demonstration trials.

Before the demonstration enabling works began, Computational Fluid Dynamic (CFD) modelling assessed the potential impacts of fuel switching from natural gas to hydrogen and so allowed optimisation of the project approach. Due to the transient nature of lime production, accurate CFD calculations would have taken years of computing power to complete. Therefore, averaged steady state conditions were assumed. Consequently, the accuracy of the CFD models was reduced.

The CFD modelling (and site-based Energy and Mass Balance) indicated that high levels of hydrogen substitution could result in damage to refractory kiln linings, increased NOx emissions, and product sintering, leading to kiln blockages. Based on the results of modelling, the project approached fuel switching to hydrogen with a reducing total energy input as the level of hydrogen substitution increased.

Process safety was a key concern and extensive standard assessments were conducted iteratively to ensure adequate process control and safety. These standard processes worked well for the project.

System modifications included changes to refractory linings and insulation to accommodate hydrogen firing and potentially higher resultant temperatures. New exhaust gas analysers were introduced to monitor NOx. Standard Operating Procedures, developed with input across all project roles, worked well. Systems were checked using nitrogen before commissioning to ensure they would work effectively when hydrogen was introduced.

The demonstration project showed that at low levels of hydrogen substitution (20% by volume) there is limited impact on kiln operation, lime product or emissions to air. However, at increasing substitution levels there are significant challenges in terms of kiln operation – risking sintering and kiln blockages. NOx emissions appeared to be lower than predicted by the CFD modelling, and manageable without the need to install additional abatement equipment.

CFD modelling was used to assess the potential for fuel switching from natural gas to hydrogen in Parallel Flow Regenerative (PFR) kilns. The modelling looked at a steady

state conditions, which can reasonably be expected to exist during the kiln cycles. The CFD modelling highlighted that product sintering leading to kiln blockages is the biggest risk presented by fuel switching, echoing the CFD modelling and practical experience on the vertical shaft kiln.

Based on the evidence gained from this project, it would be possible to convert lime manufacturing to run on a 20% v/v blend with natural gas, requiring investment between £240,000 and £360,000 per kiln – that is, between £4.5 and £7.5 million for the UK lime sector.

Capital costs to transfer to 100% hydrogen fuelled manufacturing are significantly more uncertain but, based on the experience from this project, investment of around £4 million would be needed for a lime manufacturing site with four natural gas fired kilns and if no changes to kiln refractories, kiln burning zones, NOx abatement or bag filter equipment were required.

Given the variability between manufacturing sites and the uncertainty on mitigating works, transferring the UK lime sector to 100% hydrogen firing on could require new investment between £60 and £120 million, highlighting the need for a stable and predictable policy environment.

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1 Introduction

Summary and Key Learning

Lime production is an essential UK industry that supports civil society and manufacturing. Fuel switching from natural gas to hydrogen offers a means to decarbonise production and support the transition to a net zero economy. Key parameters assessed under this project include:

- Gas density/calorific value, combustion stoichiometry, and flame speed and temperature and the impact on kiln performance and product quality

- NOx, other emissions to air and exhaust gas moisture content, including the formation of emission products in the kiln, and the impact on emissions control systems

- The long-term embrittlement and degradation of materials in kiln systems, including damage to refractories.

1.1 Introduction to lime manufacturing

Producers manufacture high calcium lime – also known as quicklime - through high temperature kiln processes heating calcium carbonate – from limestones or chalk - to drive off carbon dioxide. The chemical equation describes this process:

$$CaCO_3 + heat \rightarrow CaO + CO_2$$
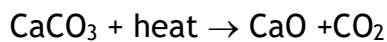
This chemical reaction occurs at about 1,000 °C and is known as calcination. The residence time of the stone in a kiln varies depending on the type of kiln and type of final product required but can be anything between six hours and two days. Emissions of CO_2 arise from the combustion of fuel (around 25%) and from the calcination of the raw materials (around 75%). The CO_2 emissions from fuel are known as 'combustion emissions' and the emissions from calcination are called 'process emissions'. For ease of reading, this document refers to 'lime' rather than high calcium lime or quicklime, from this point onward.

The UK requires high purity limes to service diverse markets, such as mortars and renders, iron and steel manufacturing, soil stabilisation, emissions control, water / wastewater treatment, and pharmaceuticals and cosmetics. To meet the demands of these markets, producers manufacture UK lime from high purity limestone. Natural gas is the preferred fuel as it introduces few impurities into the product and is readily available through the national gas transmission system. It

Figure 1: Industries supplied by lime

Industries supported by lime

- Construction
- Iron & Steel
- Water treatment
- Emissions control
- Agriculture
- Food production
- Paper products
- Glass making
- Plastics
- Pharmaceuticals
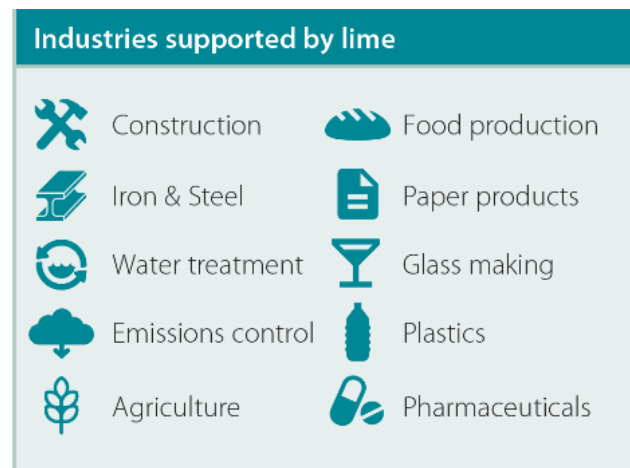
also has lower carbon emissions when compared to solid fuel alternatives such as coal or lignite.

In the UK, manufacturers produce lime using two types of gas-fired kiln; vertical shaft kilns and parallel flow regenerative (PFR) kilns – widely considered to be the most energy efficient. Investment by the UK lime sector in kiln technologies over recent decades means that, unlike continental Europe and other parts of the globe, there is no high calcium lime manufactured using less efficient horizontal kilns.

All kilns have three heat transfer zones:

Preheating zone - heating the kiln feed limestone to approximately 800 °C by direct contact with gases leaving the calcining zone.

Calcining zone – burning the combustion fuel in preheated air from the cooling zone, producing temperatures of around 1,000 °C necessary for calcination.

Cooling zone – cooling lime leaving the calcining zone by direct contact with 'cooling' air.

For limes manufactured using natural gas, the quality of the product is commonly based on its residual CO_2 content, which is a function of the degree of calcination –a product with lower CO_2 content has more lime content (CaO) and less residual limestone ($CaCO_3$). A second aspect of quality relates to the 'reactivity' that affects the rate of reaction of the product with water (although it also relates to its reactivity with other substances). Some markets prefer a high reactivity product - a 'soft burnt lime' –whilst a lower reactivity, 'hard burnt lime' is specified for others.
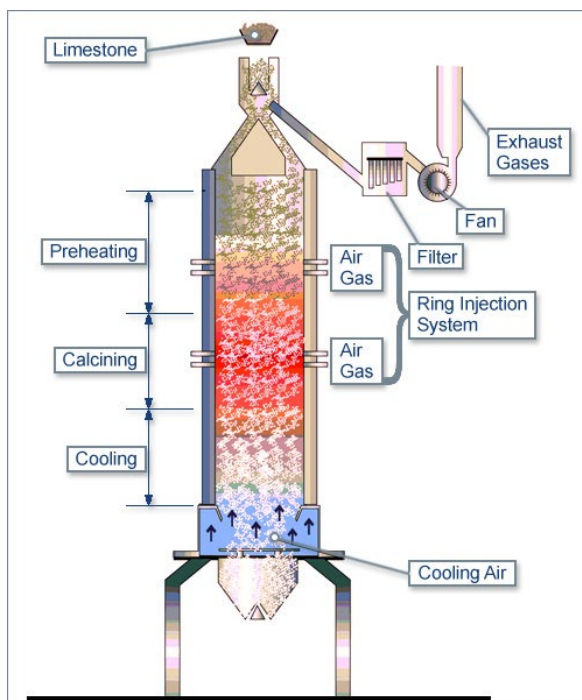
Figure 2: Vertical shaft kiln
Vertical shaft kilns feed limestone, preheated by the exhaust gases, in at the top of the kiln. Combustion of natural gas mixed with air provides the heat for calcination. Inlets feed air – preheated by the exhaust gas - into the kiln alongside the gas fuel. Fans draw the exhaust air out of the kiln – thus the kiln operates under negative pressure. In addition, the negative pressure draws air in at the bottom of the kiln, cooling the product as it leaves, thus preheating the air before combustion in the calcining zone.

The cooled product leaves the kiln at around 50 °C.
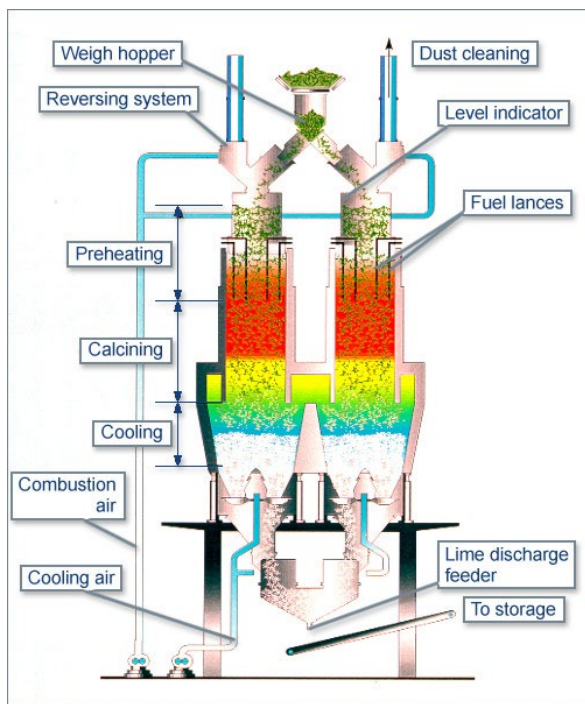
Figure 3: Parallel Flow Regenerative kiln
PFR kilns fire two inter-connected vertical shafts in sequence to maximise energy efficiency. The different shafts work in cycles, one firing whilst the other is cooling. The kiln firing cycles every five to fifteen minutes, depending on the kiln set and the product in manufacture.

The firing process in one shaft uses the 'waste' heat from the other to preheat side combustion air, whilst the exhaust gases preheat the limestone kiln feed, as with vertical shaft kilns.

PFR kilns are under positive pressure with air blown in from the base of the kiln.

1.2 Transition to net zero manufacturing

The UK lime sector can only fully decarbonise when carbon capture use and/or storage (CCUS) is commercially available to eliminate the process CO_2 emissions from limestone/chalk. The sector is actively engaged with the Track 1 industrial clusters[1] with a view to decarbonising production at the earliest opportunity.

Although the sector will be reliant on CCUS to achieve net zero manufacturing, it remains important to switch from high carbon fossil fuels to low carbon alternatives. As described in section 1.3, there is potential for the gas grid to include increasing quantities of hydrogen. In addition to this external change affecting the sector, fuel switching to low carbon hydrogen offers opportunities to lower CO_2 emissions before the deployment of CCUS and minimises the of carbon is sent for storage. Lime manufacturing using natural gas is a well understood, although highly technical, process. There are no examples of replacement gaseous fuels for natural gas which would maintain the quality of the lime product required in the UK. This makes alternatives, such as raw biogas or upgraded biomethane from anaerobic digestion and hydrogen, attractive areas of innovation. These products readily align with existing manufacturing processes and experience and offer the most effective opportunities to reduce the carbon footprint of the lime manufacturing sector dependent on fossil fuels.

There are some parts of Europe where PFR kilns have been adapted to run on solid biomass fuels, which lowers the carbon footprint of the manufactured lime. However, the reactivity of the product is generally lower than is currently sold in UK markets, and the investment for conversion to biomass burning has been made

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[1] https://questions-statements.parliament.uk/written-statements/detail/2021-10-19/hcws325

possible by local subsidies and/or an abundance of biomass. In general, the kilns using biomass are smaller than in the UK, and almost all these kilns are found in Southern Europe. The high level of investment required, the scale of UK manufacturing, the impact on product quality and the security of supply of sustainable biomass suitable for lime manufacturing make this technology unsuitable for general deployment across the UK sector.

For UK lime, manufacturers have already made significant investment in the sector to move to the most energy efficient kiln types, running on clean burning natural gas. Biogas/biomethane might be a transitional technology that could reduce emissions although the quantities required for full fuel switching are unlikely to be achievable. However, current subsidies, e.g., for electricity generation using biogas or for biomethane production and grid injection, mean that there is no business case for generating and injecting biogas/biomethane into lime kilns for unsubsidised direct firing.

Hydrogen is a viable fuel alternative for UK lime manufacturing. To enable fuel switching and the transition to net zero manufacturing, hydrogen needs to be readily available and affordable at the point of use. In addition, manufacturers need assurance regarding security of hydrogen supply before switchover as uncontrolled shutdowns can impair the operating lifespan of kilns.

Kilns generally operate continuously for between five and ten years. As such, manufacturers plan investments in lime manufacturing years in advance to ensure they retain operational and commercial resilience. Maintenance and retrofit operations take place at high temperatures by specialist staff and under strict health and safety controls. Hence. the transition to hydrogen needs strategic planning and will take several years to complete across all lime manufacturing assets. Consequently, investment in fuel switching will need stable business models that provide support to the sector for the long-term transition to hydrogen fuels.

1.3 Hydrogen as a fuel for lime manufacturing

The Government Hydrogen Strategy notes that low carbon hydrogen will be vital for the decarbonisation of hard to electrify industrial sectors, which includes the lime sector[2]. The strategy aims for 5 GW of low carbon hydrogen production by 2030 and the recent Energy Security Strategy doubles this ambition to 10 GW[3]. The Track 1 industrial clusters are targeting over 10 GW of hydrogen production by the mid-2030s[4, 5]. As an energy and carbon intensive manufacturing process currently reliant on natural gas, it is crucial for the UK lime sector, and the diverse markets using lime, that manufacturers are prepared to use hydrogen. Whilst running on hydrogen

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[2] https://www.gov.uk/government/publications/uk-hydrogen-strategy
[3] https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy
[4] https://www.zerocarbonhumber.co.uk/
[5] https://hynet.co.uk/

is clearly feasible, resolving the uncertainties require practical demonstrations– such as this project.

The replacement of natural gas with hydrogen to manufacture high quality lime to meet UK standards is extremely innovative. There are examples of lime kilns running on 'coke oven gas' from steel manufacture[6]. Raw coke oven gas contains between 39 – 65% hydrogen and producers often clean it to recover by-products (such as tar/light oils) before use, and to remove some contaminants (e.g., sulphur). Coke oven gas is a mixture of hydrogen, carbon monoxide and carbon dioxide and the lime manufactured using this gas is commonly used in metal refining as a flux, and not as the type of lime product sold into UK markets. Nevertheless, this indicates the potential to manufacture lime using hydrogen as a fuel and supported the need to demonstrate the technology in UK lime manufacturing.

The British Lime Association (BLA) has reviewed the challenges of using hydrogen as a fuel for UK lime manufacturing (Table 1). Some of the tabulated challenges have limited relevance to lime manufacturing in vertical kilns, some are believed to have a low probability of affecting manufacturing processes, and some are expected to present significant uncertainty.

Table 1:   Summary of challenges of using hydrogen as a fuel compared to natural gas

Property	Challenge
Challenges presenting significant uncertainty	
Low density/calorific value	Hydrogen has a calorific value around one third of the energy per cubic metre compared to natural gas - this will change the volumetric flows (and therefore velocity) of gas entering the kiln
Combustion stoichiometry	The lower oxygen requirement means lower combustion air requirement - affecting the volumetric flows (and therefore velocity) of gas entering the kiln; lower velocities may adversely affect fuel and air mixing
Flame speed	The shorter flame may affect the degree of heating in the central positions within the shaft
Explosivity	The lower explosive limit for hydrogen is much lower than for carbon monoxide (4% v/v compared to 12.5% v/v); imperfect mixing in a lime kiln fired by natural gas results in low levels of carbon monoxide in the exhaust gas but any residual hydrogen from combustion could result in explosive conditions in the kiln outlet

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[6] European Commission, JRC Reference Reports, Best Available Techniques (BAT) Reference Document for Iron and Steel Production, 2013 - https://eippcb.jrc.ec.europa.eu/reference/i&s.html

Property	Challenge
Flame temperature	The higher temperature flame is more likely to damage fuel inlets, refractory linings and affect product quality
NOx and other emissions	As a result of the higher flame temperature, NOx and other emissions may increase
Water combustion products	Combustion of hydrogen forms water that increases the moisture content of kiln gases and potentially causes condensation in the exhaust systems
Degradation	Damage to materials in kiln systems and a higher maintenance requirement from the use of hydrogen fuels
Challenges believed to have a low probability of affecting manufacturing processes	
Flammability/Flame arrest	Hydrogen is more prone to flashback
Challenges with limited relevant to lime manufacturing	
Molecule size	Small hydrogen molecules are more likely to leak through joints and seals
High diffusivity	Hydrogen leaks are more likely to disperse quickly.
Odour free	Hydrogen leak detection is more problematic compared to natural gas and its mercaptan additives
Flame visibility	Process control challenges arise as flame detection is difficult
Lower flame emissivity	Lower heat radiated from the flame should have limited impact as lime manufacturing in a shaft type kiln is not dependent on thermal radiation

This project took the bold step of trialling hydrogen as an alternative fuel for existing kiln systems with a view to clearly indicating whether hydrogen firing is possible or desirable within the sector – fundamental knowledge that will inform the future strategic direction of the lime industry, in the UK and across the globe. Demonstrating the viability of hydrogen as an alternative fuel for lime manufacturing, accompanied by the challenges conversion presents, enables future operational and capital investment to prepare the sector to be 'hydrogen-ready'. This project can assess short-term impacts, for example, implications on production and product quality. Longer term implications of hydrogen use will require longer term studies – for example, in process monitoring and control systems, emissions control, and in maintenance schedules.

1.4 Challenges presenting significant uncertainty

1.4.1 Gas density/calorific value, combustion stoichiometry, flame speed and temperature

Lime kilns do not 'inject' gas into burners instead they feed natural gas into the kiln through inlet pipes, mixed with the air blown into the kilns close to where the gas enters. In addition, cooling air, drawn up the kiln through the base, also enters the calcination zone. The air and fuel mix and combust creating the temperatures needed for limestone calcination.

In vertical shaft kilns, the gas, and the side combustion air (waft air), are fed through separate ports in the side of the kiln. The gas is fed into the kiln through specifically designed ports called 'gas nozzles'. This type of kiln is reliant on the fuel and air to mix within the kiln to ensure effective distribution of the gas.

In PFR kilns, the gas enters through an array of narrow pipes, called lances, which project into the kiln and are evenly distributed across the top of the kiln (shown in Figure 4). As such, PFR kilns are far less reliant on the air flow and mixing across the cross-section of the kiln to ensure the even distribution of heat.

Figure 4: **Lance array at the top of a PFR kiln (photo courtesy of Lhoist UK)**

Effective lime manufacturing relies on the correct temperature profile throughout the kiln to achieve the preferred product quality.

Given the counter-current nature of the heating, and the importance of gas distribution and mixing with air, to achieve the correct kiln conditions for lime manufacturing, there will be a greater challenge in the adoption of hydrogen as a fuel for 'side-fired' vertical shaft kilns than for 'lance-fired' PFR kilns. The learning from the introduction of hydrogen fuel to vertical shaft kilns will have direct application in PFR kilns but conversely, learning from PFR kilns would not be directly applicable to vertical shaft kilns. Hence, a vertical shaft kiln was the preferred technology for this project.

Vertical shaft kilns run using excess air to ensure complete combustion in the kiln. Hydrogen requires less air for combustion than natural gas so it should be possible to maintain the required quantity of excess air in the kiln and avoid issues relating to gas volume in the kiln.

However, a lower air input reduces the temperature of the exhaust gas and there may be consequences in preheating combustion air. This will have consequences for energy efficiency within the kiln. Additional uncertainties surround:

- Heat recovery – the effectiveness of the preheating of limestone by exhaust gases and of the cooling air by the lime product.

- Exhaust gas temperature – significant changes in the exhaust gas temperature may affect stack emissions – for example, the performance of dedusting systems.

1.4.2   NOx, other emissions to air and exhaust gas moisture content

NOx from high temperature processes, including lime manufacturing, is generated from two sources: fuel NOx and thermal NOx.

The oxidation of nitrogen in fuels during combustion produces fuel NOx. Hence, the lower the nitrogen content of the fuel, the lower the fuel NOx generated[6]. Fuel NOx formation should not be a problem as both natural gas and hydrogen contain low levels of nitrogen.

The production of thermal NOx usually occurs at temperatures above 1,300 ˚C, far above the temperatures achieved in lime kilns although flame temperatures on kilns may be more 1,300 ˚C and some parts of kilns systems may exceed this temperature. Some thermal NOx is produced in lime kilns, but not to the extent that secondary abatement is required - that is, there is no requirement for additional technology to remove NOx from emissions to air.

Lime kilns heat limestone to around, on average, 1,000 ˚C to produce high reactivity calcium oxide. For these products, higher temperatures are generally undesirable as the lime is sintered by the heat and reactivity is lower. Some markets welcome sintered products but these are usually produced from dolomitic lime (a calcium magnesium oxide) using horizontal kilns running on solid fuels and achieving higher temperatures.

When using hydrogen fuel, the higher flame temperature of hydrogen, and the uncertainty regarding heat distribution through the kiln, may result in higher peak temperatures at certain points in the kiln, and thus higher thermal NOx production.

Whilst not highlighted in the literature, the formation of SO_2 may present an issue depending on the extent of limestone calcination, which depends on the mixing of the fuel and limestone in the kiln and the temperatures achieved. Commonly, SO_2 emissions from lime manufacturing are low, because of the low sulphur content of limestone and natural gas, and because the lime produced absorbs SO_2 produced in the kiln. The cleaning of industrial exhaust gases to remove SO_2 is a key market for UK lime products. Depending on the air flows within the kiln, it is possible that hydrogen sulphide (H_2S) may form where there is an absence of oxygen. Maintaining the excess air in the kiln will ensure adequate combustion and should help prevent the formation of H_2S. Given the purity of the hydrogen available in the UK for these demonstration trials, formation of SO_2 or H_2S is unlikely to be an issue.

Similarly, dioxin formation during lime manufacturing is generally not an issue because of the high temperatures of the kiln and the low levels of chloride in the input materials. Dioxins commonly form at temperatures between 300 °C and 450 °C. Recommended approaches to avoid dioxin formation in lime kilns is to limit the time exhaust gases spend in this temperature range, and to limit the oxygen available to these gases at this temperature.

In an equivalent manner to NOx and SO_2 formation, whilst the introduction of hydrogen fuel will not specifically encourage the formation of dioxin emissions, the changes in the mixing, temperature profiles and air flows within the kiln may affect dioxin formation. Testing for dioxins is not commonplace for lime manufacturing and addressing this concern will require baseline testing and testing during a demonstration project. This requires a long sampling period to collect sufficient gas for testing since dioxins form in such small quantities. Given the low probability of dioxin formation and the difficulty in sampling on short-term demonstration trials, this project is not assessing dioxin formation.

Water is the reaction product of hydrogen combustion and hence likely to result in increased moisture content in the kiln exhaust gases. This will mean a higher dew point in the exhaust gas and the increased probability of condensation in the emissions control systems. In the case of bag filters used to remove particulate matter from emissions to air, this could result in an increased pressure drop, reduced bag life and filter housing corrosion. Average exhaust gas temperatures during a demonstration trial will predict the likelihood of significant condensation but identifying localised issues and impacts of variations between filters need longer demonstration trials. It is unlikely that increased moisture content in exhaust gases will significantly affect emissions control by wet scrubbers.

1.4.3 Degradation of materials in kiln systems

Embrittlement of metals in contact with hydrogen is a well-known phenomenon but is unlikely to be a cause of failure of pipes during a demonstration project, if at all.

The impact of hydrogen on non-metallic elements within kilns is unknown and it could affect refractories because of the changes to temperature profiles within the kiln and different fuel and air flow characteristics. It may be possible to see obvious signs of damage to kiln refractories during a demonstration project using hydrogen, but it is more likely that this will similarly be a long-term degradation that will only become apparent following conversion of existing systems to hydrogen. However, the project considers the impacts of high temperatures on kiln refractories given its importance to lime manufacturing.

Degradation due to hydrogen firing: The potential lining wear through silicon monoxide gas (SiO(g)) evolution from the refractories was identified as a low risk. A well-known phenomenon of hydrogen reduction of SiO_2 to SiO(g), known as "silica stripping", can affect aluminosilicate refractories at temperatures exceeding 800 °C. However, from supplier experience the reduction process is not significant until 1,150 °C, and specifically applies to hydrocarbon cracking processes which yield

hydrogen; as a fuel, rather than a manufacturing process that fuelled by hydrogen and therefore presents few issues.

Degradation due to water vapour stability: As noted above, firing using hydrogen will create a considerable amount of water vapour that can be detrimental to certain refractories, for example magnesia (MgO) based refractories may undergo hydration expansions up to 115%; conversely aluminosilicate refractories remain unaffected.

1.5 Challenges believed to have a low probability of impact

1.5.1 Flammability/flame arrest

The 'challenge' of flammability/flame arrest is representative of the larger challenge of using a hydrogen as a fuel. Ensuring that fuel systems can cope with the use of hydrogen fuel into the kiln is an important safety requirement. Current process controls provide adequate layers of protection and automatic fail-safes to ensure that the high temperature processes remain continuously under control when burning natural gas. The adaptability of these systems to work with hydrogen fuel is an important feature of this demonstration trial.

1.6 Challenges with limited relevance to lime manufacturing

1.6.1 Molecule size, diffusivity, and odour

Preventative maintenance and monitoring to avoid leaks and to quickly stop any natural gas leaks that occur is an important aspect of effective management of lime manufacturing. Leaks of natural gas represent a safety and fire risk, reduce manufacturing efficiency and are a direct cost to the business. This experience will be an advantage to the lime industry when running on hydrogen. Whilst manufacturers are likely to make changes to the inspection regimes, monitoring techniques and failsafe systems, the principles of safe management will remain unchanged. Whilst natural gas has mercaptan odour additions to aid leak detection, this is not a key means of leak detection in an industrial environment. Thus, the addition of odour to hydrogen will not be an essential safety requirement for its use in lime manufacturing.

1.6.2 Flame visibility

Except during kiln light up, management of lime kilns is not dependent on a visible flame, but instead relies on temperature profiles, monitoring gas flows, and similar process controls. Thus, the lack of a visible flame is unlikely to have a significant impact in the industrial setting. Alternative methods to address flame visibility during kiln light-up will be needed in the longer term but are not an insurmountable barrier to hydrogen fuel conversion.

1.6.3 Lower flame emissivity

Lime kilns are all shaft type kilns and so rely on heat convection, rather than radiant heat; hence, flame emissivity is unlikely to be an issue for lime manufacturing.

1.7 Organisations involved in the project

The project involved the following organisations:

- **The Mineral Products Association and the British Lime Association**: The British Lime Association (BLA), a Product Group within the Mineral Products Association (MPA), managed the project. The MPA is the trade association for the aggregates, asphalt, cement, concrete, dimension stone, lime, mortar, and silica sand industries (www.mineralproducts.org)

- **Tarmac Buxton Lime**: The demonstration trials took place at the Tarmac Buxton Lime Tunstead site. Tarmac Buxton Lime (a CRH company) is a global leader in the supply of lime and limestone solutions that works with associated companies operating in Germany, the Czech Republic, Ireland, Poland, and Russia to serve markets in Europe and the rest of the world. The company is a member of the MPA and the BLA (www.tarmacbuxtonlime.com).

- **Stopford**: Stopford, an international energy and environmental consultancy, provided process design and safety assessments as well on-site technical support during the demonstration trials (www.stopford.co.uk).

- **EESAC**: EESAC delivered technical oversight of the Computational Fluid Dynamic (CFD) modelling for both the demonstration vertical shaft kiln and a PFR kiln. EESAC have specialist expertise in lime manufacturing and provided the interface between the BLA Members and their CFD provider (www.eesac.eu).

- **BOC**: BOC (a Linde company) supplied the hydrogen in tube trailers and provided a reception skid to reduce hydrogen gas pressure from around 230 barg (as delivered) to 10 barg. BOC is the largest provider of industrial, medical, and special gases in the UK and Ireland and has been producing atmospheric gases, including oxygen, nitrogen, and argon for over 120 years.

- **Lhoist UK**: The Lhoist Group is a global leader in lime, dolomitic lime and minerals. The main centre of Lhoist UK operations in the Peak District deliver high purity products that underpin its longstanding success. Lhoist UK provided the technical data and expertise for the PFR kiln CFD modelling. The company is a member of the MPA and the BLA (www.lhoist.com/uk).

- **Singleton Birch**: Singleton Birch is the UK's leading independent lime supplier based in North Lincolnshire. The company is a member of the MPA and the BLA and provided technical input in the PFR kiln CFD modelling (www.singletonbirch.co.uk).

1.8 Project governance

Figure 5 shows the governance structure and project team for the project. The COVID-19 outbreak and the availability of hydrogen in the UK delayed the project.

The COVID-19 pandemic impacted project, leading to a delay to the project end date. During the pandemic, the Tarmac Buxton Lime Tunstead site operated on an essential-personnel-only basis, delaying the on-site project related tasks until the

situation changed allowing staff and contractors assigned to the project back on-site.

In addition, BOC had to prioritise oxygen supply and any related engineering work for medical needs due to the pandemic, over the production of hydrogen. This resulted in delays to the engineering designs for the project hydrogen infrastructure and delays to the supply of hydrogen.

The MPA Project Manager maintained a comprehensive risk assessment for the project that BEIS reviewed in monthly meetings.

Figure 5: Project team structure
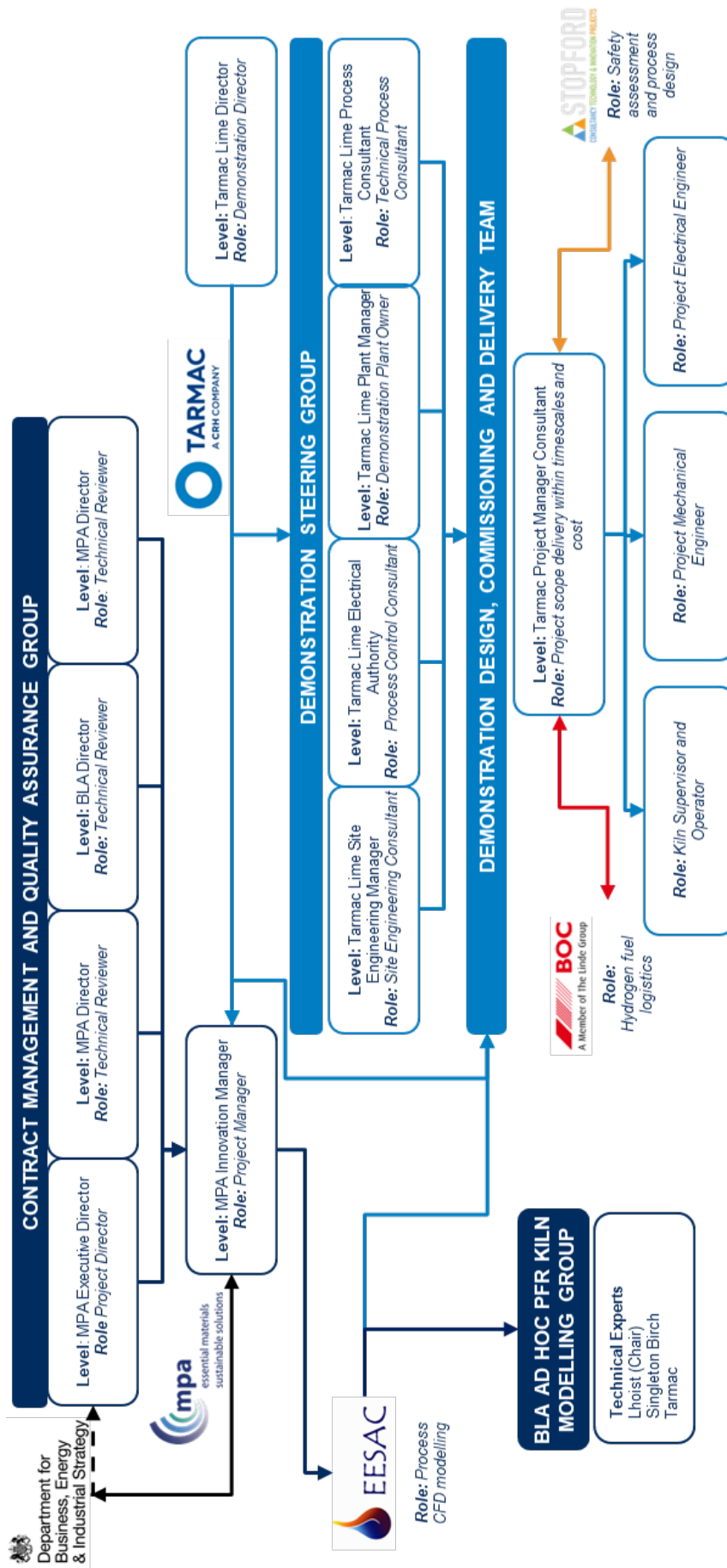
2   Pre-Trial Planning and Assessment

Summary and Key Learning

Prior to the demonstration trial, the project assessed three pieces of legislation:

- Planning Regulations.

- Environmental Permitting Regulations.

- Control of Major Accident Hazards (COMAH) Regulations.

Environmental Permitting Regulations in England were relevant to this demonstration project, planning and COMAH conditions were not. Based on the experience of this project, the environmental regulator is likely to require changes to permits, even for demonstration trials, meaning early engagement with the environmental regulator is desirable.

2.1   Planning Regulations

Due to the temporary nature of the demonstration trial, the project did not require additional planning permission to proceed. However, out of courtesy and to maintain good ongoing communications, Tarmac Buxton Lime notified the Local Authority of the project and its scope.

2.2   Environmental Permitting Regulations

Industrial scale lime manufacturing is within the scope of the Environmental Permitting Regulations (EPR) in England[7] and the Tarmac Buxton Lime Tunstead site operates under a permit issued by the Environment Agency (EA). The demonstration project was first discussed with the EA on 28th January 2020 with a view to understanding if any changes to the permit were required given the short-term nature of the project, its low risk of environmental impact, and its relation to decarbonisation innovation.

Legal advice from within the EA stated that there was no exemption to the permitting of this project and as such, required a permit variation for the research and development activities. Obtaining a permit variation requires operators (in this case Tarmac Buxton Lime) to request a change to their permit conditions through an extensive application process. There is a fee for this application process that depends on the complexity of the proposed change (for example, a minor, normal significant variation).

However, given the importance of the project, and as the EA did not want to be a barrier to net zero innovation, the EA implemented a 'prioritised normal variation', with EA staff made specifically available to work on the variation when it was received. Tarmac Buxton Lime made an application to the EA on 1st May 2020 to vary the Tunstead site environmental permit to enable the use of the shaft kilns for a

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[7]   Similar Regulations apply in Northern Ireland, Scotland and Wales and lime manufacturing would also be in scope of these Regulations.

demonstration trial involving the introduction of hydrogen gas into the normal natural gas stream used to heat the shaft kilns. The EA granted the variation on 9th November 2020.

Additional conditions set out in the permit variation approved by the EA included providing a written report to the EA detailing the dates of the demonstration trials and the performance impacts during the demonstration trial for activity. There were no changes to the environmental monitoring requirements on-site.

Following approval of the application to vary the permit, Tarmac Buxton Lime kept the EA informed of project progress (including a site visit). From the initial discussion to permitting approval took around 11 months to complete using the prioritised process. The EA recognised the need for future regulatory flexibility to enable innovation and are looking at how to achieve this outcome.

Currently, the route for future environmental permitting of innovations remains unclear. This project has highlighted that environment permitting can be a barrier that projects need to tackle at the earliest opportunity. In addition to presenting a potential barrier to research and development projects, it is possible that First of a Kind (FOAK) projects to deliver hydrogen fuel switching (or potentially other innovations), and First in Class projects (applying existing technology into a new sectors) may also encounter barriers derived from environmental regulation.

2.3 Control of Major Accident Hazards (COMAH) Regulations

The purpose of the COMAH Regulations is to prevent major accidents involving dangerous substances and limit the consequences to people and the environment if any accidents occur. An establishment having any specified dangerous substance present at or above the qualifying quantity is subject to the Regulations. There are two threshold levels for dangerous substances under COMAH. The threshold quantities vary for differing categories of substances. For more information on the COMAH Regulations visit the Health and Safety Executive website (www.hse.gov.uk/comah).

The volume of hazardous substances (including hydrogen) held on-site during the demonstration project did not trigger the lower tier or the need for a Hazardous Substances Application under the Regulations.

Where an operating site utilises more than one "hazardous substance" above or equal to a relevant controlled quantity, then an "aggregation" rule is applied to determine whether the site is covered by the relevant requirements in the Regulations. In the case of this project, after accounting for the aggregate quantities of hazardous substances held on-site during the demonstration project, then the relevant controlled quantity of hydrogen would be around 4.5 te (tonnes equivalent). As the maximum amount of hydrogen held on-site at any one time would be less than 2.5 te, the project did not fall within the scope of COMAH Regulations.

3   Modelling Fuel Switching on the Vertical Shaft Kiln

Summary and Key Learning

Computational Fluid Dynamic (CFD) modelling assessed the potential impacts of fuel switching from natural gas to hydrogen and so allowed optimisation of the project approach. The modelling was only able to look at a steady state conditions, which approximate kiln conditions but do not reproduce.

The CFD modelling highlighted that high levels of hydrogen substitution could result in damage to refractory kiln linings, increased NOx emissions, and product sintering leading to kiln blockages. Based on the results of modelling, the project approached fuel switching to hydrogen with a reducing total energy input as the level of hydrogen substitution increased.

3.1   Computational Fluid Dynamic (CFD) modelling

To assess the possible impacts from substituting natural gas with hydrogen in a vertical shaft kiln operating at the Tarmac Buxton Lime Tunstead site, Computational Fluid Dynamic (CFD) modelling was carried out. CFD modelling was used to predict the heat transfer, temperature profiles and calcination levels in lime kilns operated in steady state conditions. The CFD model selected in this study is the one developed by CINAR specifically for lime kilns (www.cinar.co.uk). The technical interface between the project team and the CFD modellers was provided by EESAC.

The operation mode of the Tarmac Buxton Lime vertical shaft kilns is unique in the lime sector, making the exact modelling of the burning conditions extremely challenging. To accurately model the burning conditions would require transient CFD calculations that take years of computing power to complete. Therefore, a simplification of the modelling was crucial. Consequently, limitations in the results of the CFD modelling are expected. For most of the CFD scenarios averaged steady state conditions were assumed. In one case, the real burning conditions prevailing during a 1-minute phase were modelled to check the sensitivity of the modelling assumptions on the numerical results.

Initially, five scenarios were modelled – a base case (BC) and four alternative cases (AC) with differing hydrogen substitution levels:

1.   BC: Base Case - Current operation with 100% natural gas firing.

2.   AC 23%:   50% on a volumetric basis hydrogen substitution. This equates to 23% (energy basis).

3.   AC 50%:   77% on a volumetric basis hydrogen substitution. This equates to 50% (energy basis).

4.   AC 50%-P: Similar to scenario 3 but assuming fewer inlets in operation representing the conditions prevailing in the kiln during 1 minute of the burning cycle.

5.   AC 100%:   100% hydrogen substitution.

Full detail of these calculations is given in Annex A.

Figure 6:   CFD modelling results showing temperature distribution in a vertical shaft kiln fired using
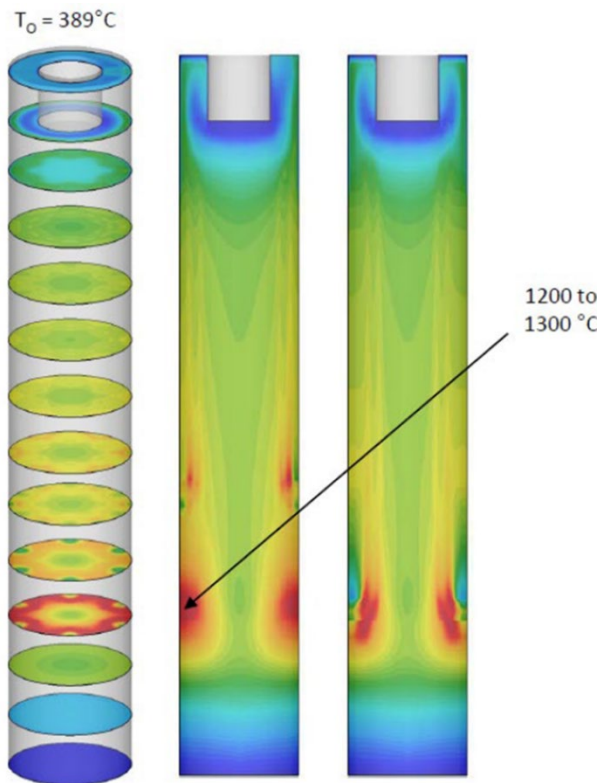
Figure 7:   Illustration of the Tarmac Buxton Lime Energy and Mass Balance (EMB) model (information redacted)
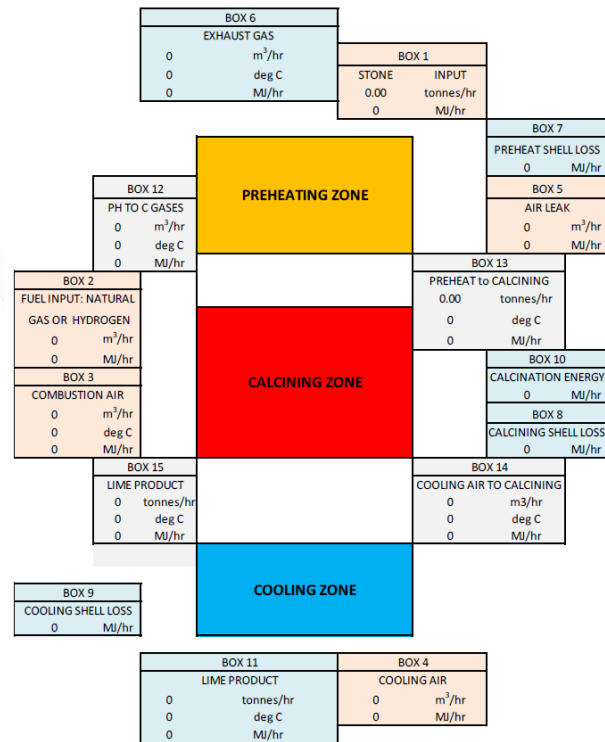
Due to the requirement to simplify the CFD calculations and assume steady state conditions, Tarmac Buxton Lime carried out Energy and Mass Balance (EMB) modelling to help predict the potential impact on several process parameters and to calculate the process inputs to be used during the demonstration trials.

The CFD and EMB models use different approaches to model the kiln data. The EMB model uses known kiln mass and energy inputs and outputs to create a balanced model of the kiln in the preheating, calcining, and cooling zones. Varying mass and energy inputs (e.g., fuel type and quantity) are then input into the EMB model and the outputs are recalculated to achieve an overall kiln balance in terms of input and outputs, in all three zones. This modelling approach has its limitations in that It balances mass and energy but cannot calculate internal kiln parameters such as NOx generation, kiln bed temperatures or internal exhaust gas temperatures. However, it does calculate external (flue) exhaust gas temperature.

The CFD model aims to look at the kiln internal flows and temperatures in more detail and provides a prediction of the impact of changing the fuel input, not only

on kiln outputs, but also on NOx generation, kiln bed temperatures, and internal exhaust gas temperatures and flows.

Both models assume steady state conditions and under these circumstances there is good agreement between several parameters used in the base case. As noted above, because the CFD model used a steady state assumption it is not able to accurately predict parameters such as kiln temperatures, calcination levels or NOx emissions for the base case. However, the CFD does provide an indication of relative impact of increasing hydrogen substitution on these parameters.

With the EMB model, as the hydrogen input is increased, the calculations rebalance the kiln outputs. This can be achieved in several ways, for example, increasing the calcination level or reducing the energy input. For this project, the balance was achieved by reducing the energy input to maintain the base case calcination levels.

With the CFD initial scenarios, as the hydrogen input increased, the predicted calcination levels increased (from a known underestimate in the base case). The kiln bed, internal exhaust gas temperatures as well as NOx emissions also increased. Operating the kiln under these conditions would inevitably lead to a blockage and refractory damage. A further scenario was modelled using a similar energy reduction as used in the EMB model for the 77% (v/v) substitution level.

3.2 Modelling results

3.2.1   Exhaust gases

The CFD and EMB models were in close agreement on the major components of the exhaust gas. They both calculated a similar decrease in CO_2 and CO and an increase in H_2O with increasing hydrogen fuel substitution. The CFD model predicted a lower-than-expected base case NOx value, compared to the base case data – meaning that the absolute value predicted by the model could not be used. However, the model predicted a possible threefold increase with 77% (v/v) hydrogen substitution and tenfold increase at 100% replacement. This strongly indicates that the NOx emissions will increase significantly. The shaft kilns have a typical NOx emission of 60 mg/Nm^3 and the permitted limit is 150 mg/Nm^3.

The CFD model predicted much higher exhaust gas temperatures than the EMB model (over 100 $^\circ$C higher than the base case data), but both agreed that the temperature would decrease, and the moisture would increase as the hydrogen input was increased.

3.2.2   Calcination levels

The CFD model predicted much lower calcination levels than expected, due mainly to the limitations of the model, as described above. It also predicted an increase in calcination levels as the hydrogen substitution levels were increased. The EMB model reduced the specific energy input as the hydrogen levels were increased to maintain a constant calcination level; the specific energy input can be reduced due to the increased kiln energy efficiency that is expected with hydrogen combustion.

3.2.3　Bed and gas temperatures

The CFD model predicted an increase in both the internal exhaust gas and bed temperatures in the kiln as the hydrogen substitution increased, up to 90 °C at 77% v/v substitution and 176 °C at 100% substitution. Again, the absolute value of this increase is unlikely to be accurate but suggests that there is high potential for temperature increases that would result in 'over-burning' of the lime. This would lead to a lower reactivity product and there is a strong possibility of sintering and kiln blockage. There would also be the possibility of refractory damage. The EMB model did not calculate kiln temperatures but reduced the specific energy input as the hydrogen substitution level increased.

3.2.4　Lime discharge temperatures

The CFD model predicted lime temperatures about 200 °C above the base case data. However, it predicted little or no impact on lime discharge temperatures with increased hydrogen substitution.

3.3　Additional modelling

Both the CFD and EMB modelling concluded that if the shaft kiln was run without changes in operation, that is, with identical energy inputs, stoichiometric factors, amounts of cooling air, and so on, running at 50% v/v substitution by hydrogen is to have little impact (AC 22.8%). However, with 77% v/v to 100% hydrogen substitution the models raised the concern that high temperatures could lead to refractory damage, lime over-burning (sintering) and NOx emissions exceeding emission thresholds.

Based on these conclusions, two further scenarios were CFD modelled:

1. AC 50%-NPAW:　Equating to 77% (v/v basis) hydrogen substitution and using cold side combustion air.

2. AC 50%-LE:　Equating to 77% (v/v basis) hydrogen substitution and reducing the total thermal energy input into the kiln by 5% - so a lower total energy input.

Full details of these additional CFD scenarios can be found in Annexes B and C

3.3.1　Cold combustion air option (AC 50%-NPAW)

The combustion air in a shaft kiln is supplied from two sources, namely the cooling air that is preheated by the hot lime in the cooling zone, and the side fired combustion air also known as the "waft air". The combustion air is preheated in the heat exchanger used to cool the kiln exhaust gases.

An additional scenario, reducing the temperature of the side combustion air was CFD modelled. The model predicted reductions in both the internal kiln temperatures and NOx emission values compared to the same model with side combustion air that had passed through the heat exchanger (AC 50%).

The modelling indicates that kiln temperatures would reduce to below base case levels and NOx emissions to less than 50% of the base case. This would be a sixfold

reduction compared to the CFD scenario at 50% hydrogen substitution with preheated side combustion air (AC 50%). However, modelling also predicted lower calcination levels, which indicates increased specific energy input would be needed to achieve the correct level of calcination.

Since installation of preheated combustion air in 2005, which would have increased the natural gas flame temperature, the shaft kilns have required reduced kiln energy input and have not seen any increase in NOx emissions or decrease in product reactivity.

3.3.2   Lower total energy input option (AC 50%-LE)

The EMB model predicted that a 5% reduction in specific energy at the 77% v/v hydrogen substitution level would result in a similar calcination level to the base case. To assess the likely impact on kiln conditions, this scenario was CFD modelled.

The CFD model predicted similar calcination levels compared to the base case (which were lower than the predictions from EMB model base case). It also predicted 30% lower NOx emissions compared to the 77% v/v substitution without the lower total energy input (AC50%). This CFD modelled scenario also predicted smaller increases in bed and internal exhaust gas temperatures; about 20 °C above the CFD modelled base case compared to 70–90 °C above the base case for the AC50% scenario.

3.4 Conclusions from the CFD and EMB modelling of shaft kilns

Although there are limitations to both the CFD and the EMB models, the results provide evidence that reducing the total energy input into the kiln with increasing hydrogen fuel substitution reduces the likelihood of:

1. Refractory damage
2. High NOx emissions
3. Potential for sintering (which could block the kiln)

This information was used to design the kiln demonstration trials.

4 Process Design and Control Philosophy

> ## Summary and Key Learning
>
> Process safety was a key concern and extensive standard assessments were conducted iteratively to ensure adequate process control and safety. These standard processes worked well for the project. Risks were minimised through:
>
> - Design – e.g., engineering compliance, following the actions arising from the HAZOP and LOPA studies to ensure the safe introduction of hydrogen to the existing kiln process.
>
> - Control – e.g., including slam shut valves for over-pressurisation, setting maximum valve opening levels, measuring gas flow at multiple points.
>
> - Procedures – e.g., standard operating procedures to minimise human error, designating competent operators.
>
> - Remedial works – e.g., upgrading to existing infrastructure to mitigate risks.
>
> - Commissioning – e.g., ensuring safe operation using nitrogen, planning for increasing hydrogen substitution.
>
> - Monitoring – e.g., monitoring emissions to understand environmental impacts, continuously monitoring gas flows.
>
> - Mitigation – e.g., designating safety zones around key equipment and requiring, for example, the use of anti-static personal protective equipment.

4.1 Process safety

Process safety assessment provides assurance that risks are adequately controlled. Assessments highlight weaknesses in control systems and aim to avoid major incidents through failures in control and management systems. Key assessments undertaken for this project include:

- HAZOP – Hazard and Operability Assessment
- DSEAR – Dangerous Substances and Explosive Atmosphere Regulations Assessment
- LOPA – Layer of Protection Analysis

4.1.1 HAZOP - Hazard and Operability Assessment

HAZOP study is a recognised technique for evaluating the risks arising from deviations to the design intent of a project. In this case, the project is the use of hydrogen fuel in place of natural gas in a vertical shaft kiln. The hydrogen firing process was subdivided into discrete blocks and subjected to rigorous, line by line review. The blocks are described below and shown schematically in Fig

Trailer discharge: Connection of the BOC hydrogen trailers to the No. 1 Skid

No1 Skid: A two stage pressure reduction system supplied by BOC

No2 Skid: A singlet stage pressure reduction system supplied by FT Pipeline Systems – referred to as the FTP skid.

Upper stage gas inlet: Hydrogen flow to the upper gas inlets on the kiln

Lower stage gas inlet: Hydrogen flow to the lower gas inlets on the kiln

Remaining kiln system: Remaining kiln system including kiln shell, refractory and emissions monitoring

Figure 8: Schematic diagram of 'blocks' used during the HAZOP assessment
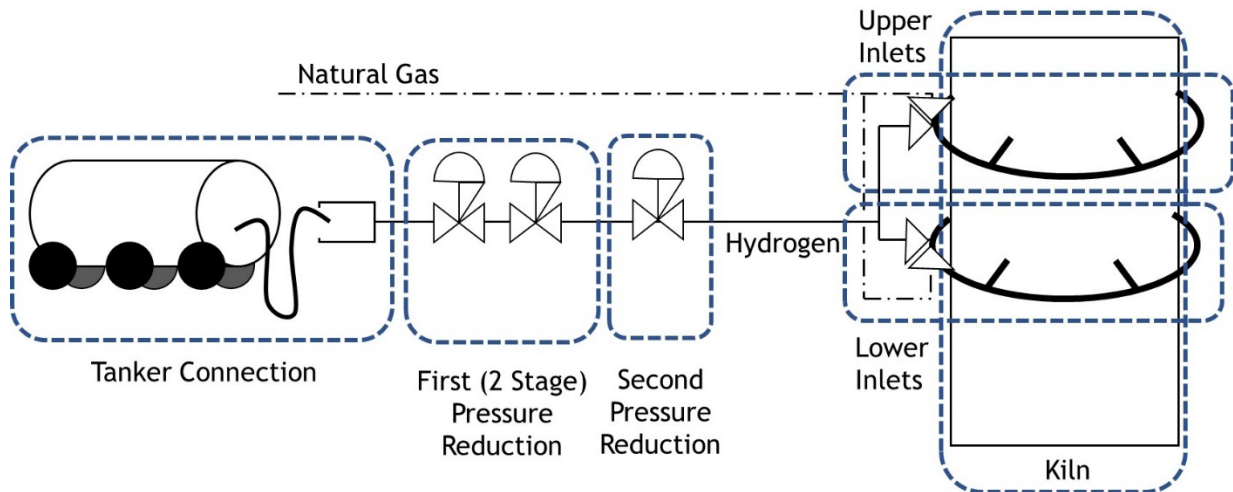
The study did not review the existing operation of the kiln. Kiln start-up was not reviewed because hydrogen was not used for this operation. The main issues arising from the HAZOP study were:

- **Loss of containment**: Hydrogen is highly buoyant and disperses easily; most of the hydrogen pipework installation was located outside in well-ventilated areas so there is low likelihood of hydrogen build up if there is loss of containment in these areas. However, as the kiln is sheltered at the points where hydrogen is fed into the kiln, the impact of 'reduced' ventilation was reviewed during the hazardous area assessment. The solution was to drill several 5 cm holes in locations directly above the gas inlets to reduce the likelihood of gas accumulation.

- **Human error**: To minimise the likelihood of human error, detailed Standard Operating Procedures (SOPs) and close technical supervision were specified.

- **Environmental impact**: The increased flame temperature associated with hydrogen combustion has the potential to increase thermal NOx levels; as understanding this potential impact was part of the demonstration trial, monitoring systems would be put in place.

- **Fire/Explosion**: Hydrogen has a wider flammable range compared to natural gas (methane), and its ignition energy is significantly lower, and it is susceptible to ignition from static discharge. However, if there were a loss of containment, the measures detailed above provided adequate levels of ventilation to disperse the hydrogen rapidly and so reduce the risks of fire/explosion.

New hazards are created with the introduction of hydrogen into the kiln system, and existing equipment were checked for their suitability for operations when using both hydrogen and natural gas.

- **Unburnt hydrogen**: Hydrogen has a minimum limiting oxygen concentration at approximately half that of natural gas (methane). If there were fault conditions where unburnt hydrogen and natural gas accumulated in the exhaust gas, then the likelihood of the exhaust gas becoming flammable would increase. Recognising this hazard, a hydrogen exhaust gas analyser was installed. Hydrogen and natural gas supplies were configured to trip closed if "high" levels of hydrogen were detected.

- **Lime quality**: The higher hydrogen flame temperature has the potential to sinter lime, degrading its quality and potentially resulting in kiln blockages. The manufacturing process requires a long residence time in the kiln and so there is an extended time before the quality of the lime can be assessed. Safeguards including the control of energy input into the kiln, monitoring kiln temperatures and NOx levels in the exhaust gas were put in place to mitigate this risk.

- **Asset damage**: The higher flame temperatures from hydrogen firing could damage the kiln refractory lining. Safeguards identified included (partial) replacement of the existing refractory lining, control of hydrogen flow, temperature monitoring and thermal imaging of the kiln.

- **Commissioning**: Tarmac Buxton Lime has an established Safe to Operate process, which was implemented as part of the commissioning process. The Safe to Operate process requires a multifunctional pre-inspection and sign off against a proven set of checklists covering mechanical, electrical, operations and safety criteria. Separate actions were raised to clarify how the system was to be purged prior to the introduction of hydrogen.

4.1.2   DSEAR - Dangerous Substances and Explosive Atmosphere Regulations Assessment

Under the Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR), employers have a duty to identify areas where explosive atmospheres may occur. A Hazardous Area Classification was undertaken on the kiln used for operation with hydrogen. DSEAR classifies hazardous areas into Zones, for example:

- Zone 0: An area in which an explosive gas atmosphere is present continuously or for long periods or frequently.

- Zone 1: An area in which an explosive gas atmosphere is likely to occur in normal operation.

- Zone 2: An area in which an explosive gas atmosphere is not likely to occur in normal operation but, if it does occur, will persist for a short period only.

The main conclusions of the report were:

- New hazardous zone areas were required to protect from potential hydrogen leaks local to the BOC hydrogen trailers, No1 skid and FTP skid. A new DSEAR Zone 2 area was designated.

- As the hydrogen pipework was welded with only a few flanges there were few risks from loss of containment. However, the flange areas were designated as a local Zone 2 with an extent of 1 m radius from the flange.

- A new hydrogen control station was located with the gas monitoring and control station in the kiln building (referred to as the gas gallery). This was designated as a Zone 2 of 1.5 m radius from all the sides of the control station extending horizontally and up to the ceiling.

- The upper and lower kiln gas inlet points had limited ventilation. Normally, when burning natural gas this area has a blanket DSEAR Zone 2. However, the high buoyancy of hydrogen could lead to accumulation of any leaked hydrogen below the ceilings of two floors in the kiln building (floors 3 and 4), which would have required designation as a DSEAR Zone 1. To mitigate the risks of hydrogen accumulation, both floors had several 5 cm holes drilled in locations directly above the gas inlets. The potential accumulation of hydrogen was then assessed to be minimal and a Zone 2 DSEAR classification applied. Existing equipment located within the DSEAR Zone 2 areas was assessed for its suitability for hydrogen; specifically, ensuring the equipment was rated for Gas Group IIC (i.e. suitable for use with easily ignited gases).

- The vent from the hydrogen supply pipework was routed horizontally approximately 5 m to the side of the kiln building/gas gallery and had a 1° continuous fall. The hydrogen vent was used infrequently; and a DSEAR Zone 2 of 3 m radius existed at the vent outlet.

Figure 9:   A hydrogen tube trailer

Figure 10: No1 skid and FTP skid

Figure 11: Tarmac Buxton Lime shaft kilns and kiln building

4.1.3 LOPA - Layer of Protection Analysis

LOPA ascertained whether there were sufficient layers of protection to prevent accumulation of combustible gases in the filter plant during the hydrogen demonstration trials. The worst-case scenario identified was an on-site fatality following ignition of combustible gas in the filter plant.

Credit was taken for the limited time that hydrogen was utilised on the kiln and combined with the proposed design safeguards, the analysis confirmed that there were sufficient layers of protection in place for the risk to be acceptable.

4.2 Design and control philosophy

The gas flows specified for each demonstration trial were derived from a base case condition when operating with natural gas.

Pressurised hydrogen gas was supplied and delivered to site by BOC. The No1 skid regulated pressure from hydrogen tube trailers, typically at up to 228 barg, to around 10 barg as it left the No1 skid. The No1 skid was designed to take a feed from between one to two tube trailers depending on demand with up to two trailers waiting on standby.

Exhaust pipework from safety relief devices mounted within the No1 skid was routed to one of three vent stacks. In the event of over-pressurisation, hydrogen would be safely discharged to atmosphere. All vent stacks were designed to 40 barg to safeguard against hydrogen detonation over-pressure. A pressure trip and an emergency shut-off valve were designed to isolate the high-pressure tube trailer supply to the No1 skid during unplanned high-pressure deviations. An external signal initiated via the Tarmac Buxton Lime break glass system would also initiate closure of this valve. Additional break glass units were provided at the pressure let-down area.

Anti-towaway protection was a safety critical element and a requirement for all trailers in use. Towaway protection is a device on the hose coupling interlocked with the brake to prevent towaway scenarios. The trailers were always exchanged and connected by an experienced BOC operator familiar with trailer delivery procedures.

Hydrogen was fired to the kiln via pipeline, designed in accordance with American Society of Mechanical Engineers standard ASME B31.12-2019. The pipeline was also designed to minimise the potential for failure at joints and seals. The existing natural gas pipeline (local to the kiln) was re-qualified for its suitability in hydrogen service – a short piece of pipeline supplying the combined hydrogen and natural gas mixture to the kiln.

All hydrogen containing equipment was suitably earthed. Pipework, including hydrogen vent stacks and pressure let-down skids, were designed for electrical continuity across all connections in accordance with ASME standard, to protect against the effects of lightning and static electricity. The resistance to ground was specified to not exceed 10 Ohms at any point throughout the installation. The

hydrogen trailers were also suitably earthed. The PPE (Personal Protective Equipment) worn within and around any area where hydrogen was being used was anti-static to prevent the build-up of static electricity and the potential for sparks.

Hydrogen was let-down from 10 barg from the No1 skid using a (secondary) let-down station designed and supplied by FT Pipeline Systems (the FTP skid). The design was in accordance with the Institution of Gas Engineers and Managers (IGEM) standards IGE/TD/13 and IGE/GM/8 Part 1. The secondary skid (and the downstream hydrogen pipeline) was designed for 15 barg and housed two slam shut valves of differing design, designed to isolate hydrogen supply if hydrogen pipeline pressure exceeded 4.5 barg / 5.0 barg. The valves were also designed to shut if pipeline pressure fell below 0.6 barg. A Gascat Domus Pilot HF regulator accurately controlled pressure and could be adjusted to control pipeline pressure between 2 and 4 barg depending upon which hydrogen demonstration trial was being undertaken (www.gascat.com.br).

Control of hydrogen flow downstream of the FTP skid was via a programmable logic controller (PLC). Safety critical trips were via a Pilz safety shutdown relay (referred to as a Pilz - www.pilz.com). A kiln Pilz provided key shutdown interlocks on the kiln. A hydrogen Pilz hard-wired to the kiln Pilz was configured for critical interlocks on the hydrogen supply line. When a hydrogen demonstration trial was selected, all essential (critical) interlocks associated with the kiln Pilz had to be 'healthy' for the hydrogen Pilz to be 'healthy'. Likewise, all inputs associated with the hydrogen Pilz needed to be in a safe condition (that is, not in alarm/trip) for the natural gas Pilz to be 'healthy'. Critical interlocks were repeated via the PLC which in turn provided various calculation sequences and control logic required for kiln operation.

Each demonstration trial was selected at the supervisory control and data acquisition system (SCADA). This enabled the download of specific flow and process alarm/trip settings for that demonstration trial.

Figure 12: Secondary pressure let-down skid (FTP Skid)

Figure 13: Control room showing SCADA user interfaces

4.3 Rationale for demonstration trial hydrogen substitution levels

Seven demonstration trials, with four different hydrogen substitution levels were targeted:

1. 4 hours at 20% v/v (~6% energy basis).
2. 36 hours at 20% v/v (~6% energy basis).
3. 4 hours at 50% v/v (~23% energy basis).
4. 36 hours at 50% v/v (~23% energy basis).
5. 4 hours at 77% v/v (~50% energy basis).
6. 36 hours at 77% v/v (~50% energy basis).
7. 1 to 2 hours at 100%.

The proposed % hydrogen substitution volumes equate to a net energy requirement met via hydrogen substitution of natural gas.

All substitution levels, except 100%, were proposed to start with short demonstration trial of around 4 hours to 'prove the concept' and ensure plant data was prepared for longer demonstration trials (data such as pressure drop profile, maximum hydrogen flow). Longer (up to 36 hours) were planned. The 36 hour demonstration trials provided sufficient residence time for a full analysis of lime production to be undertaken.

The 100% demonstration trial was only planned for 1 to 2 hours as there was insufficient hydrogen available to enable a longer demonstration trial at full substitution. In the end, it was not possible to complete Trial 3 as planned.

4.4 General comments on gas train and design for industry

Gaseous hydrogen was supplied from a tube trailer manifold at 228 to 40 ±10 barg depending on tube trailer pressure and demonstration trial flow requirements. Due to the requirement for a steady outlet pressure from the No1 skid (±0.5 barg) and a significantly varying inlet pressure (228 to 40 barg) regulation across the skid was undertaken in two stages.

There were no control valves on either the No1 or FTP skids. Flow control was downstream at the hydrogen pipeline. Installation of flow nozzles downstream of the flow control valves provided back pressure enhancing control valve operability and reducing gas velocity.

Pressure was continuously monitored; high-pressure trips ensured a safe shutdⁿwn in the event of a high flow or control valve failure scenario. Differential pressure on the hydrogen pipeline was also monitored to minimise the likelihood of a back-flow scenario. Following a process trip, actuated on/off valves in series ensured safe isolation of hydrogen flow; the PLC also ensured that the hydrogen control valves closed in this event.

To safeguard against failure/error in hydrogen flow measurement, the hydrogen flow control valve position was monitored to check whether the valve had drifted towards a fully open position. For each demonstration trial a maximum open limit was set for the valve. There was also a limit on the maximum hydrogen flow, inputted at the SCADA interface, called the hydrogen flow set-point. A manual flow check utilising the control valve position/ Valve Flow Coefficient (CV) curve enabled accurate flow checks to be made. If the difference between a calculated flow and a measured flow was greater than 10% a correction factor would be applied via the SCADA. The corrected flow measurement was utilised by the kiln PLC for all associated hydrogen mass flow and energy calculations.

A hydrogen vent pipeline was designed to allow safe depressurisation of the hydrogen feed pipeline. The vent pipeline was designed in accordance with American Petroleum Institute standard, API 521 and Compressed Gas Association standard, CGA-G_5.5-2021. The vent exit was sufficiently elevated to reduce potential thermal radiation doses to an acceptable level. Consideration was also given to a non-burning hydrogen cloud dispersion. Vapour dispersion modelling was undertaken, and a restriction orifice inserted in the vent pipeline to control vent discharge. The vent stack was fabricated from grade 304 stainless steel and designed to 40 barg to ensure any potential over-pressure generated inside the piping by ignition of a flammable hydrogen air mixture would not rupture the pipework. The vent system design incorporated a purge valve to allow any air in the piping to be purged with nitrogen prior to the introduction of hydrogen. If the hydrogen vent valve was inadvertently opened during a demonstration trial, the loss of a closed limit switch signal would initiate a process trip and automatically close the actuated hydrogen isolation valves.

The hydrogen pipeline system was designed with a noise level (at 1 m) of <80 dB(A).

5 Plant Modifications and Enabling Works

Summary and Key Learning

Modifications included changes to refractory linings and insulation to accommodate hydrogen firing and potentially higher resultant temperatures. New exhaust gas analysers were introduced to monitor NOx, which worked well, and hydrogen. The hydrogen analyser did not work well as it relied on thermal conductivity to measure hydrogen, a property affected by the CO_2 in the exhaust gasses. If a hydrogen exhaust gas analyser is needed in the future, a different technology would be required (see also section 6.3).

The thermal mass hydrogen flow meter selected worked well when the hydrogen flow was high, but for lower flows the accuracy was reduced.

5.1 Kiln selection and enabling works

Shaft kiln 1 was chosen to carry out the demonstration trials using hydrogen as an alternative fuel to natural gas. Kiln 1 is the first of a bank of 8 shaft kilns. The kiln used was not in operation before the demonstration trials but had undergone a recent electrical refurbishment and was therefore the best option for the upgrade of the safety and control systems required for the additional layers of protection to run the hydrogen demonstration trials. It was also located at one end of the plant and could be segregated, and access easily controlled from normal operation. It was also hoped that only limited refractory repairs would be required but upon internal inspection and removal of blockages, continuing with the existing refractory lining, even after repairs, was deemed an unsafe and unreliable option. The kiln was therefore extensively re-lined with a carefully selected brick and insulation mix (see section 5.3)

5.2 Location of the hydrogen trailers and pressure let-down skids

The location chosen was adjacent to the shaft kiln offices in an area cleared when the old rotary lime kilns were removed. A visit by the BOC transport manager to review ground conditions and vehicle manoeuvring confirmed its orientation and suitability for a four-trailer storage and operating area. Within 200 yards, further trailer parking was identified on a secure asphalt area for up to ten additional trailers, facilitating a quick turnaround time when switching supplies on the skid connections. Construction required no planning permission and was carried out within the existing authorised developments. The local fire authority was notified to make them aware of the proposed temporary changes.

Figure 14: The location of the trailer parking and skids

Figure 15: Vehicle and pedestrian management plan
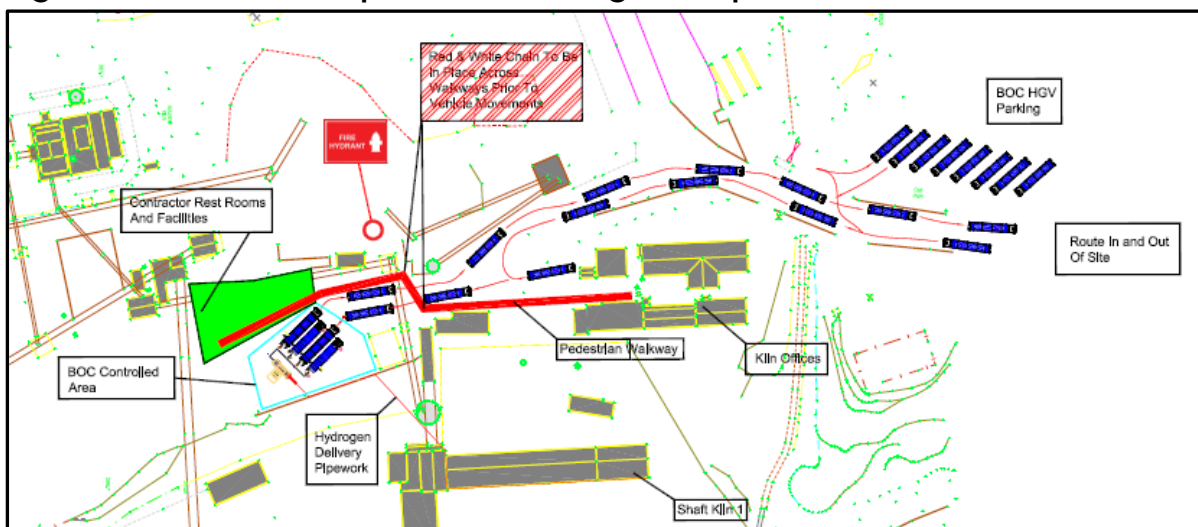
5.3 Refractory design considerations

Following an internal inspection of the kiln 1 refractory, it was deemed necessary to make a substantive refractory re-line to ensure the kiln could be put back into operation safely and to maximise the probability of undertaking successful hydrogen demonstration trials.

The insulation characteristics of the total refractory lining were also investigated to ensure the refractory protected the kiln steel shell as the internal kiln temperatures were predicted to increase because of the higher flame temperature. (Readings of

shell temperature were taken when firing using natural gas and during the demonstration trials, with no significant change in results).

A final specification was agreed using a four-layer 80% alumina brick backed by two differing insulation materials. Four refractory suppliers were asked to quote for the supply of the brick lining.

After detailed examination of all companies' tenders, PCO (www.pco.pl), was selected to supply the lining based on, in part, on having the highest thermal insulation property values across the refractory lining.

5.4 Secondary skid rationale and selection

A secondary skid was required to reduce the pressure from the exit of the No1 skid (at around 10 barg) down to 2 to 4 barg (as required). A process data sheet detailed a secondary skid design and fabrication to be in accordance with American Society of Mechanical Engineers standard ASME B31.12-2019, and British/European standards BS EN 12186:2014, BS EN 334 and BS EN 14382. A design pressure of 15 barg ensured over-pressure protection from the No1 skid second stage pressure reduction (relief set pressure at 14 barg). A monitor regulator and two over-pressure slam shut valves ensured downstream equipment was similarly safeguarded from over-pressure. Preparation of the process data sheet smoothed the way for vendor selection.

Initially several potential fabricators were approached. Further to initial meetings and discussions, two companies were down selected. A formal pre-qualification and technical bid evaluation concluded that FT Pipeline Systems (www.ftpipelinesystems.co.uk) was the preferred bidder.

The skid was CE (conformity) marked and assessed under PED (Pressure Equipment Directive) requirements as Category 1 (PSxDN ≤ 1000).

5.5 Gas analysers

A new gas analyser was installed to record kiln emissions for monitoring and control purposes. The analyser recorded NO, CO, H_2 and CH_4. It is existing practice to monitor CO and CH_4 on the shaft kiln and therefore these measurements are not discussed further in this section.

5.5.1   NOx analysers

The NOx analyser was an infrared photometer used to analyse for NO. This was validated against an external MCERTS accredited measurement over 20 hours and was found to be in good agreement.

MCERTS accredited measurements were carried out by Element (www.element.com) to BS EN 14792 using Chemiluminescence by Horiba (PG-250 SRM).

In line with most combustion processes it was assumed that NO made up over 95% of the total NOx emissions. The NOx analyser reported emissions around 8% higher than the MCERTS measurements.

A further check was carried out, comparing a Tarmac Buxton Lime portable Kane analyser (www.kane.co.uk) with the NOx analyser data collected during the various demonstration trials. Both analysers measure NO only. The online analyser was reading about 15% higher than the Kane analyser. This shows reasonable consistency in the measurement for the purposes of the demonstration trials.

Figure 16: Comparison of NOx validation measurements by Element to NOx analyser measurements recorded by the SCADA
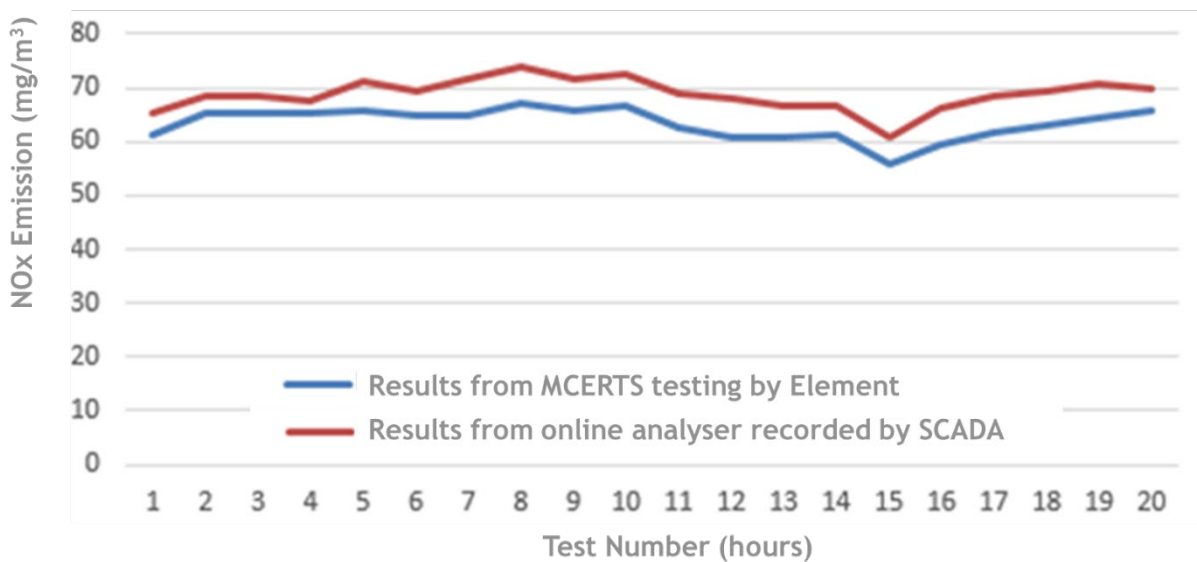
Figure 17: Comparison on NO measurements using the Kane portable analyser to the NOx analyser measurements recorded by the SCADA
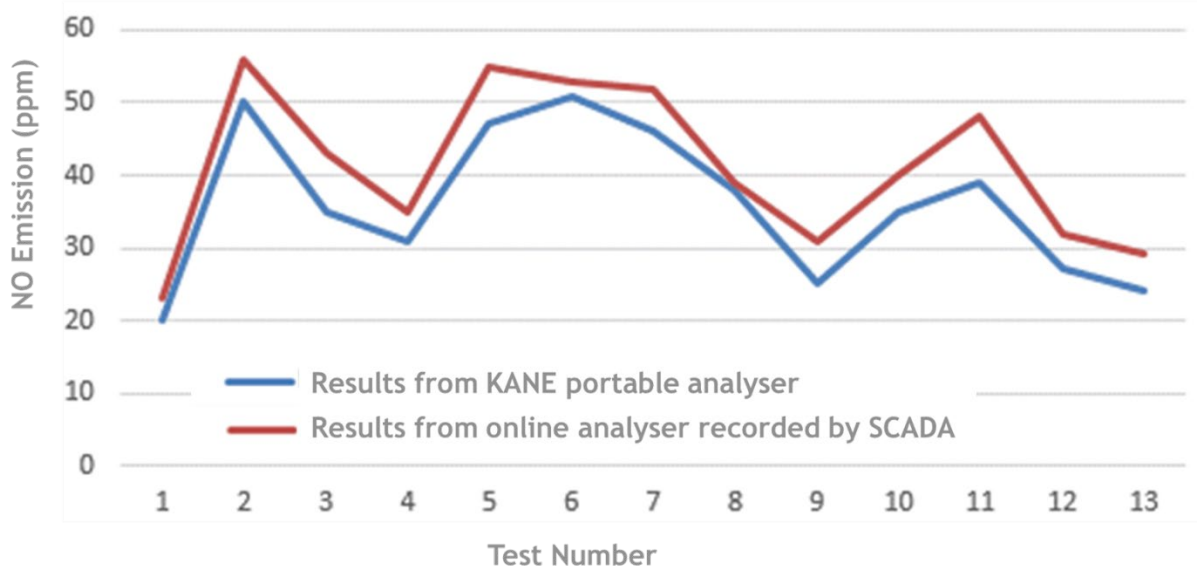
This assessment concluded that the online monitor could be relied on during the demonstration trials to measure and record relative changes in NOx levels when using hydrogen fuel although absolute emissions monitoring would require the instrumentation to be calibrated to accord with the MCERTs accredited standard.

5.5.2 Hydrogen analysers

The hydrogen analyser took measurements based on measurement of exhaust gas thermal conductivity. Unfortunately, the impact on thermal conductivity and analyser hydrogen reading due to changes in exhaust gas composition presented difficulties in interpreting analyser output data. As the demonstration trials progressed, CO_2 concentration in the exhaust gas reduced, giving rise to increased exhaust gas thermal conductivity (and an equivalent 'high' reading of H_2). Measurement and correction for CO_2 concentration is required if thermal conductivity measurement is used for any future hydrogen firing application.

5.6 Hydrogen flow meter

A number of flow metering technologies were considered including differential pressure (DP), coriolis, vortex, turbine flow meters and thermal mass flow meters.

Several technologies have difficulty in measuring flow accurately since hydrogen gas inertia/density is so low. This was particularly evident when considering coriolis and turbine flow meters. In addition, the required turndown range was not achievable with both the turbine flow meter and vortex meter.

A DP flow meter requires a stack arrangement including pressure and temperature measurement to accurately determine flow over the required range, which given the exhaust ducting arrangements on-site, was not possible. A single DP would have generated significant pressure losses at higher flows.

A thermal mass flow meter can measure gas velocity from 150 Nm/s to 3.5 Nm/s and was selected as it offered good accuracy over the required flow range. Also, no temperature or pressure compensation was required allowing for a straightforward installation.

A Sierra 780i In-Line Mass Flow meter was selected (www.sierrainstruments.com). The accuracy offered was ±3% of the full-scale reading value. The two flow meters (one for the upper and one for the lower kiln gas inlets) generally worked well although the lower kiln gas inlet was only about 80% accurate during the lower hydrogen flow demonstration trials.

5.7 Pipework design

To deliver hydrogen gas to the kiln, a new 150 m long pipeline and hydrogen gas gallery (to control the flow of gas into the kiln) had to be constructed.

Dr R Paxton of R Paxton Associates (www.rpaxton.co.uk) was engaged to produce a detailed piping specification capable of conveying hydrogen gas. This specification covered materials to be used in its construction plus the testing regimes needed for quality control and pressure testing.

All piping fabrication and installation works was carried out by subcontract company Sigma 6 Ltd (www.sigma6.co.uk) with weld testing carried out by a certified QA specialist, and final pressure test being undertaken by JMC Northern Ltd

(www.jmcnw.co.uk). All test certificates are held within the Tarmac Buxton Lime engineering filing system.

5.8 Valve selection and seals

Process datasheets were prepared for all new equipment items. In addition, any existing equipment items that would utilise hydrogen as well as natural gas were replaced (with new) for the hydrogen demonstration trials.

On/off valves were specified to comply with ASME 16.34/API 6D. A Rate-A leak test in accordance with BS EN 12266/API 6D was also specified. Fugitive gas emissions were required to meet the International standard ISO 15848-1:2015.

The Fisher GX valve was selected for flow control on both the upper and lower hydrogen gas inlets (www.emerson.com). The flow trim of the valve enabled good control during all the demonstration trials. The GX utilises a "Enviro-Seal" PTFE packing at its stem seal. A Class VI shut-off capability was specified.

5.9 Pilz safety system

The LOPA assessed the fundamental and basic control measures. This highlighted the requirement for a Safety Instrumented System (SIS) and that a Safety Integrity Level (SIL) at Level 1 would reduce the foreseeable risk to below the 'accepted' value. This was then discussed by the project team who collectively increased the desired SIL to SIL2 for additional layers of redundancy.

The existing kiln natural gas system was monitored by a Pilz configurable safety relay (www.pilz.com). For simplicity, the existing safety relay was left to monitor the kiln natural gas base conditions and critical air pressure/flow measurements. An additional configurable safety relay was then installed within the hydrogen control panel to monitor the hydrogen safety critical interlocks only.

Once in 'trial mode', both safety relays were interlocked such that if a safety critical condition was detected by either safety relay, all fuel sources were isolated from the kiln. The safety relays had overall control of the actuated gas isolation valves.

Figure 18: PLC/Pilz system architecture
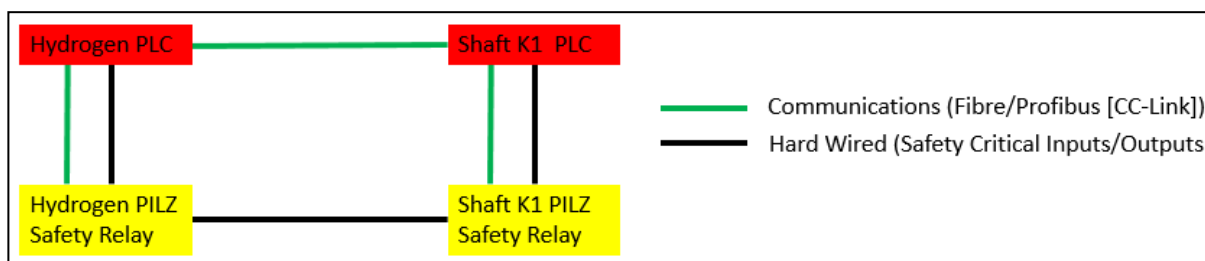
This type of system was used as a retrofit at site but if designed from new, a different system would be used.

6 Pre-Trial Works

Summary and Key Learning

Standard Operating Procedures, developed with input across all project roles, worked well and were adapted according to existing management of change practices. Systems were checked using nitrogen before commissioning to ensure they would work effectively when hydrogen was introduced. Lime manufacturing relies on high temperature autoignition of fuels. Existing burners used to preheat the kiln when starting from cold would need to be adapted to enable an equivalent start-up on hydrogen – although this work was not necessary for this project.

6.1 SOP – Standard Operating Procedures

SOPs were developed to ensure the safe operation and integration of the hydrogen equipment within the site and into the existing shaft kiln infrastructure and control systems.

SOPs included:

- Hydrogen delivery to site and daily checks on equipment including tankers.

- Maintenance and operation of the hydrogen equipment.

- Pipeline purging and hydrogen introduction.

- Kiln parameter measurement including inlet port temperatures and quality control.

- Kiln and hydrogen operation for and during each demonstration trial.

The control philosophy formed the basis for the operational SOPs, which required the engagement of all project roles including the Trial Controllers, who would be responsible for operating the kiln during the hydrogen fuel demonstration trials. The process of developing robust SOPs enabled the team to test the control philosophy and to gain a thorough understanding of the control logic, which contributed to the successful and efficient operation of the demonstration trials.

All SOPs underwent a review and authorisation process with Plant Manager sign-off before being issued.

There was an understanding that changes might be required as the demonstration trials progressed and learning could be evaluated. It was agreed that the current Tarmac Buxton Lime management of change process could be utilised to manage any ongoing changes during the demonstration trials with change approval as per the agreed demonstration trial role structure.

6.2 Pre-commissioning on nitrogen / purging

The hydrogen pipeline installation was firstly checked against the "Approved for Construction" Process and Instrumentation Diagrams (P&IDs).

Figure 19: The Standard Operating Procedure (SOP) index

SOP No	Title	Written by	Date	Authorised by	Authorised Date
HYD-SOP01	FTP Skid Reset	KH	30/09/2021	A Flanagan	09/02/2022
HYD-SOP02	Nitrogen Purge	KH	30/09/2021	A Flanagan	09/02/2022
HYD-SOP03	Initial Setup	KH	28/10/2022	A Flanagan	09/02/2022
HYD-SOP04	Hydrogen Flow Check	RC, CT, SP, JP	23/11/2021	A Flanagan	09/02/2022
HYD-SOP05	Trial Start-up	RC, CT, SP, JP	30/10/2021	A Flanagan	09/02/2022
HYD-SOP06	Startup after trip	RC, CT, SP, JP	04/10/2021	A Flanagan	09/02/2022
HYD-SOP07	Crash stop	RC, CT, SP, JP	20/10/2021	A Flanagan	09/02/2022
HYD-SOP08	End of Trial	RC, CT, SP, JP	30/10/2021	A Flanagan	09/02/2022
HYD-SOP09	Long term shutdown	SK, AF	27/09/2021	A Flanagan	09/02/2022
HYD-SOP10	Temperature Measurements	RC	30/09/2021	A Flanagan	09/02/2022
HYD-SOP11	Exhaust gas measurement	RC	30/10/2021	A Flanagan	09/02/2022
HYD-SOP12	Product testing	RC	30/10/2021	A Flanagan	09/02/2022
HYD- SOP13	100% Trial	SK,AF,KH,DM	11/03/2022	A Flanagan	12/03/2022
HYD-SOP14	End 100% Trial	RC,SP,AF	11/03/2022	A Flanagan	12/03/2022

Figure 20: Example of a Standard Operating Procedure used during the demonstration trials

STANDARD OPERATING PROCEDURE						
THEME		*K1 - Hydrogen Project – **Trial start-up***				
WRITTEN BY	RC, JP, SP	date	30/10/2021	checked by	A. Flanagan	date 09/02/2022

Purpose

To guide kiln operator how to start hydrogen trial.

This is follow-up of initial setup **HYD-SOP03** which is setup of the pipework and valves.

Control hazards

Gas monitor, Radio, Authorization, Anti-Static PPE, Anti-static tools

Trial start-up process

1. **Trial shift supervisor contact BOC** to agree trial start

2. Trial Kiln is running **stable at 1100 m^3/h** NG gas rate.

3. Check **hydrogen system & Pilz is healthy** on Scada

4.
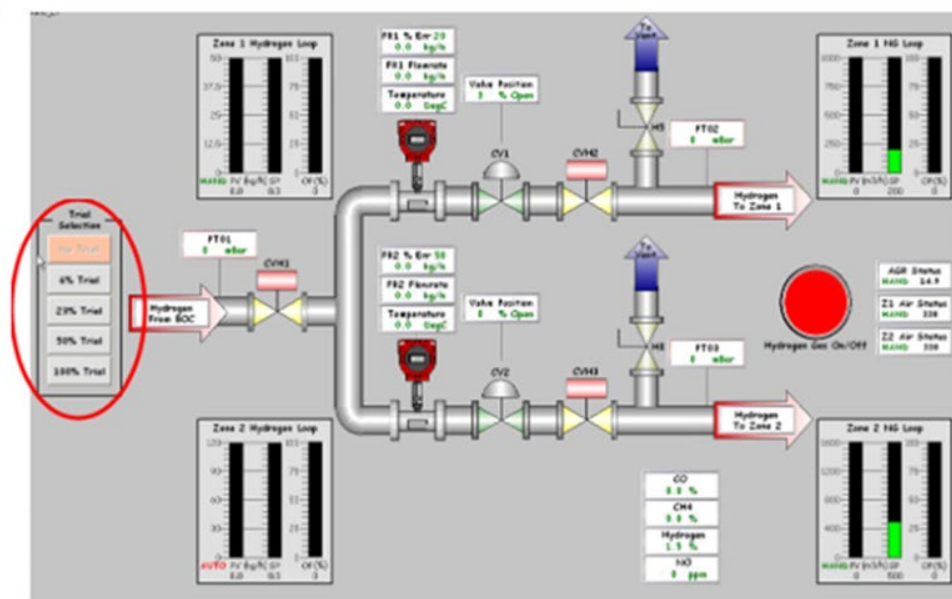
Select which **trial** to proceed with

5. Site manager to **unlock and open Zone 1** (H6) and **Zone 2** (H9) hydrogen valves

A factory acceptance testing had previously been undertaken for the FTP skid at the fabrication workshop. Further on-site checks were undertaken to ratify the operability of the regulator and slam shut valves. No faults were observed.

Pre-commissioning of the hydrogen pipeline was undertaken using pressure regulated nitrogen from a gas cylinder. The nitrogen was administered into the upstream side of the FTP skid and routed through the 'hydrogen' flow control valves to atmosphere via the hydrogen vent pipeline. The hydrogen flow control valves were operated in manual mode. The hydrogen feed pipeline to the kiln remained isolated via a locked closed isolation valve and closed spectacle plate. Pressure alarms were triggered as anticipated, and an excellent correlation was observed between the pressure gauge readings and SCADA based pressure transmitter readings.

The thermal mass flowmeters had been configured to measure nitrogen as well as hydrogen flow. During commissioning, nitrogen flow checks were undertaken. An excellent comparison was observed for flow to the upper gas inlets on the kiln (around <95% accuracy); and around 80% accuracy was observed at the lower gas inlets.

6.3 Considerations for hydrogen kiln start-up

Prior to the demonstration trials, the kiln was running on 100% natural gas. During normal operation the kiln temperature is greater than the autoignition temperature of natural gas (and hydrogen). A gas burner is not utilised; natural gas (and hydrogen) automatically combusts at the calcining zone in the kiln.

During kiln start-up when the kiln is cold, a start-up burner is utilised to provide heat to the kiln. If hydrogen was used in preference to natural gas a new dedicated burner may be required, since it is unlikely that the existing start-up burner could be utilised. The high flame speed of hydrogen may lead to flashback. Flashback occurs when gas velocity is slower than flame speed. An increased fuel (hydrogen) supply pressure may be required, since hydrogen also requires three times the volumetric fuel flow compared to natural gas. Less combustion air is required with hydrogen fuel.

The rapid combustion of hydrogen releases its combustion energy in a small area, leading to localised elevated temperatures near the flame region. The materials used within the burner would need to be carefully evaluated. Hydrogen firing has a higher adiabatic flame temperature (2,182 °C) compared to natural gas (1,937 °C).

Flame visibility can be managed via UV/IR detectors, although no visual checks would be possible.

The current exhaust gas analyser detects CO and CH_4; hydrogen concentration is inferred from exhaust gas mixture thermal conductivity. Specific analysis/detection of hydrogen would be preferred if a kiln start-up using hydrogen was being considered.

7   Demonstration Trials and Product Assessment

Summary and Key Learning

At low levels of hydrogen substitution (20% by volume) there is limited impact on kiln operation, lime product or emissions to air. However, at increasing substitution levels there are significant challenges in terms of kiln operation – risking sintering and kiln blockages. NOx emissions appeared to be lower than predicted by the CFD modelling, and manageable without the need to install additional abatement equipment.

7.1   Demonstration trials

As noted in section 4.3, seven demonstration trials, with four different hydrogen substitution levels were planned:

1.   4 hours at 20% v/v (~6% energy basis).
2.   36 hours at 20% v/v (~6% energy basis).
3.   4 hours at 50% v/v (~23% energy basis).
4.   36 hours at 50% v/v (~23% energy basis).
5.   4 hours at 77% v/v (~50% energy basis).
6.   36 hours at 77% v/v (~50% energy basis).
7.   1 to 2 hours at 100%.

7.1.1   Trials 1 and 2 – 20% v/v (~6% energy basis)

No operational difficulties were experienced during either Trial 1 (short 4 hour trial) or Trial 2 (the 36 hour trial). Any variation in measured parameters were within the normal operational range of the kiln.

7.1.2   Trials 3 and 4 – 50% v/v (~23% energy basis)

After the 20% trials, a short 4 hour trial at 50% v/v was started. This was stopped due to higher levels of NOx. Based on the higher NOx emissions, Trial 3 for 4 hours and Trial 4 for 36 hours were run with a 5% reduction in total energy input. Even at this lower energy input, the trials produced evidence of product sintering, assumed to be from localised high temperatures.

7.1.3   Trials 5 and 6 – 77% v/v (~50% energy basis)

Trial 5 (a short 4 hour trial) was completed, with further high temperatures and indication of sintering. As a result, Trial 6 (long 36 hour trial) was cancelled due to the high likelihood that the kiln would become blocked with sintered material.

7.1.4   Trial 7 – 100% hydrogen substitution

A short 20 minute trial to test the updated control logic was completed at the end of Trial 5. This was performed by stopping the flow of natural gas whilst the hydrogen was still running such that the kiln was being fired at 100% hydrogen substitution but at reduced total energy input. Despite the lower energy input, the kiln system did successfully run on 100% hydrogen without fault.

The 4 hour trial at 100% hydrogen substitution was cancelled due to the high likelihood that the kiln would become blocked with sintered material.

7.2 Results and discussion

The results of key parameters measured during the trials are discussed in the sections below

7.2.1 NOx emissions

As highlighted in section 5.5.1, the online monitor used during the trials can be measure and record relative changes in NOx levels when using hydrogen fuel, although absolute emissions monitoring would require the instrumentation to be calibrated to accord with the MCERTs accredited standard. However, the results do indicate that the NOx can be managed by managing kiln operating parameter (e.g., energy input).

Table 2:   NOx emissions

Date of Trial	Hydrogen substitution (% v/v)	Length of trial (hr)	Nominal trial number	Trial average NOx emission (mg/Nm^3)
-	0	-	Base Case	60
21/02/2002	20	4	1	67
22/02/2022	20	36	2	104
23/02/2022	50	2	3	130
02/03/2022	50	4	3	58
07/03/2022	50	36	4	80
10/03/2022	77	4	5	67

The CFD modelling predicted that, without changes in kiln operation, NOx emissions increase substantially with increasing substitution of hydrogen. During the long period 20% v/v trial (Trial 2) an increase in NO of around 50% was recorded (see Table 2). Although the specific energy input had been reduced to the kiln to allow for the improved efficiency of the hydrogen combustion and provide a safety margin to reduce the risk of blockages, the kiln energy input was thought to still be too high leading to an artificially high NO reading. The specific energy input was further reduced for both the 4 and 36 hour 50% v/v trials, and this appeared to control the NO to normal levels. During the short 77% trial, a further energy reduction was made, to allow for increased efficiency of hydrogen combustion, and the NO remained at normal levels. All NOx data during the demonstration trials was below the current permitted limit.

The nature of the combustion in a shaft kiln is expected to restrict the formation of thermal NOx due to the staged nature of the fuel and air addition. The high flame propagation speed of hydrogen allows the combustion process to occur more rapidly

than with natural gas, that in turn releases the combustion energy in a relatively small area leading to localised elevated temperatures, which is the main cause of elevated thermal NOx emissions. In a shaft kiln, the fuel and air enter the kiln at separate locations. This allows some of the exhaust gas to mix with the fuel prior to combustion and so reduce NOx generation. It is this premixing with exhaust gases that is used by conventional low NOx burners that pre-mix the input fuel with exhaust gases to reduce the formation of thermal NOx. In addition, with the shaft kiln, to ensure energy distribution across the kiln, the fuel and air are not mixed until they enter the kiln, so that the combustion process is stretched across the kiln cross section. This distribution of the combustion process lowers the maximum combustion temperature and helps to limit NOx formation. These two processes, mixing with exhaust gases and combustion distribution, accompanied by the lower energy input used when fuelled by hydrogen, should help limit the NOx formation in the shaft kiln.

The CFD modelling report suggested a possible increase in NOx emissions due to the reduction of carbon monoxide within the kiln (due to the replacement of methane by hydrogen), whilst it is acknowledged that carbon monoxide can have a reductive effect on NOx, no evidence of this effect was observed during the trials even at 100% replacement.

Overall, the demonstration trials suggest that the dramatic increase in NOx predicted by the CFD modelling is less concerning than anticipated and that it may be possible to control the NOx levels, even at 100% substitution, without the need to install additional abatement to reduce levels in the exhaust gas.

7.2.2   Exhaust gas temperature

The use of hydrogen reduces exhaust gas temperature. The trend to lower temperatures was confirmed during the 36-hour demonstration trials. A reduction of 7°C was observed with the 20% trial and a reduction of 15°C observed during the 50% v/v trial. This trend to lower exhaust temperatures was confirmed during the demonstration trials (Table 3). Since the exhaust gas from the demonstration trial kiln were mixed with that of other operating kilns, and the resulting combination remained above dew point temperature, and no significant issues were observed with respect to the filter performance.

Table 3:   Reductions in exhaust gas temperature

Hydrogen substitution (% v/v)	Nominal trial numbers	Trial exhaust gas average temperature reduction (°C)	Exhaust gas temperature reduction predicted by the EMB model (°C)
20	1 and 2	7	4
50	3 and 4	15	19
77	5 and 6	57*	45
100	7	Not Completed	83

* For trials 5 and 6, the exhaust gas temperature was artificially affected by the bleeding in of cold air for control purposes. Therefore, data given should be used with caution.

7.2.3 Other exhaust gas parameters

- **Moisture:** Based on both the CFD and EMB modelling results, moisture increases from about 8% v/v with no hydrogen fuel up to 13.5% v/v at 100% hydrogen fuel, with a potential to increase the sulphurous acid dew point of the exhaust gas by around 10°C. It is not possible to record moisture at the kiln exhaust, but no issues were observed in the filter plant, suggesting that changes to the acid dew point were not an issue during the demonstration trials.

- **Carbon Monoxide (CO):** Based on both the CFD and EMB modelling, CO levels reduce as hydrogen substitution increases and the levels are insignificant at 100% hydrogen, reducing energy loss and improving kiln thermal efficiency. No significant change in CO was recorded by the gas analyser during the demonstration trials.

- **Carbon Dioxide (CO_2):** Based on both the CFD and EMB modelling, CO_2 levels reduce as the hydrogen substitution increases. The reduction of CO_2 resulting from the combustion of natural gas would be proportional to the level of hydrogen substitution. Data for CO_2 was not recorded during the demonstration trials as it is easily calculated from the EMB model as shown in Table 4 below:

Table 4: CO_2 Reduction with increased hydrogen substitution rates

Hydrogen Substitution % v/v	Fuel CO_2 Emissions t/t_{Lime}	Total CO_2 Emissions t/t_{Lime}
0 (Base Case)	0.23	0.95
20	0.22	0.94
50	0.18	0.90
77	0.12	0.83
100	0.00	0.72

Calculation of CO_2 emissions from lime manufacturing is subject to monitoring, reporting and verification under the UK Emissions Trading Scheme and agreed methods exist that could be adapted for hydrogen firing if required.

- **Hydrogen (H_2):** There was no evidence of any unburnt hydrogen in the exhaust gas, as predicted by the CFD model. This is a key finding with respect to this type of kiln where gas mixing is thought to be sub-optimal and results in unburnt fuel (CH_4) in the exhaust gas as well as CO from incomplete combustion. The lower explosive limit (LEL) of hydrogen (4% v/v) is lower than for either CO (12.5% v/v) or CH_4 (5% v/v) and so the presence of unburnt H_2 would have been a safety concern given the risk of explosions in the filter plant. Furthermore, the

limiting oxygen content (LOC) for hydrogen combustion is only 5% compared to 12% for CH_4 (see section 4.1.1).

- **Mass flow rate**: Based on the EMB model, the use of hydrogen reduces the exhaust flow rate by 16% with 100% substitution. Less heat input to the kiln is required when using hydrogen to maintain the same gas temperature (and same degree of calcination) leaving the burning zone, as compared to the natural gas base case. As the mass of gas entering the preheating zone is reduced, there is a reduction in the exhaust gas temperature following preheat of the same mass of stone charged, as compared to the natural gas base case. As shaft kilns operate under negative pressure (see section 1.1), where fans draw air through the kiln by drawing out the exhaust gases, a lower mass flow rate means that there will be a lower load on the fans. Depending on how the kiln and fans operate, this could mean, for example, that the fans can operate with a lower energy consumption, or the kiln output can be increased.

7.2.4   Kiln temperatures

For the demonstration trials, thermocouples were situated in the brick work at two levels around the kiln (three at each level). The three at the lower gas inlets area were situated near to the combustion air inlet ports. The thermocouple readings for the 36 hour trials (Trials 2 and 4) are shown in Figure 21 and Figure 22.

There is no sustained change in temperature during the 36 hour trial at 20% v/v replacement of natural gas with hydrogen (Trial 2). During the 36 hour 50% v/v demonstration trial (Trial 4) the temperature increases ranged between 22 °C and 135 °C but only one remained high (about 85 °C) by the end of the demonstration trial. This is the area that the CFD model predicted for maximum temperature increase. The three thermocouples in the upper gas inlets showed no increase in temperature.

Manual spot measurements were also taken with an infrared camera through ports situated around the kiln shell. These measured temperatures at the outside of the kiln burden (the material passing through the kiln) indicated a localised increase in kiln temperature. Based on the product quality (no reduction in lime reactivity), NOx levels (no significant increase) and CFD model output, it suggests that the high temperatures were localised around the fuel and air injection points. Higher temperature towards the outside of the kiln could result in higher refractory wear rates and sintering of lime, making kiln quality control more challenging without some process modifications.

Sintering is the biggest concern for the use of hydrogen and the likelihood increases with higher hydrogen percentage replacement levels. The effect could be offset by the use of exhaust gas recycle. However, it should be noted that employing this technique will negate (partially) the thermal efficiency or kiln output benefits of using hydrogen but would aid in the minimisation of NOx formation.

7.2.5 Kiln shell temperatures

The kiln shell temperatures were monitored during both completed 36 hour trials (Trials 2 and 4). Before, through and after trials shell temperatures were monitored using a thermal camera. During each monitoring assessment, a picture was taken from each side of the kiln (west and east).

To evaluate changes in the kiln shell temperature, each side of the kiln was split into three parts (and the results from hot ducting were ignored) and average temperatures were plotted graphically. The baseline for each side was established as an average from all before and after trial readings. The results compared to the temperatures from kiln thermocouples, are shown in Figure 24 and Figure 25.

For Trial 2, at 20% v/v hydrogen substitution, there was no observed increase in kiln temperature measured by the thermocouples but there was an overall increase in shell temperatures was observed (Figure 21 and Figure 24). The observed shell temperature increase, which only reached baseline temperatures could be caused by kiln disturbances before the trial.

Shell temperatures during Trial 4 were stable at around the baseline temperatures, which is similar to most of the kiln temperature measurements taken by the thermocouples. One thermocouple showed a sustained increase in kiln temperature.

Figure 21: Kiln temperatures during Trial 2 (20% v/v hydrogen substitution)
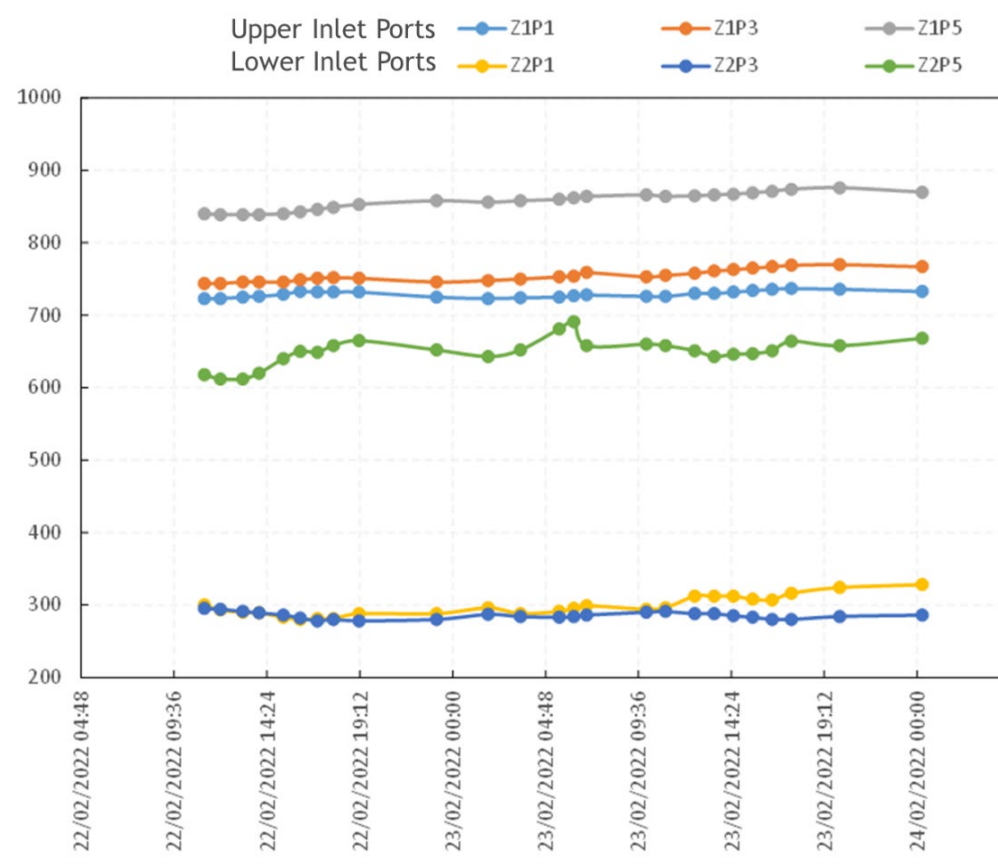
Figure 22: Kiln temperatures during Trial 4 (50% v/v hydrogen substitution)

Figure 23: Thermal images of kiln shell during hydrogen trials taken from the west (left hand picture) and east (right hand picture)

Figure 24: Kiln shell temperatures during Trial 2 (20% v/v hydrogen substitution)

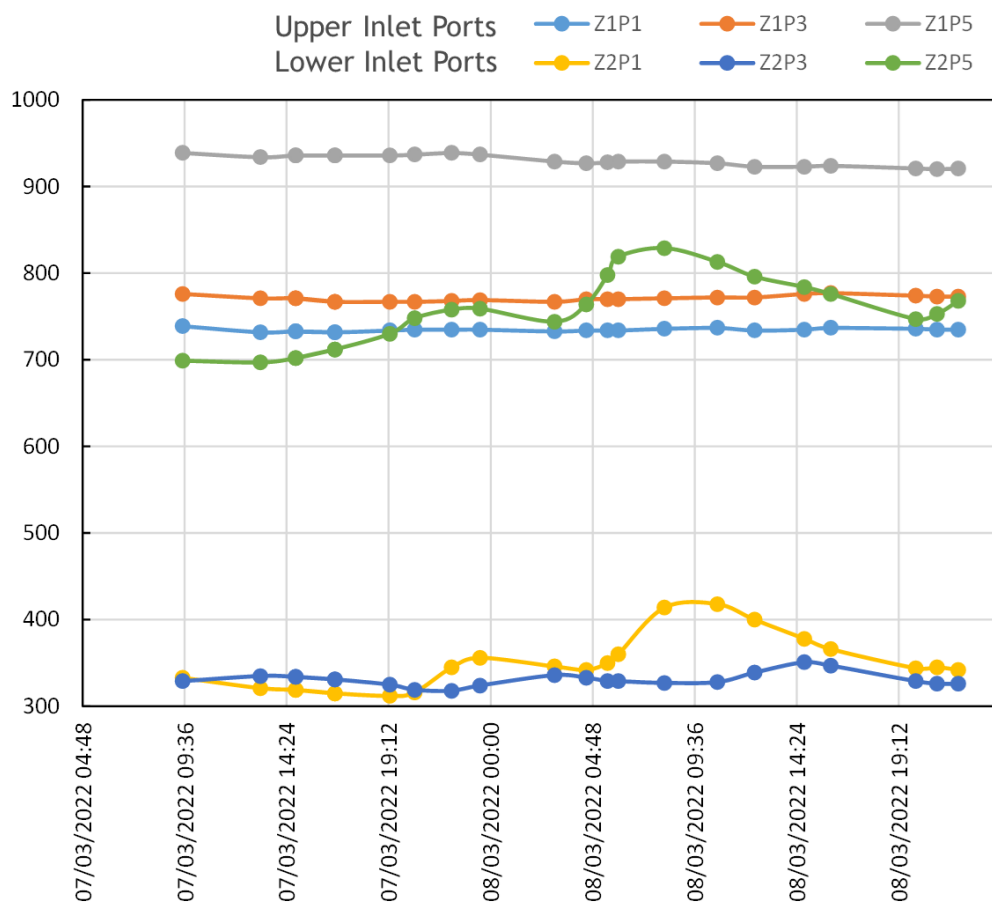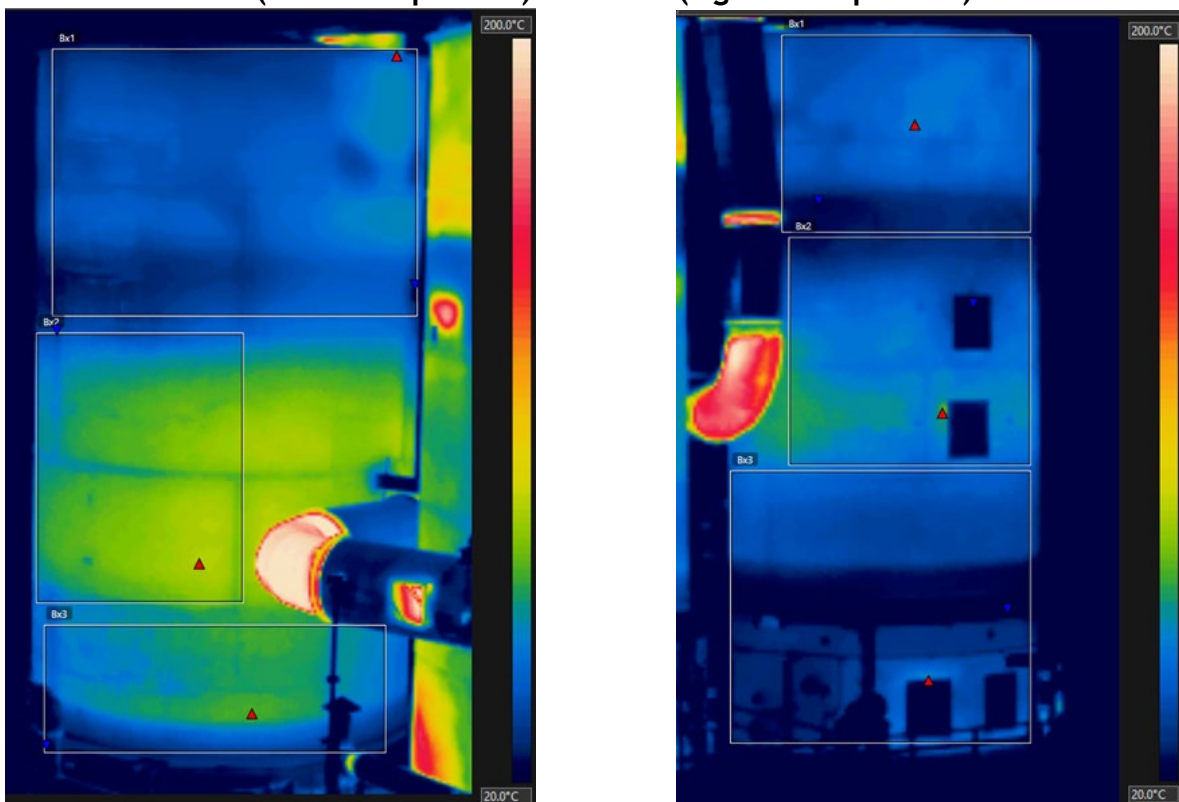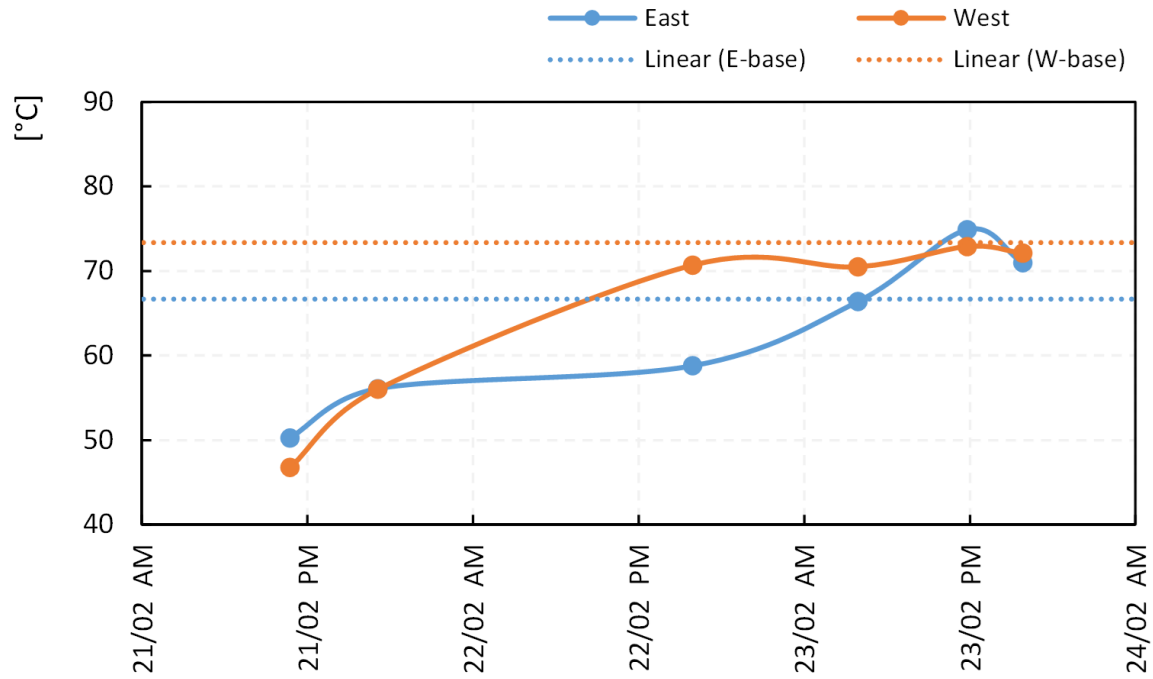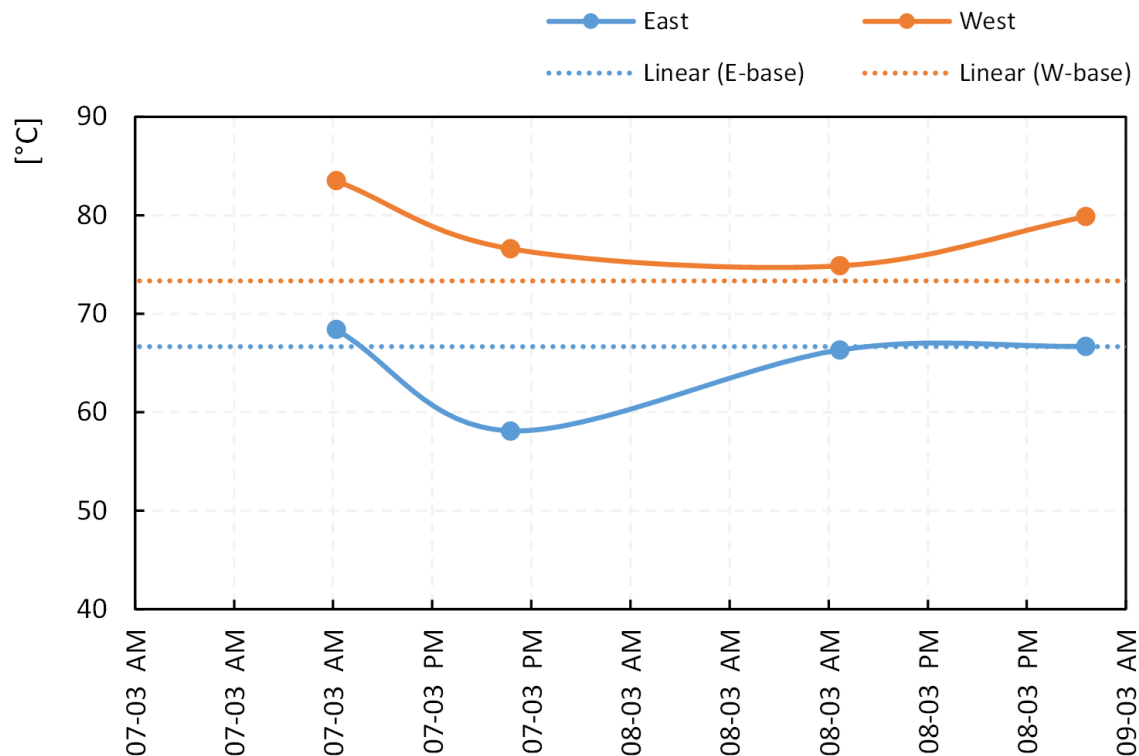**Figure 25: Kiln shell temperatures during Trial 4 (50% v/v hydrogen substitution)**

7.2.6   Lime discharge temperature

No significant change in discharge temperature was measured. This agreed with the CFD modelling.

7.2.7   Lime product quality

Reactivity was measured by mixing 150g lime with 600g water at 20°C, measuring the temperature after 2 minutes. The exothermic reaction with water to produce calcium hydroxide increases the water temperature and is an indication of the reactivity of the lime. A high reactivity lime will take less than 2 minutes to reach 60°C and the results in Table 5 indicate a medium reactivity lime is being produced (normal for the vertical shaft kiln).

Table 5:   Lime product quality

Date of Trial	Hydrogen substitution (% v/v)	Length of trial (hr)	Nominal trial number	$CaCO_3$ content (%mass)	2 minute reactivity (°C) *
-	0	-	Base Case	4.1	48
22/02/2022	20	36	2	5.4	52
07/03/2022	50	36	4	4.5	52

The reactivity of the product was not affected, indicating that most of the product had not been sintered due to exposure to high temperatures. The calcination levels were maintained, there was a slight increase in carbonate levels, but this was expected given the reduction in the specific energy input to the kiln. However, there was some fused material discharged from the kiln following the demonstration trials. Although it is not possible to be certain of the cause, given the higher temperatures at times observed around the kiln, it is likely that this resulted from the higher localised temperatures in some parts of the kiln (despite the reduction in energy input to the kiln).

7.2.8   Thermal efficiency

The thermal efficiency of the kiln is improved when utilising hydrogen. Based on the EMB modelling, this could be as much as a 12% net improvement with a 100% hydrogen substitution level. However, due to the need to moderate the localised over-heating, it is unlikely that this figure would ever be achieved. If, for example, exhaust gas recycling was used to moderate temperatures and improve heat distribution this would increase the mass flow of exhaust gases leaving the burning zone and hence the excess heat leaving this zone and entering the preheating zone. As there is already more heat in these exhaust gases entering the preheating zone than is needed to preheat the stone all this extra heat would exit in the kiln exhaust gases.

7.2.9   Combustion air demand

Hydrogen has a lower stoichiometric air requirement than natural gas to achieve complete combustion. Due to this and the improved efficiency, the air requirement is lower when firing using hydrogen. This reduction could be as high as 27% when firing with 100% hydrogen.

As cooling air needs to be maintained to cool the product, only the side combustion air that enters the kiln alongside the natural gas or hydrogen could be reduced. This could lower the side combustion air demand by nearly 50% and would be detrimental to the heat distribution and gas penetration through the kiln bed, although the increase in fuel volume (hydrogen has 3.5 times the volume of natural gas) could help to reduce some of this effect. During the demonstration trials, the side combustion air volume was decreased in proportion to the total air requirements calculated in the EMB model for each of the hydrogen substitution levels.

7.3 Demonstration trial conclusions

Operation at 20% hydrogen by volume could be safely achieved with little impact on the kiln design or process. This is the most likely initial substitution level to the UK gas grid within the next ten years and bodes well for the adaptability of the lime sector.

At higher hydrogen substitution levels, the kiln could still produce an acceptable product, however there is potential for localised increases kiln temperatures that might have the following positive and negative effects.

- Higher NOx emissions.
- Sintered product.
- Increased refractory wear.
- Lower exhaust temperatures.
- Improved efficiency.
- Reduced combustion air requirements.
- Reduced exhaust volumes (meaning output could be increased).

Given the above affects are temperature related, modifications to reduce kiln temperatures and improve the heat distribution would impact on all of them. Such modifications might include:

- Exhaust gas recycling.
- Using side combustion air with less preheat.
- Adjusting side combustion air flow rates and/or combustion patterns.

With these modifications the kiln likely to be able to operate without NOx abatement. Current shaft kiln operation has been developed to maximise efficiency and minimise CO emissions. It may be possible to adjust the operation of the kiln to reduce NOx emissions.

Other affects of using hydrogen as a fuel include an increase in exhaust gas moisture content, a decrease in exhaust gas temperature and an increase in the acid dew point of the exhaust gases. Although the filter plant can be safely operated above the resultant dew point there is likely to be increased levels of corrosion in the

filter housing when operating over an extended period. This might be more of a consideration for different types of kilns.

8   Using Hydrogen in Parallel Flow Regenerative Kilns

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Summary and Key Learning

Computational Fluid Dynamic (CFD) modelling was used to assess the potential for fuel switching from natural gas to hydrogen in Parallel Flow Regenerative (PFR) kilns. The modelling looked at a steady state conditions, which can reasonably be expected to exist during the kiln cycles. The CFD modelling highlighted that product sintering leading to kiln blockages is the biggest risk presented by fuel switching, echoing the CFD modelling and practical experience on the vertical shaft kiln.

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8.1   The importance of considering Parallel Flow Regenerative (PFR) kilns

As discussed in section 1.1, Parallel Flow Regenerative (PFR) kilns are one of the most efficient forms of lime production. Most UK lime production is in PFR kilns, fired with natural gas.

In a PFR kiln there are two kiln shafts that fire in sequence every ten to fifteen minutes, so that the waste heat from one shaft can be reused in the other. This enhances the efficiency of production. Natural gas enters the kiln from the top through 'lances', which distribute the gas, therefore the energy is distributed more evenly across the kiln, The energy distribution from lances in a PFR kiln is more uniform than for the 'side firing' of vertical shaft kilns. A detailed description of the kiln firing process is given in the report from the Computational Fluid Dynamic (CFD) modelling (Annex D).

Figure 26: Schematic diagram of a PFR kiln
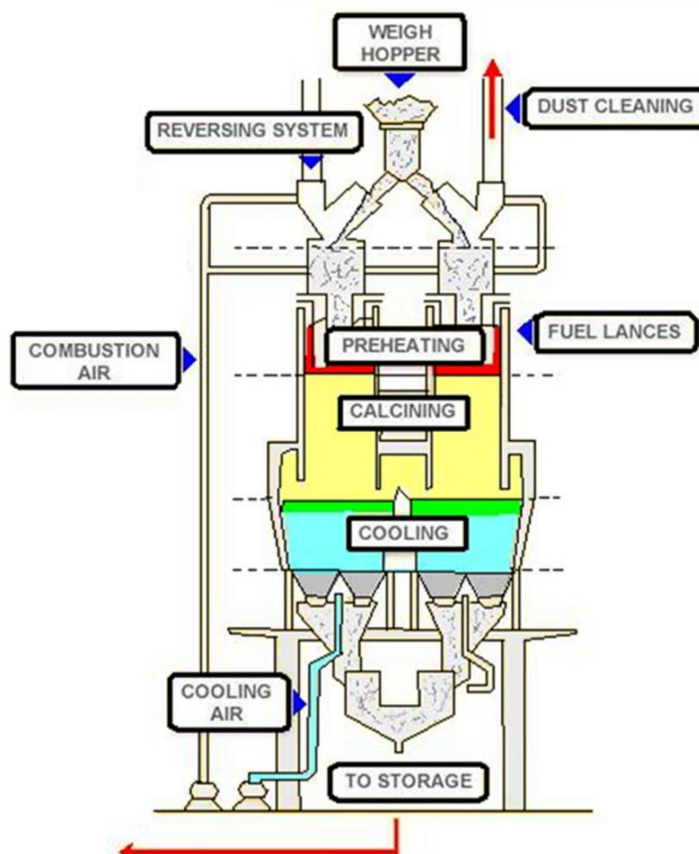
8.2 Computational Fluid Dynamic modelling of a PFR kiln

A special sub-group of representatives from the British Lime Association Member companies was formed to inform the CFD modelling, under the technical guidance of EESAC. Lhoist chaired the group and provided the base case data that was used to perform the modelling.

As with the previous CFD modelling of the vertical shaft kilns, discussed in section 3, the time and computational effort required to deliver a 'transient' model of PFR kiln is such that 'steady state' modelling is preferred.

- Given the design of the PFR kiln described above, it is reasonable to assume that gas flow and energy distribution in the PFR kiln achieve a steady state during the firing cycle.

- It is a simplification to assume a steady state for the limestone in the kiln, but this is considered acceptable given the thermal inertia of the stone bed.

- Previous modelling experience indicates that good alignment between actual PFR kiln and modelled systems is possible using a steady state approach.

Building on the knowledge gained from modelling the vertical shaft kilns, only four scenarios were modelled for the PFR kiln – the base case (BC) and three alternative cases (AC).

1. BC: Current operation with 100% natural gas firing.

2. AC 100%:   100% hydrogen substitution of natural gas.

3. AC 95%:   100% hydrogen substitution of natural gas but energy input reduced to 95% of natural gas equivalent.

4. AC 91.7%   100% hydrogen substitution of natural gas but with the energy supplied to the outer lances reduced by 10% and energy to the inner lances reduced to by 5% - this equates to the total energy being reduced by 8.3% to 91.7%.

There was good agreement between the base case (BC) modelled parameters and the kiln data monitored or estimated by Lhoist, which further endorsed the use of steady state assumptions.

Figure 27: CFD modelled gas temperature distribution for BC and AC 100% - note the elevated temperature at the crossover channel
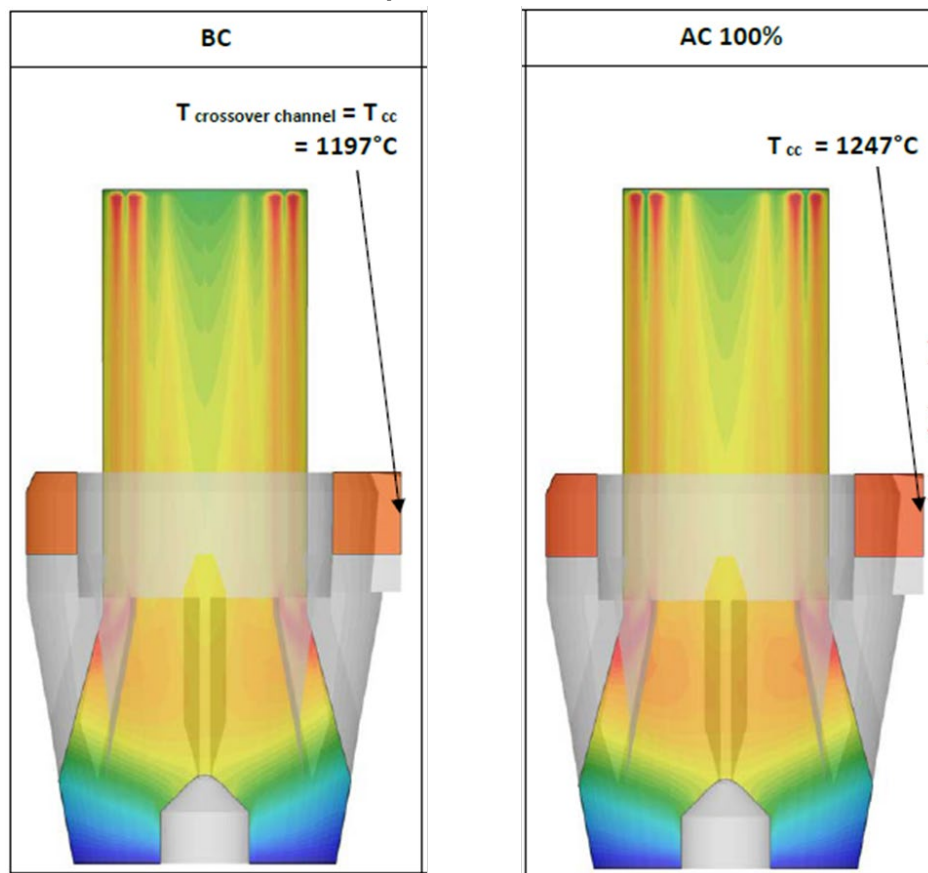
8.3 Results of the PFR kiln modelling

8.3.1 Exhaust gases

In changing from natural gas firing in the base case to hydrogen firing, the CFD modelling suggests that:

- Oxygen content remains stable.

- There is a decrease in CO_2 content – expected as hydrogen does not produce CO_2 on combustion.

- The water vapour content is almost doubled – expected as water is the combustion product of hydrogen fuel.

NOx concentrations may possibly double due to hydrogen deployment. However, it should be noted that the level of NOx emissions in the base case are relatively small – between 40 to 50 mg/Nm^3 and so a doubling of emissions would remain below the emission limit value of 150 mg/Nm^3 specified in environmental permits.

This suggests that it may be possible replace natural gas with hydrogen fuel without the need to implement additional NOx abatement. This accords with the findings from the demonstration trials on the vertical shaft kiln where NOx emissions were controlled by managing the specific energy input and even at high hydrogen fuel substitution levels, the NOx levels were lower than predicted by the modelling.

However, it is worth noting that the PFR kiln CFD modelling predicts higher NOx emissions when the energy input into the lances is not evenly distributed (AC 91.7%) because the outer lances create a fuel and oxygen rich region that favours NOx formation. In practice, such localised effects might increase the risks that NOx emissions limits are occasionally breached. A greater understanding of these implications might be achieved by full scale demonstration trials using a PFR kiln.

8.3.2   Calcination levels

The calcination in the shaft when fuel is being burnt (burning shaft) and in the shaft when only residual heat is present (preheating shaft) were modelled. The calcination levels are high in the burning shaft and much lower in the preheating shaft where there is only residual heat (around 65%). For the base case, calcination in the burning shaft is around 100%, and around 65% in the preheating shaft. Overall, the calcination level is expected to fall somewhere between the two numbers and be closer to the upper number in the burning shaft – around 98% as measured by Lhoist in the base case.

When hydrogen fuel is substituted. The calcination level in the burning shaft remains high (above 99%) but is lower in the preheating shaft (dropping to 58% for AC 91.7%). This is not surprising – for AC 95% and AC 91.7% there is less energy entering the kiln.

Given that overall calcination levels are likely to be closer to the calcination level in the burning shaft, it is possible that calcination would not be affected by hydrogen fuel replacing natural gas. This accords with the findings for the demonstration trials on the vertical shaft kiln but would benefit from confirmation through demonstration trial deployment of hydrogen fuel on a PFR kiln.

8.3.3   Bed and gas temperatures

The maximum temperatures in the stone bed are expected to increase with the use of hydrogen. However, this effect is mitigated by the reduction in energy input – AC 91.7%. Without this energy reduction, that is, for the complete replacement of natural gas with hydrogen (AC 100%), it is extremely likely that the lime would be over-burnt or sintered and could result in kiln blockages. There is also a higher risk of refractory damage under these circumstances.

In all instances, the highest temperature is at the burner outlets, and there is a significant increase in predicted temperature when hydrogen fuel replaces natural gas. This highlights the potential risk that, even where energy input is reduced, the maximum localised temperature could result in product sintering and potential blockages. This resembles the issues experienced on the vertical shaft kiln and presents one of the most significant concerns to the deployment of hydrogen for lime manufacturing.

8.3.4   Lime discharge temperatures

The PFR kiln CFD model did not correlate well with the base case data from Lhoist so the actual discharge temperatures cannot be forecast by the model. However,

the CFD model did show limited impact on the discharge temperature with fuel switching. This accords with the CFD modelling and practical experience on the vertical shaft kiln.

8.4 PFR kiln modelling conclusions

The CFD modelling highlights that it is feasible to manufacture lime using hydrogen fuel in a PFR kiln and to remain within environmental limits by managing the energy input. However, high localised temperatures may result in over-burning and sintering of the product. This has significant production implications and was apparent on the vertical shaft kilns. This appears to be the largest barrier to implementing high levels of hydrogen fuel substitution in lime manufacturing in the UK, whether using PFR kiln or vertical shaft kilns. However, due to the nature of a PFR kiln the heat distribution is more effective than with the side fired kiln (vertical) at Tarmac. Further potential modification suggested in section 7.3 could also be used to mitigate the above concerns.

9 Hydrogen Scale Up Potential and Cost Estimates

> ## Summary and Key Learning
>
> Based on the evidence gained from this project, it would be possible to convert lime manufacturing to run on a 20% v/v blend with natural gas, requiring investment between £240,000 and £360,000 per kiln – that is, between £4.5 and £7.5 million for the UK lime sector.
>
> Capital costs to transfer to 100% hydrogen fuelled manufacturing are significantly more uncertain but, based on the experience from this project, investment of around £4 million would be needed for a lime manufacturing site with four natural gas fired kilns and if no changes to kiln refractories, kiln burning zones, NOx abatement or bag filter equipment were required.
>
> Given the variability between manufacturing sites and the uncertainty on mitigating works, transferring the UK lime sector to 100% hydrogen firing on could require new investment between £60 and £120 million, highlighting the need for a stable and predictable policy environment.

The experience gained from this project has allowed better estimates of potential and costs of deploying hydrogen fuel at lime manufacturing sites. Two scenarios are considered, 20% v/v substitution into the natural gas supply (around 6% energy basis) and 100% replacement of natural gas energy with hydrogen fuel. In all instances, it is assumed that the fuel mixture is delivered to site via a gas transmission and distribution system, in a similar manner to the current natural gas system. It would not be cost-effective or have sufficient security of supply for hydrogen gas to be delivered by tube trailer in either scenario.

9.1 20% v/v hydrogen/natural gas blends

The Government's Ten Point Plan for a Green Recovery targets 2023 as the year to complete the testing necessary to allow up to 20% blending of hydrogen into the gas distribution grid for all homes. All UK Lime manufacturers currently receive their natural gas from the gas distribution grid, so introducing 20% v/v hydrogen in natural gas into the lime manufacturing process appears to be the most likely initial scenario for the deployment of hydrogen.

However, to enable this transition, the following areas will need to be considered for plant (e.g., kilns and process controls) and site-wide (e.g., gas entry pressure).

- Reduce the number of pipe flanges - replacing them with welded joints.

- Change out any remaining flange gaskets to specifications compatible with hydrogen gas.

- Refurbish or replace existing valves to eliminate / reduce leakage.

- Check slam shut valves suitability for use with hydrogen and natural gas blends and replace as required.

- Install thermal mass flow meters to support process accuracy.

- Check the necessity/suitability of incomer (7 bar), and any subsequent pressure let down (4 bar), and metering prior to each process plant – with the works finally needed on the complexity of individual sites.

- Undertake HAZOP, LOPA, DSEAR analysis and sign off as actions completed.

For a single kiln, based on current prices, the cost estimate to complete these work packages is around £300,000 ± 25%. This suggests that, to complete works across all the 20 gas fired lime kilns in the UK, would cost between £4.5 million and £7.5 million.

9.2 100% replacement of natural gas with hydrogen

Based on the experience in these demonstration trials, to move to 100% hydrogen fuel the changes to the system classification and design tabulated below must be considered. Given the significant uncertainty regarding the need for some items, they have not been included in the cost estimate, but rough estimates are provided based on the best available data.

Table 6: Considerations for replacement to 100% hydrogen fuel

Consideration		Certainty
1.	Pipework changes to a hydrogen specification to prevent embrittlement and size increases to accommodate volume flow	Medium uncertainty
2.	Equipment changes to meet the new designs and specifications including, slam shuts, manual valves, flow meters, and temperature and pressure gauges	
3.	Increased height on vent stacks and possible relocation, with redesigned stacks that are more robust and designed to accommodate internal detonation	
4.	Redesign with rewiring of new control circuits and equipment	
5.	Formation of new safety architecture, probably resulting in new programmable logic controllers and software	
6.	Installation of new gas analysers as part of the safety controls and stack monitoring	
7.	Creation of new exclusion zones with potential to drive solutions for additional ventilation and gas monitoring	
8.	Development of safe systems of work with staff training and the provision of anti-static personal protective equipment	
9.	Refractory suitability and condition	High uncertainty
10.	Burning zone design optimisation for flame velocity	
11.	NOx abatement / reduction	
12.	Bag filter condition / design for moisture and dew point	

9.2.1 Cost estimates with medium uncertainty

Looking at items 5-12 in Table 6, the increase to 100% hydrogen will cost around £800,000 per plant with a further £750,000 per site for infrastructure changes (both ±25%) – based on current prices. This is in addition to the £350,000 per kiln already noted for transfer to 20% v/v hydrogen/natural gas blend. There are around 20 natural gas fired kilns in the UK, operating across 5 sites. This suggests that these basic costs could be between £15 million and £25 million for the UK lime sector.

9.2.2 Cost estimates with high uncertainty

This does not account for items 1-4 in Table 6, which cannot be defined as the demonstration project was not able to define the requirement with any certainty. However, the following estimates are provided based on costs from publicly available information (e.g., from web searches, from the lime Best Available Reference Document). BLA Members have confirmed these numbers as broadly correct – recognising that actual costs will depend on individual circumstances.

- Replacing refractories per kiln – including materials, installation costs and waste disposal – estimated between £500,000 and £1.5 million per kiln. Refractory usually lasts ~10 years. If the transfer to 100% hydrogen is at the end of a 10 year cycle then the cost would be Zero.

- Redesign of burning zones to optimise energy distribution - estimated between £500,000 and £1 million per kiln – assuming that this work would be undertaken in parallel to kiln works (e.g., replacing refractories).

- Bag filter plant upgrades and operations – based on costs of bag filter plant installed at lime manufacturing sites, changes to processes will cost around £300,000 to £700,000. Due to the high degree of uncertainty of the changes that would be required, increases in operating costs are not estimated. This might not be required if the redesign of the burning zone is 100% successful.

- NOx abatement using selective catalytic reduction- based on cement sector experience, installing abatement equipment will cost around £10 million to £15 million per site, with operating costs increasing between £5 and £7 per tonne of lime. Currently NOx abatement if not required at any UK gas-fired lime manufacturing plant as emission levels are low -this means that, if NOx emissions increase beyond permitted thresholds due to the introduction of hydrogen fuel, new abatement equipment will need to be installed.

Taken alongside the reasonably certain cost estimates, the investment costs to the sector for conversion to 100% hydrogen fuelled manufacturing might be between £60 million and £120 million. Clearly, the level of cost is highly uncertain, but does emphasise the level of policy stability and predictability needed to support such a transition within sector currently reliant on natural gas.