State of the art fuel mix for UK cement production to test the path for 'Net Zero': a technical, environmental and safety demonstration.

Summary Report

Demonstration for the Department for Business Energy and Industrial Strategy
A report funded by an SBRI Competition: TRN 2021/08/2019

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1. Executive Summary

1.1. Demonstration aim

This demonstration is part of Phase 3 of a BEIS funded Industrial Fuel Switching competition aimed at showing the potential for using 100% net zero fuels in industry. In Phase 2 of the competition, a feasibility study demonstrated that a theoretical combination of 70% biomass, 20% hydrogen, and 10% plasma energy could be used to switch cement manufacture to 0% fossil fuel CO_2 emissions[1], in keeping with the industry's decarbonisation goals[2] and the UK's decarbonisation legislation. The study also identified some uncertainties that required a physical trial before these technologies could be commercially scaled and deployed.

This demonstration phase aimed to address the issues identified in the feasibility study by trialling high levels (up to 100%) of net zero fuels on working cement manufacture sites in the UK. Two sites were chosen to undertake the physical trials to allow fuel switching of the main kiln burner and calciner input energy to be investigated separately which reduced the interruption to daily operations for each site. The UK cement manufacturing sites used for the trials were:

- Hanson Cement: Ribblesdale site: trialling hydrogen and biomass in the main kiln burner
- Tarmac Cement: Tunstead site: trialling plasma and biomass in the calciner

1.2. Computational modelling

For both trials, CINAR used process knowledge driven, mineral interactive computational fluid dynamics (MI-CFD modelling) to model a range of scenarios to determine the optimum plant trial conditions and understand the potential impact of the changes on the specific site plant. For the hydrogen/biomass trial the modelling highlighted that a switch to 100% carbon neutral fuels is possible in the existing main kiln burner with minor variation to the flow aerodynamics and temperature fields. MI-CFD modelling for the plasma/biomass trial tested different injection points for biomass fuels including wood pellets and investigated what impact the plasma torch would have. The modelling concluded that wood pellets would be well suspended with good burnout[3] for the design and operating conditions modelled, and that the small plasma torch sourced for the trial would have limited impact on the process.

1.3. Trial fuel mix

During the demonstration, the biomass sources chosen for the hydrogen/biomass trial were meat and bone meal (MBM, a solid fuel derived from abattoir and rendering waste) and glycerine (a by-product of the biodiesel production process). The trial was planned to take place over the course of a month on 5 separate days, but net zero was reached on the 4th trial day for a few hours, and the 5th trial day, where it was planned to run the 100% net zero mix for a longer duration, was unable

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[1] "Options for switching UK cement production sites to near zero CO_2 emission fuel: Technical and financial feasibility", Summary report, 2018, TRN 1674/10/2018, Options for switching UK cement production sites to near zero CO2 emission fuel: Technical and financial feasibility (publishing.service.gov.uk)

[2] "UK Concrete and Cement Industry Roadmap to Beyond Net Zero", 2020, MPA, Decarbonising UK Concrete and Cement (thisisukconcrete.co.uk)

[3] Burnout is the term used to describe how fully the fuel particles are combusted in the process.

to go ahead due to a kiln stop for a problem unrelated to the trial.

On each trial day, hydrogen/biomass was ramped up and coal ramped down until the net zero fuel mix was achieved. At the point of net zero, the thermal input from hydrogen was 40% of the total energy required by the main kiln burner, and the remaining 60% came from biomass.

For the plasma/biomass part of the demonstration, tests were conducted using wood pellets which showed that with a heating value of approximately 18 GJ/t they were a suitable fuel with options for mechanical or pneumatic delivery into the calciner. The plasma energy would be delivered using a 100kW plasma torch. However, during the trial itself, it was not possible to use high proportions of biomass due to recent plant modifications that altered the fuel delivery systems. Instead, the plasma torch was tested with the calciner running on its business-as-usual fuel mix which included tyre chips, wood chips and solid recovered fuel. Unfortunately, the plasma torch failed after only 30 minutes which has limited the useful information obtained on the use of plasma in cement manufacture.

1.4. Trial assessment

VDZ undertook a technical audit as part of the hydrogen/biomass trial to evaluate the effect of the net zero fuel mix (note that this analysis was not possible for the plasma/biomass trial which was only able to run for 30 minutes). This analysis is summarised below:

Energy consumption: The hydrogen-rich net zero fuel mix had a neutral impact on the thermal energy consumption of the kiln line, i.e., no thermal energy efficiency gains or losses were noticed.

CO_2 emissions: The fuel-based CO_2 emissions of the kiln were significantly reduced when firing a net zero fuel mix. Considering the thermal energy consumption and fuel mix of the kiln at Ribblesdale with its normal fuel mix of pulverised coal and Cemfuel in the main kiln burner, the CO_2 emissions avoided using the trial net zero fuel mix are greater than 40% of the whole fuel-based CO_2 emissions of the kiln line.

Other emissions: The amount of carbon monoxide (CO) at the kiln inlet (kiln material feed end) doubled (from 10 parts per million (ppm) to approximately 21 ppm) most probably related to a slight reduction of Oxygen (O_2) during the combustion process. Simultaneously, an increase of Nitrous Oxides (NOx) measured at the kiln inlet was observed (from 857 ppm in the baseline to an average value of 1215 ppm and a peak value of around 1560 ppm during the trial). This was likely due to higher peak temperatures in the flame when hydrogen was burned compared to coal.

Flame shape and temperature: There was no significant change in the flame shape or in the peak temperature when the kiln was operated at net zero compared to the baseline.

Temperature profile and build-up formation in the kiln: During the trial there were no changes of note on coating formation.

Impacts on clinker and cement quality: All clinker samples showed a typical intermediate chemical composition for Portland cement clinker. No significant impact of the use of hydrogen in the main kiln burner on the clinker quality could be verified based on the microscopical investigations. Analysis of cement samples from the trial were found to be at least on the same performance level as the reference cement.

1.5. Cost of CO_2 Avoided (CAC)

The "*Cost of CO_2 Avoided (CAC)*" of 1559 €/t_{CO2} was estimated for a main kiln burner fired with hydrogen and biomass. This is based on hydrogen composing 40% of the thermal input to the main burner compared to a reference based on 100% coal. The impact of increased use of biomass has not been factored in because it is already state of the art in cement manufacture (although not at the high proportions demonstrated in this trial), So this cost assessment is for the introduction of hydrogen as the innovative fuel. This found that the CAC is strongly driven by the cost of the net zero carbon fuel mix and respective operation and maintenance cost, which includes fuel transport, taxes and charges. The impact of CAPEX on the cost of clinker is negligible compared to OPEX. To compete with other decarbonisation technologies, such as carbon capture, the cost of hydrogen at the burner tip would have to be a twelfth of the value (hydrogen gas, transport and environmental charges) reported by in this trial in order to bring the CAC closer to 85 €/t_{CO2}.

1.6. Outcome of the plasma/biomass trial

The scope of the plasma/biomass trial was heavily reduced due to plant modifications that altered the fuel delivery systems during the demonstration and before the trial took place. This meant that the use of high proportions of biomass was not possible.

The plasma torch was successfully designed, modified to comply with the technical electrical requirements of the site and operated in the kiln riser duct for around 30 minutes before its safety module was overloaded and subsequently destroyed. No evidence of damage to the 'head' of the plasma torch was observed but given the short trial duration conclusions could not be drawn on how well a plasma torch would withstand the environment in a calciner over a longer period.

The low heat input of the plasma torch and the relatively short operation period could not provide the necessary experimental data to validate the technology, properly assess its impacts on the clinker manufacturing process, evaluate the feasibility of a technological scale up and perform a fair benchmarking assessment against alternative decarbonisation technologies such as carbon capture.

1.7. Development of fuel switching in cement manufacture

The failure of the plasma trial has cast doubt on future use of plasma in cement manufacture. However, the efficiency of plasma technology to generate heat means that consideration should be given to repeating the trial with another 100kW torch to see if the issues of using it in the calciner can be overcome. If successful, this could be scaled up to a torch sufficiently powered torch to test the impact on the calciner and the clinker produced. However, high electricity prices remain a barrier to greater electrification of cement production. An alternative option to decarbonise the calciner, which requires lower flame temperatures than the main kiln burner, could be the use of 100% biomass fuels. This would be worth exploring as a next step providing a secure supply of cost competitive waste biomass fuel at the required specification can be sourced.

The use of hydrogen was highly successful. The next steps should be to optimise the use of waste biomass sources combined with hydrogen at the main kiln burner focussing on bringing the rate of hydrogen to a minimum whilst ensuring the required flame temperature for the clinker burning process is reached. The deployment of hydrogen at scale across the sector is very much tied to UK plans for increasing hydrogen production and scaling up the infrastructure to enable its delivery. The high quantities required in cement manufacture would require pipeline infrastructure rather than delivery by tube trailer.

If costs could be reduced and a net zero fuel mix of hydrogen and biomass were deployed across the sector to make up 40% of the thermal energy to the kiln system (i.e., 100% net zero fuel on the main kiln burner), as demonstrated in this trial, this would reduce the annual CO_2 emissions of the sector by around 875ktCO_2 (based on 2019 levels of production). This represents a reduction of 13% of total CO_2 emissions (fuel and process emissions) across the sector.

There is far greater potential for the scale up of biomass fuel across the sector. As noted above, it could be used with hydrogen (acting as a burning aid) in the main kiln burner or potentially providing 100% of the calciner energy requirement. However, current biomass quantities available in the UK are not sufficient to achieve the net zero fuel mix therefore H_2 is required.

In summary, the key remaining barriers to deployment of a net zero fuel mix following this demonstration are:

- Hydrogen: obtaining a secure supply of cost competitive zero carbon hydrogen. Optimising the net zero carbon fuel mix to use biomass sources combined with a lower proportion of hydrogen at the main kiln burner to reduce the use of hydrogen to a minimum while ensuring the required flame temperature for the clinker burning process
- Plasma: development of plasma technology to be of sufficient power and energy and further testing in the cement manufacturing environment
- Biomass: obtaining a secure supply of waste biomass and testing the use of 100% biomass fuel in the calciner

2. Introduction

2.1. Background to cement manufacture

Cement is the essential ingredient in concrete, which is the world's second most consumed substance after water. Portland cement was first patented in Britain by a bricklayer, Joseph Aspdin, from Leeds in 1824 and to this day is one of society's most useful materials; no modern school, house, road, hospital or bridge could be built without it.

Cement is a manufactured powder that, when mixed with water and aggregates, produces concrete. The cement-making process can be summarised in three basic steps:

1. Raw material preparation: Calcium carbonate from chalk or limestone plus smaller amounts of clay are quarried, crushed, and balanced to the correct specification to produce raw meal.
2. Clinker production: The raw meal is heated in a kiln at temperatures around 1,450°C, then cooled to produce an intermediate component known as clinker.
3. Cement production: The clinker is ground with other minerals including gypsum to produce cement.

The manufacture of cement is an energy and CO_2 intensive process with around 70% of total emissions arising from the chemical decomposition of calcium carbonate minerals (process emissions) and only 30% from the combustion of fuels. The split varies from plant to plant and country to country largely based on the CO_2 intensity of the local fuel mix. Considerable progress has already been made in reducing emissions in UK cement manufacture (Figure 2.1) through investment in newer more efficient plant and fuel switching to biomass fuels. In 2020 a wide range of waste biomass and part biomass fuels contributed 18% to the total thermal input across the UK cement sector.

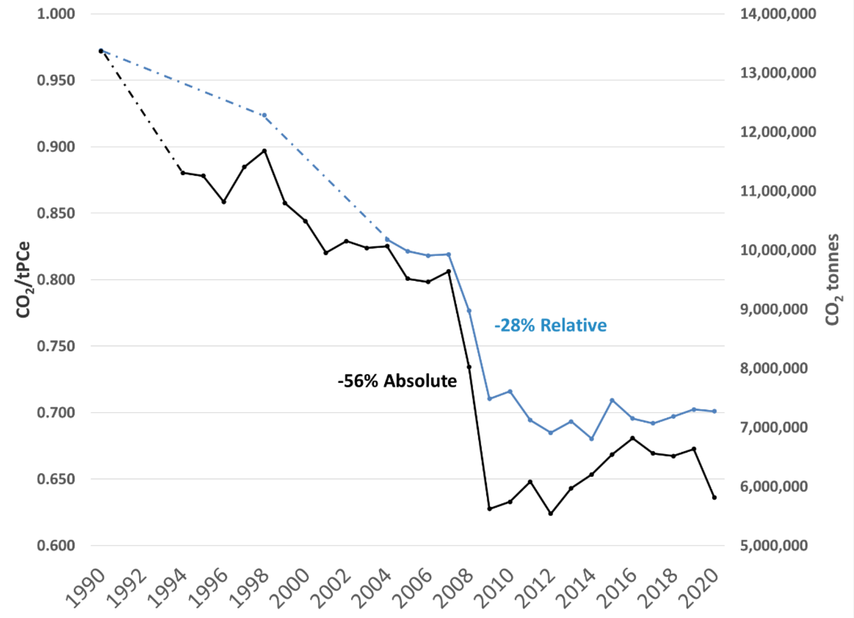

Figure 2.1: Reduction in Absolute and Relative Emissions from UK Cement Manufacture 1990-2020

Historically cement manufacture has relied on fossil fuels such as coal and petcoke to generate the high temperatures (in excess of 1450°C) required to drive the chemical reaction that produces cement from calcium carbonate (chalk or limestone) and clay raw materials. However, over the last two decades considerable investment has been put into fuel switching to waste derived fuels. These waste derived fuels include some that are fossil fuels (e.g., waste oils and waste solvents), some that are a mix of fossil and biomass (e.g., tyres and refuse derived fuel) and some that are biomass only (e.g., meat and bone meal and sludges). Currently UK cement manufacturers do not utilise any virgin biomass fuels, all the fuels are wastes that have gone through at least one previous use. As such, the sustainability issues that hinder the reputation of biomass burnt for electricity production before the CO_2 can be fully returned to carbon in tree growth, is not an issue for second use biomass. The use of waste biomass fuels in the cement sector provides a considerable reduction in the emission of fossil CO_2. Reductions occur not only from the associated emissions being carbon neutral (because they arise from biomass) but from avoided emissions from coal, which instead remains in the ground. In 2019 use of waste 100% biomass and waste part-biomass fuels lowered absolute emissions in the cement sector by 200ktCO_2. However, the switch away from coal avoided 500kt of fossil coal emissions. Furthermore, the use of waste biomass avoided the use of biomass crops or forest products.

Additionally, unlike other combustion processes, such as power generation, incineration and biomass boilers, the ash from fossil and waste derived fuel forms part of the mineral content of the cement and is not a waste residue. Some waste derived fuels, such as tyres, contain additional mineral and metal content which is required in the cement manufacturing process and their use can therefore offset some small amounts of virgin raw materials. Thus, cement manufacturing recycles the mineral content of wastes with energy recovery as a co-benefit of that recycling, known as ‘co-processing’. The use of waste as raw materials combined with the ash from co-processed waste derived fuel, means that on average, UK produced cement has a recycled content of around 10%.

Co-processing does mean that any fuels, waste or otherwise that are used, must meet a certain specification to ensure there is no detrimental impact on the cement product or the environment. More information on the specification is available in the MPA Cement Waste Code of Practice[4].

2.2. Aim of the demonstration project

In Phase 2 of the BEIS funded Industrial Fuel Switching competition, a feasibility study demonstrated that theoretically a combination of 70% biomass, 20% hydrogen and 10% plasma energy could be used to switch cement manufacture to 0% fossil

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[4] “MPA Code of Practice for the use of Waste Materials in Cement and Dolomitic Lime Manufacture”, MPA Cement, 2014, https://cement.mineralproducts.org/documents/2014_10_01_Waste_code_of_practice_plus_annexes.pdf

fuel CO_2 emissions[5], in keeping with the industry's decarbonisation goals[6] and the UK's decarbonisation legislation. The study also identified some uncertainties and issues that required a physical trial before these technologies could be commercially scaled and deployed. These are outlined below.

2.2.1. Plasma

In the feasibility study, knowledge was drawn from the incineration sector for the use of plasma torches to illustrate the potential to reach high temperature low carbon heat with a renewable power source. It highlighted that plasma technology in cement production had not been globally tested or demonstrated. The feasibility study indicated the next step was to demonstrate the use of plasma as a heat source to the calciner.

The initial cost assessment conducted as part of the feasibility study suggested that a 10% plasma thermal replacement of the total fuel would require capital expenditure in the order of £4.6m to £8.4m with operating costs double this value. Capital costs are high for plasma energy and the torches may need replacing often, however, they are very efficient in changing electrical energy to heat (around 70-90% efficient). Key areas identified for investigation in a demonstration were:

- Power supply requirements
- Cement kiln specific prototype plasma torch design
- Composition and choice of plasma gases
- Thermal stress tests of plasma torch electrodes
- Thermal efficiency assessment
- Cost benefit analysis of power fired heat vs combustion fuel
- Optimised location of the plasma torches and relationship with calciner meal inlets and degree of calcination assessment
- Kiln riser velocities and aerodynamics

2.2.2. Hydrogen

The physical and chemical properties of hydrogen present entirely new challenges to cement production. The feasibility study concluded that hydrogen is most suitable for the main kiln burner where its high heat generation (and flame temperature) can be used to address some of the calorific limitations associated with high levels of biomass. The analysis indicated that the high flame temperature would require a modification to the main kiln burner to have a flame similar to coal where it is centred in the kiln and does not impinge on the kiln wall refractory. The new burner design would aim to reduce hot spots in the kiln and, if possible, avoid additional creation of thermal nitrous oxides (NOx). A full renovation of the burner with associated hydrogen storage and pipework modifications was analysed to result in a minimum CAPEX of £350,000. Efficiencies of hydrogen production by water electrolysis is in the range of 70-80% however this may improve as the technology matures. Key areas identified for investigation in a demonstration were:

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[5] "Options for switching UK cement production sites to near zero CO_2 emission fuel: Technical and financial feasibility", Summary report, 2018, TRN 1674/10/2018, Options for switching UK cement production sites to near zero CO2 emission fuel: Technical and financial feasibility (publishing.service.gov.uk)

[6] "UK Concrete and Cement Industry Roadmap to Beyond Net Zero", 2020, MPA, Decarbonising UK Concrete and Cement (thisisukconcrete.co.uk)

- Hydrogen delivery to the burner
- Storage and handling / Safety assessments
- Hydrogen compatible prototype burner/lance design
- Empirical assessment of NOx formation
- Kiln wall hot spot minimisation
- Gas flow rate observations
- Clinker formation evaluation
- Whole life CO_2 assessment of hydrogen use in cement manufacture

2.2.3. Biomass

Biomass is a familiar fuel to many cement plants but to achieve a net zero fuel mix, very high levels of biomass are needed; levels that have not previously been tested. Use of such high levels of biomass presents the following challenges:

- Higher moisture in the biomass reduces the energy input per tonne of material
- Biomass particle size distribution can be wider than coal
- Potential for increased NOx formation where biomass contains a higher nitrogen content than the coal base case.

The feasibility study assumed a high-quality biomass fuel in the modelling; a fuel that is not currently abundant in the UK. Therefore, a demonstration using a bespoke fuel design was proposed to assess if the kiln performance can match that of a coal fired baseline when very high levels of biomass are introduced. Key areas identified for investigation in a demonstration were:

- Optimised biomass fuel design
- Main kiln burner/lance prototype design and optimisation
- Assessment of flame characteristics, velocities, recirculation and burnout
- Temperature, oxygen, CO_2, H_2O empirical profile assessment
- Calciner residence time
- Riser duct velocity design and modification
- NOx formation assessment

In addition to the fuel specific tests outlined in sections 2.2.1 to 2.2.3 above, the demonstrations were also needed to analyse clinker quality and mineralogy and provide greater understanding of the overall techno-economic assessment of potential scale up of net zero fuelled cement manufacture.

2.3. Project partners

2.3.1. Mineral Products Association (MPA), project coordinator

The Mineral Products Association (MPA) is an association of member companies dedicated to working together to better serve the industry’s needs and aspirations. The MPA represent the interests of all UK cement manufacturers by providing guidance and support on decarbonisation policy, sustainability, health and safety, as well as industry legislation and liaison with government.

MPA’s key role was as overall project manager, managing the project and providing widespread dissemination of the results to help ensure all cement manufacturers have access to the information required to inform future decisions on fuel switching.

2.3.2. CINAR Ltd

CINAR Ltd was incorporated in 1988, since then it has 30 years of combustion engineering and academic experience in solving industrial problems using physical and mathematical modelling techniques.

For cement and lime industries, CINAR has completed over 350 projects, dealing with various combustion, emissions, and process issues. CINAR has developed, together with its industrial partners, a unique tool; MI-CFD (Mineral Interactive Computational fluid dynamics) which accounts for calculation of combustion and mineral reactions simultaneously. This makes calculated results more realistic in terms of temperatures and gas species' composition, and enables prediction of CO, NOx which cannot be predicted with general purpose CFD tools. CINAR therefore offers alternative fuels and raw materials (AFR), Process, Emissions, and Clinker Quality assessments for cement and lime producers for reducing operating costs and to find low-Capex solutions for kiln/calciner upgrades.

The unique MI-CFD has been used to resolve cement process combustion related issues by its ability to track and monitor the progress of combustion and its location for, not only multiple fuels simultaneously, but for as many size fractions of any fuel as is needed to resolve the associated combustion issue, at the same time as interacting with kiln and calciner feed.

2.3.3. VDZ gGmbH – Research Institute German Cement Works Association

For over 140 years the German Cement Works Association (Verein Deutscher Zementwerke – VDZ gGmbH) has been contributing with its research both to competitive and environmentally compatible cement production, to the development of high-quality concrete constructions as well as cost-effective cement production. With its Research Institute of the Cement Industry, VDZ is a renowned and internationally acknowledged scientific institution, which is characterised by its services for cement producers worldwide.

VDZ operates its Research Institute of the Cement Industry (Forschungsinstitut der Zementindustrie) in Düsseldorf, a facility with 180 employees; more than 60 of them are academics. With its five departments Cement Chemistry, Concrete Technology, Environment and Plant Technology, Environment Measuring and Quality Assurance, the Research Institute covers all aspects of cement production and application.

VDZ is a founding member of the European Cement Research Academy (ECRA) founded in 2003 as a platform on which the European cement industry supports, organises and undertakes research activities within the context of the production of cement and its application in concrete. By creating and disseminating knowledge from research findings, ECRA's aim is to facilitate and accelerate innovation to guide the cement industry in the 21st century.

2.3.4. Hanson

At Hanson and HeidelbergCement our building materials and solutions shape significant development worldwide. We build on one and a half centuries of experience. Now is the time to lay the foundation for our future.

At the centre of our actions lies our responsibility for the environment. We want to be the leader in the industry on the path to carbon-neutrality. We deliver long-term financial performance through operational excellence, dedication, and openness for change.

We are progressive minds with the ambition to drive transformation. We push the boundaries to strengthen innovation and deepen partnerships with our customers and other stakeholders. Together we craft material solutions for the future. So that the world can always build on us.

2.3.5. Tarmac

Tarmac is the UK's leading sustainable building materials and construction solutions business. Our innovative services and solutions help to deliver the infrastructure needed to grow the economy today and create a more sustainable built environment to support our future prosperity. We employ approximately 7000 people at more than 400 operational locations across the UK and are the largest manufacturer of cement and lime with facilities based in England, Wales and Scotland.

Tarmac is a part of CRH, the world's leading building materials business which manufactures and distributes a diverse range of superior building materials products and solutions, which are used extensively in construction projects of all sizes, across the world.

Tarmac Tunstead site has been in operation since the 1920s, with production of Lime, Aggregates and Ready Mix, with a cement operation since 1965. The new cement kiln line was commissioned in 2004 with a significant capacity upgrade completed in 2008.

3. Overall demonstration design

This project aimed to address the issues identified in the feasibility study by trialling high levels (up to 100%) of net zero fuels on working cement manufacture sites in the UK.

The BAT (Best Available Technology) for cement manufacturing is a calciner kiln system (Figure 3.1). In this system, process heat (from fuel) is added to both a precalciner (~60% of heat requirements) and the rotary kiln (~40% of heat required).

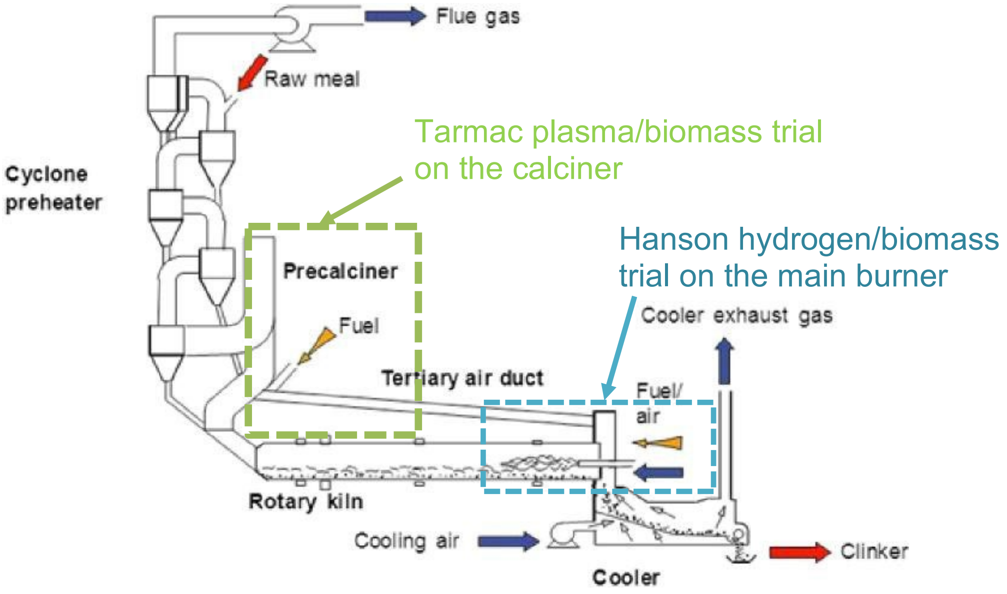


Figure 3.1: Schematic of a calciner kiln system.

Two sites were chosen to undertake the physical trials to allow fuel switching of the kiln and calciner input energy to be investigated separately, which reduced the potential interruption to daily operations for each site. The UK cement manufacturing sites used for the trials were:

- Hanson Cement, Ribblesdale site trial: burning hydrogen and biomass in the main kiln burner
- Tarmac Cement, Tunstead site trial: burning biomass in conjunction with plasma energy in the calciner.

During the demonstration, the biomass sources chosen for the hydrogen/biomass trial were meat and bone meal (MBM, a solid fuel derived from abattoir and rendering waste) and glycerine (a by-product of the biodiesel production process). The trial took place over the course of a month on 5 separate days during which hydrogen/biomass was ramped up and coal ramped down until the net zero fuel mix was achieved. At the point of net zero, the thermal input from hydrogen was 40% of the total energy required by the main kiln burner, and the remaining 60% came from biomass.

For the plasma/biomass part of the demonstration, tests were conducted using wood pellets which showed that with a heating value of approximately 18 GJ/t, they were a suitable fuel with options for mechanical or pneumatic delivery into the calciner. The plasma energy would be delivered using a 100kW plasma torch. However, during the trial itself, it was not possible to use high proportions of biomass due to recent plant modifications that altered the fuel delivery systems. Instead, the plasma torch was tested with the calciner running on its business-as-usual fuel mix which included tyre chips, wood chips and solid recovered fuel. Unfortunately, the plasma torch failed after only 30 minutes which has limited the useful information obtained on the use of plasma in cement manufacture.

Detailed information on each of these trials is provided in separate chapters below.

4. Hanson hydrogen/ biomass trial

4.1. Introduction

The initial intention for the hydrogen/biomass trial was to test the net zero fuel mix during a number of trials over the period of a month and for hydrogen to form 50% of the thermal input to the main kiln burner with biomass making up the remaining 50%. However, it became clear that it was not possible for hydrogen suppliers to meet this demand for hydrogen. Not only would this require more hydrogen production capacity than was available in the UK at the time, but the need to deliver the hydrogen via tube trailer to site and the logistics of then transferring the hydrogen from the tube trailers to the kiln, meant that the trial had to be scaled back.

The trial was then planned to take place over 5 trial days spread over a month during which hydrogen/biomass would be ramped up and coal ramped down. At the point of net zero the intention was for hydrogen to make up 28% of the thermal input to the main kiln burner. However, as hydrogen/biomass was ramped up, it was found that the fuel delivery system (skid and pipeline) could accept a much higher quantity of hydrogen. As a result, net zero was reached on the 4th trial day for a few hours and at that point, hydrogen made up 40% of the thermal input. The 5th trial day, where it was planned to run the 100% net zero mix for a longer duration, was unable to go ahead due to a kiln stop for a problem unrelated to the trial. Information and learning from the trial, including a techno-economic assessment, are presented in this chapter.

4.2. Planning and assessments

Before starting the trial there were a number of assessments and permitting requirements that had to be fulfilled. A summary of each of these is provided here.

Environmental permit: The use and storage of hydrogen required a variation to the Ribblesdale environmental permit. This required an assessment of all the potential environmental impacts arising from the trial. The variation was treated as a high priority application for a standard variation and did not require any formal public consultation. The permit application was submitted in April 2020 and determined in October 2020. Alongside the permit variation, several changes were made to the work’s environmental management system including updating the emergency procedures, fire risk assessment and environmental aspects.

Planning permission: The scale of the additional equipment required on site for the trial was relatively small. It included a 100 m^2 concrete pad for trailer discharge and hydrogen pressure reduction skids, a small diameter pipe run to the kiln platform and valve train (including flow controller) prior to flow through a specifically engineered lance. As these changes were temporary, no planning permission was required.

Hazardous Substances Consent: The trial required the storage of hydrogen in tube trailers on site. This required a hazardous substance consent to be issued by the planning authority. The application required information on all hazardous substances stored on site including, gas oil, diesel, hazardous liquid waste fuel (Cemfuel) and ammonium nitrate (quarry explosive). The consenting process included a formal statutory public consultation which was advertised in the local newspaper and notices outside the works entrance. A press release accompanied the statutory advertising. No public representations were made during the consultation.

Control of Major Accident Hazards (COMAH): Up to 5 tonnes of hydrogen can be stored without requiring COMAH registration. However, the cumulative inventory of hazardous substances needs to be assessed. In this application the cumulative inventory of hydrogen and Cemfuel in relation to their respective thresholds meant the works become a lower tier COMAH site for the duration of the trial. Following completion of the trial and the removal of all the hydrogen tube trailers the lower tier COMAH registration was rescinded, and the site was returned to non COMAH status.

4.3. Biomass selection

The MPA feasibility study was based on the use of sewage sludge pellets, meat and bone meal (MBM) and wood chips as the biomass source. In the early stages of the project these options were reviewed, and it was discovered that dried sewage sludge in the UK has limited availability. Most sewage sludge available was being dewatered and spread on land and the small volume of dried sludge produced is all under contract so was not available for the trial.

An MBM handling system was already in place at Ribblesdale, which normally supplies the calciner. Additional pipework to transport MBM to the main kiln burner was also available. This system was renovated, and a short proving trial carried out in January 2021. Following this trial, modifications to the MBM fan on the burner were made to increase the air flow to enable a higher usage of MBM at the main kiln burner.

The supply of wood chips was reviewed, typically wood chips arising from shredding waste wood are around 40mm in the longest dimension. This is too large for use at the main kiln burner which requires finely divided wood typically less than 100µm in diameter. Reducing the wood chips that are available to this size would require significant processing using specialised equipment either on or offsite. Furthermore, the low Calorific Value (CV) and high moisture content of the wood would make handling finely ground wood difficult, therefore alternatives to these materials were investigated.

Hanson's alternative fuel suppliers, Tradebe, identified glycerine, a by-product of biodiesel production, as a potential liquid biomass fuel for the trial. Biodiesel is manufactured from waste vegetable oils from the catering industry. This product is normally used in anaerobic digestors where it improves bacterial activity. As a consequence of the COVID-19 pandemic and the restrictions on hospitality, the raw material stream was greatly reduced. This resulted in the cost of glycerine trebling between selecting the material in February 2020 and the trial in September 2021.

The Ribblesdale kiln already has a liquid fuel system. This was adapted to handle glycerine for the purposes of the demonstration. Like MBM, the CV of glycerine is relatively low and has a high moisture content. The glycerine system was commissioned in May 2021 and tested in combination with coal. A glycerine flow rate of less than 3tph was found to cool the kiln burning zone, resulting in the quality of kiln clinker to deteriorate.

Heat input from glycerine and MBM without using hydrogen was only possible at low levels because the flame temperature dropped and clinker quality deteriorated. However, it was anticipated that the use of hydrogen would enable higher levels of MBM, and glycerine use without any drop in flame temperature. For the main net zero trial, hydrogen, MBM and glycerine were therefore selected.

4.4. Hydrogen supply

The lack of sufficient quantities of green hydrogen in the UK meant that grey hydrogen had to be used for the trial. BOC (a Linde company) provided the hydrogen supply to the main kiln burner in tube trailers storing approximately 250kg of usable hydrogen each at ~230 bar pressure. The pressure was reduced to 10 bar using a skid (with two stage pressure reduction) developed and provided by BOC. The use of grey hydrogen meant that the demonstration was net zero at point of use and not net zero across the entire supply chain.

4.5. MI-CFD modelling

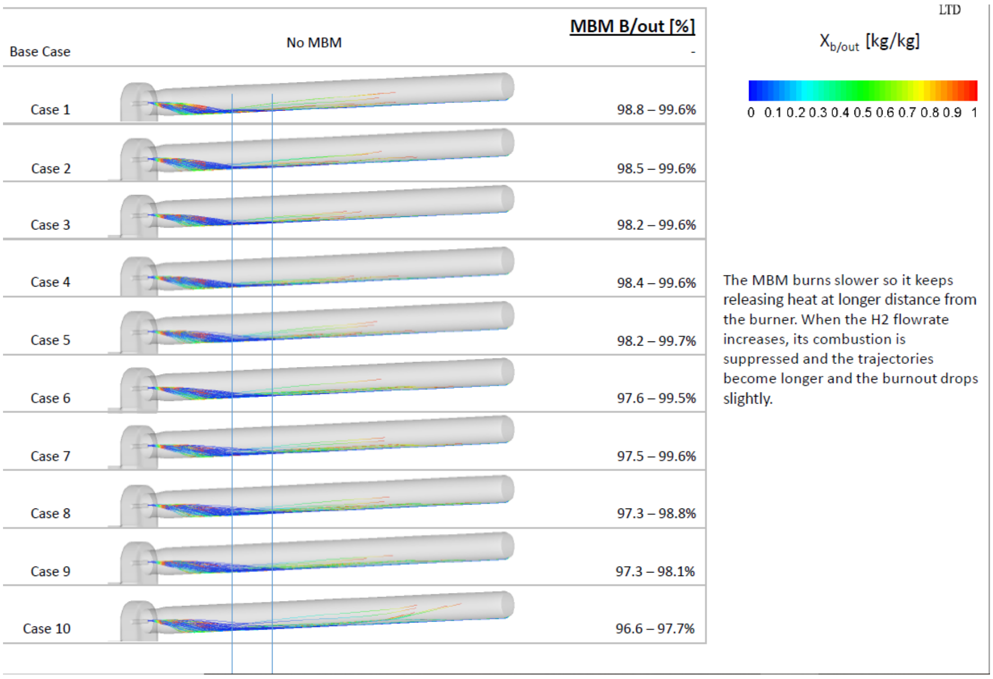
Once the biomass fuels had been selected, CINAR used their process knowledge driven, mineral interactive computational fluid dynamics (MI-CFD modelling) to model a range of scenarios to determine the optimum plant trial conditions and understand the impact of the progressive changes that are expected during the originally 5 planned trial days. The modelling was initially used to analyse the base case (48% coal, 52% Cemfuel) and compare it to 10 cases that progressively replaced coal and Cemfuel with hydrogen, glycerine and MBM. In this modelling exercise all the input conditions (airstreams of burner, bed material and secondary and false air) were kept as close as possible to the same level as the base case. The percentage thermal input of each fuel in each case is shown in Table 4.1 below. Note that the original design of the trial was for hydrogen to make up 28% of the fuel mix when net zero was reached and this was what was modelled. However, as hydrogen/biomass was ramped up, it was found that the fuel delivery system (skid and pipeline) could accept a much higher proportion of hydrogen. As a result, at the point that net zero was reached, hydrogen made up 40% of the thermal input.

Table 4.1: % thermal input of fuels modelled in the base case and Cases 1-10.

	% Thermal input			
	Coal	**Glycerine (Cemfuel for base case)**	**MBM**	**Hydrogen**
Base Case	48	52	9	0
Case 1	60	31	9	0
Case 2	57	31	9	3
Case 3	55	31	9	5
Case 4	53	31	9	7
Case 5	50	31	9	10
Case 6	33	33	22	12
Case 7	30	33	22	15
Case 8	15	35	30	20
Case 9	7	36	36	21
Case 10	0	36	36	28

The main observations from this initial modelling were:

1. Glycerine devolatilised quickly but released higher levels of vapour compared to Cemfuel. This increased the production of gases, and the peak temperatures were reduced.
2. MBM burns more slowly than other fuels, so it continued to release heat at longer distance from the burner. When the hydrogen flowrate increases, its combustion is suppressed and the MBM burnout drops slightly (Figure 4.1).
3. The hydrogen is oxidized with the available oxygen. The expanded gases increase the velocity locally and then the hydrogen remains unburnt until more oxygen is mixed into the flame. Due to the hydrogen consuming the available oxygen it becomes more difficult for the other fuels mostly coal and MBM to burn as they also compete for the remaining oxygen available.
4. The gas temperature is increased close to the tip of the burner as the hydrogen ignites as soon as it mixes with the primary air. As the thermal input of hydrogen increases beyond case 3 or 4 no large variation close to the burner tip is observed because the hydrogen has to travel further before mixing with available oxygen.
5. Case 10, with maximum hydrogen, shows an increase in the temperature of the bed material due to quick burning of hydrogen. As mentioned above, the MBM burnout was reduced which resulted in the kiln inlet temperature dropping slightly.
6. At the higher levels of hydrogen input, the flame is characterised by a larger envelope of high temperature.
7. The increased input of hydrogen results in a change of the exit gases with increase of water in the products of combustion and reduction of the CO_2.
8. Values for bed temperature and clinker chemical processes, show similar trends to the Base Case, with some minimal variations at the start of some reactions.



The MBM burns slower so it keeps releasing heat at longer distance from the burner. When the H2 flowrate increases, its combustion is suppressed and the trajectories become longer and the burnout drops slightly.

Figure 4.1: Example of MI-CFD modelling results for burnout of MBM for Case 1 (base case before fuel switch) and cases 2-10 as hydrogen is progressively increased.

Following modelling of the ten cases above, five were repeated whilst keeping the kiln inlet oxygen value the same as in the base case. This was done by a reduction of supplied combustion air, either of the false air and when that was not enough, with some part of air from the cooler to attain similar oxygen levels to the base case. A reduction of supplied air was found to reduce the coal and/or the MBM burnout. Moreover, as the hydrogen proportion increased, the reduction in supplied air resulted in higher temperatures as heat was released closer to the burner which enabled more heat to be transferred to the material bed. As a result of both air reduction and reduced burnout, a small reduction in the volume of the kiln gases occurred while the temperatures reduced slightly.

Model variations were then made to investigate; the cooling of the hydrogen lance (fresh air around the outside of the lance) and its impact on the flame envelope. The model indicated no noticeable changes in the burnout and temperature profiles, species concentrations or changes to the bed material sintering reactions.

Also modelled, for safety purposes, was the impact on heat exchange within the kiln in the case of valve malfunction where uncontrolled overdosing of hydrogen to the main kiln burner represented the maximum possible hydrogen flowrate while the rest of the fuels remain in high dosing. In this case, an increase in local temperatures due to the increased fuel supply was observed. The available hydrogen quickly consumed available oxygen which led to a slowdown of the burnout of the solid fuels which must travel further to mix with available oxygen. This can lead to higher carbon in the meal in the calcination region of the kiln which can have some impact on the whole kiln operation. Due to increased heat, the phase transformations happened sooner in the kiln at a further distance from the burner.

Finally, the injection velocity of the hydrogen was varied to determine what effect, if any, this would have on flame shape and intensity. Lower hydrogen injection velocities were found not to alter the flame and heat release in the near burner region of the kiln. However, as temperature increases were observed closer to the tip of the burner, it was recommended to use at least 275 m/s injection velocity of hydrogen to ensure the flame is not pulled closer to the burner tip, which could cause serious damage to the burner in the short to mid-term.

In summary, MI-CFD modelling results show that use of 100% net zero fuels is possible in the existing main kiln burner with minor variation to the flow aerodynamics and temperature fields.

4.6. Safety

Critical decisions had to be made regarding safety aspects associated with the fuel switching trial. The majority of these decisions stemmed from the highly explosive nature of hydrogen gas. All trial fuel systems were designed to adhere to ATEX[7] regulations. Hazard Identification (HAZID) and Hazard and Operability (HAZOP) studies focused on issues which may arise during the operation such as changes in pressure and set out associated actions to remedy and reduce the impact of these changes.

As part of the design process, an early stage HAZID was completed covering the full trial from reception of each fuel at Ribblesdale to combustion in the kiln. HAZOP studies were carried out for each fuel system; MBM, Glycerine and Hydrogen. In the case of MBM and glycerine these studies covered the changes to existing systems as the installed equipment design had previously been subject to HAZOP.

A Dangerous Substances and Explosive Atmospheres Regulation (DSEAR) assessment was also completed for the full installation from the BOC skid to the kiln platform.

These studies and assessments identified several risks which are set out below along with the corresponding mitigation:

- The potential for an uncontrolled release of hydrogen from the BOC skid and stored hydrogen tube trailers was used to set an exclusion zone which was securely fenced to prevent unauthorized access to the skid and trailers during the period when hydrogen was stored on site. When the skid was in operation only BOC and Hanson personnel with appropriate PPE and training were permitted access to the hazardous areas.

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[7] ATEX is the name commonly given to the two European Directives for controlling explosive atmospheres:
1) Directive 99/92/EC (also known as 'ATEX 137' or the 'ATEX Workplace Directive') on minimum requirements for improving the health and safety protection of workers potentially at risk from explosive atmospheres. In Great Britain the requirements of Directive 99/92/EC were put into effect through regulations 7 and 11 of the Dangerous Substances and Explosive Atmospheres Regulations 2002 (DSEAR).
2) Directive 2014/34/EU (also known as 'ATEX 114' or 'the ATEX Equipment Directive') on the approximation of the laws of Members States concerning equipment and protective systems intended for use in potentially explosive atmospheres. In Great Britain, the requirements of the Directive were put into effect through BIS Equipment and Protective Systems Intended for Use in Potentially Explosive Atmospheres Regulations 1996 (SI 1996/192). More information available at: ATEX and explosive atmospheres - Fire and explosion (hse.gov.uk)

- Associated with the risk of a hydrogen leak, another risk of ignition was identified. To help combat this, the risk of a spark being present was removed from both the offloading skid area and the kiln platform skid. These areas were controlled by limiting access, all personnel having to wear ATEX rated PPE and remove any electronic devices before accessing the area. Staff training through a site wide toolbox talk was undertaken to ensure that all personnel on site were aware of the risks associated with the hydrogen on site and the precautions they should take.
- Another potential issue was the security related to hydrogen storage. This risk was also controlled through the hydrogen storage area being fenced off and locked to prevent unapproved access. A security camera was also installed to provide a live stream of the area.
- The hydrogen gas HAZOP identified one potential high severity event, a potential carbon monoxide (CO) explosion in the bypass electrostatic precipitator that was then considered in a layer of protection analysis (LOPA). The LOPA review concluded this event was unlikely to arise in the trial as the cause identified in the HAZOP related to the use of Cemfuel which was not present in the net zero demonstration fuel mix.
- The main risk associated with the hydrogen fuel system involved a hydrogen leak. This was incorporated into the design stage of the line with as few flanges as possible being incorporated on the line. Pipework installed was subjected to non-destructive testing on all welds. During commissioning the integrity of the pipe was further proved using water and nitrogen to pressure test the line and confirm no leakage. All valves and instrument fittings were leak tested and torque on flanges was tested. Pressure relief valves were also fitted on the skids and associated pipework to account for any abnormal changes in pressure during the entirety of the trial. At the end of each trial day, the system was purged with nitrogen and left in a pressurised state between trial days. In this interim period, checks were undertaken on the system pressure gauges and trailers to identify any leakage. During the trial prestart check lists were completed to ensure the system was fit for operation.
- Using the existing Cemfuel system to supply glycerine gave rise to the risk of contamination of fuel supply. This was controlled by the incorporation of a non-return valve on the glycerine line and a lock off procedure on the Cemfuel line.
- Negligible risks were identified with the MBM fuel line as it was already an existing method of supply on the site and had not been developed solely for the trial.

4.6.1. Control of fuel to the kiln

At Ribblesdale, standard operating practice for the day-to-day control of fuel to the kiln is largely at the control of the kiln operators who aim to maintain optimum burning conditions by manually increasing or decreasing fuelling to the main kiln burner and/or altering the tertiary air volume. This judgement is based on several available instruments including a kiln inlet gas analyser (Iteca) that measures O_2% (Oxygen), NOx ppm (Nitrous Oxides) and CO ppm (carbon monoxide), and a visual monitor of the flame condition by means of a Thermoteknix thermal camera (Figure 4.2) that also provides live data of the flame temperatures.

Figure 4.2: Image of the flame condition using a Thermoteknix thermal camera.

When introducing hydrogen and glycerine to the main kiln burner as new fuels that had not been previously used, an estimate of the fuel replacement from heat balance modelling, was used by the kiln controllers to gradually introduce the new fuels from a coal only flame and make the adjustments to settle the kiln into normal operating conditions.

4.7. Plant modifications and enabling works

4.7.1. Glycerine

To remove the requirement for the installation of an additional fuel system to the kiln, the glycerine supply was installed as an addition to the existing liquid Cemfuel delivery system This required new equipment in the form of an offloading pump, pipe bridge, an IBC (Intermediate Bulk Container), connecting pipe work and valves, and associated electric panels.

4.7.2. Hydrogen

The hydrogen supply to the main kiln burner was provided in tube trailers storing approximately 250kg of usable hydrogen each at ~230 bar pressure. The pressure was reduced to 10 bar using a skid (with two stage pressure reduction) developed and provided by BOC, the hydrogen supplier. The skid was installed on a new concrete pad, electrically earthed and fitted with lightning protection. The skid was designed to have two tube trailers discharging simultaneously and two on standby so that there would be no loss of hydrogen supply during the trial. A 24V electrical control panel to operate the skid was provided with an emergency shutdown that could be operated locally or in the plant control room. A second pressure reduction stage from 10 bar to 3 bar was rented from FT Pipeline Systems. 3 Bar was set as the skid outlet pressure to allow for the expected pressure drop across the flow control valves and burner nozzle. Figure 4.3 shows the hydrogen reception area on site.

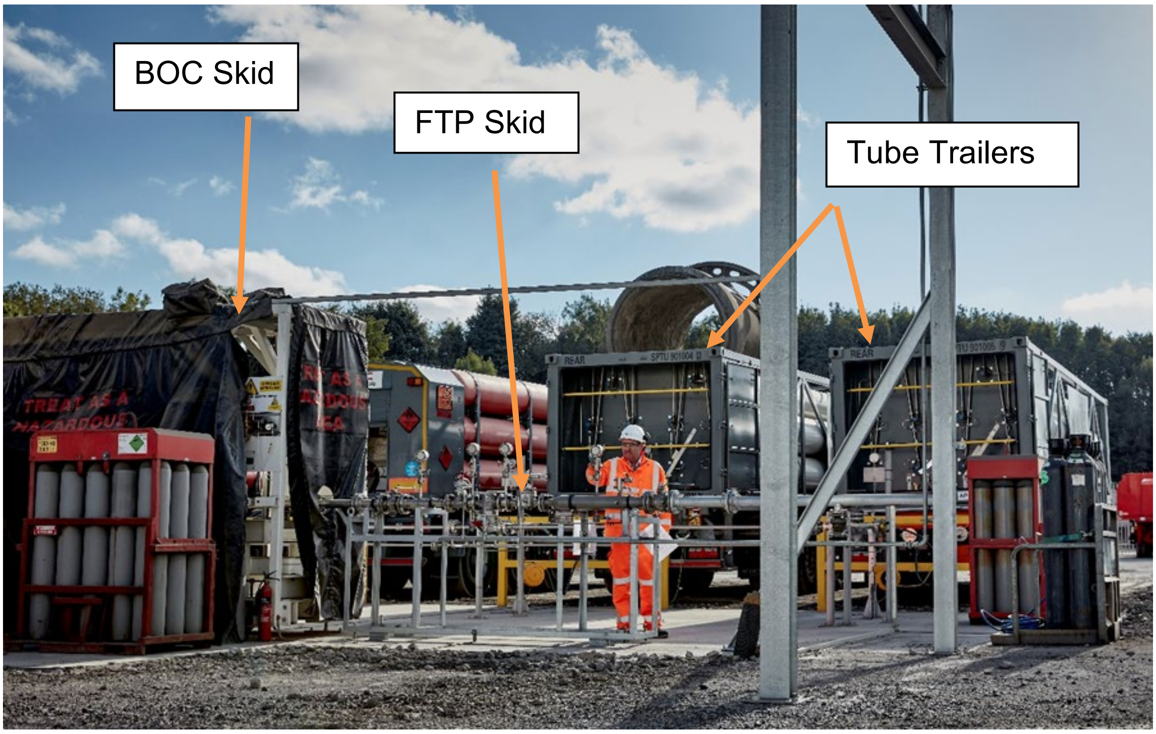

Figure 4.3: Photo of the hydrogen reception area on site indicating the hydrogen tube trailers, BOC skid and FTP skid.

This equipment was located approximately 30m from buildings to ensure full safe dispersal of hydrogen in the event of an incident requiring a full trailer to be vented. The tube trailer location was approximately 150m from the kiln platform.

At the kiln platform, the flow of hydrogen to the kiln was regulated using a flow meter and flow control valve in a valve train (see Figure 4.4). This also included a number of protection devices to prevent over pressurization of the system and emergency shutdown valves to protect the plant if there was an uncontrolled release. All this equipment was integrated into the existing works control system to enable remote operation thus minimizing the time spent by process operators within the ATEX zoned area. Personnel access was only needed during start up and shut down to open and close manual isolation valves. For planned shutdowns of the hydrogen feed system, for example overnight between trials, the Hydrogen line from the last BOC flange was purged with nitrogen into the kiln and the pressure maintained at around 3 bar. Before reintroducing hydrogen to the system, checks were completed for any pressure loss which would indicate a leak or passing valve.

Figure 4.4: Kiln platform hydrogen “valve train”.

The valve train was connected to the hydrogen lance using an armoured flexible hose. This allowed the lance to be withdrawn from the main kiln burner to protect it from heat damage when it was not in use. The lance was designed to fit within an empty channel on the current main kiln burner, it had two concentric channels for hydrogen and cooling air. Under normal operation the hydrogen flow was sufficient to keep the burner tip cool, if the hydrogen flow stopped then the air flow provided sufficient cooling to prevent damage to the burner tip (see Figure 4.5). The lance was equipped with 2 nozzles to ensure high gas velocities at the tip under low flow and high flow conditions. The low flow nozzle was only used on the first trial day. Both nozzles were adjustable to control hydrogen flow in addition to the flow control valve, in practice the nozzle was set at the maximum aperture to minimize system pressure drop.

Figure 4.5: Hydrogen lance burner tip (nozzle) shown outside of the kiln.

A high injection velocity was required to ensure the hydrogen ignited as far from the burner tip as possible to prevent damage to the burner. There were some concerns that high (supersonic) tip velocities would lead to excessive noise levels, however at maximum hydrogen flow the tip velocity was over 900m/s and there was no audible difference on the kiln platform.

4.7.3. MBM

The MBM supply for the trial used existing infrastructure. For the demonstration the normal MBM supplied to the calciner was diverted to the main kiln burner using a pre-existing pipeline left over from an initial trial with MBM on the main kiln burner that was carried out in January 2021. The 2021 trial had found that to operate at more than 1tph MBM at the main kiln burner required greater air flow than that provided by the MBM transport air alone. Therefore, for the hydrogen trial an existing primary air fan was modified to provide greater air flow to the burner.

4.8. Trial plan

The trial was set to commence over a month on 5 separate days, each day increasing the proportion of net zero fuels to achieve net zero carbon by the 5th trial day. In total, 11 runs were planned with coal gradually being ramped down and the biomass and hydrogen fuels ramped up. The thermal input as a percentage of total fuel energy for each planned run is shown in Figure 4.6 below. However, as noted previously, as hydrogen/biomass was ramped up, it was found that the fuel delivery system (skids and pipeline) could accept a much higher quantity of hydrogen. As a result, net zero was reached on day 4 for a few hours and at that point, hydrogen made up 40% of the thermal input. The 5th trial day was unable to go ahead due to a kiln stop for a problem unrelated to the trial.

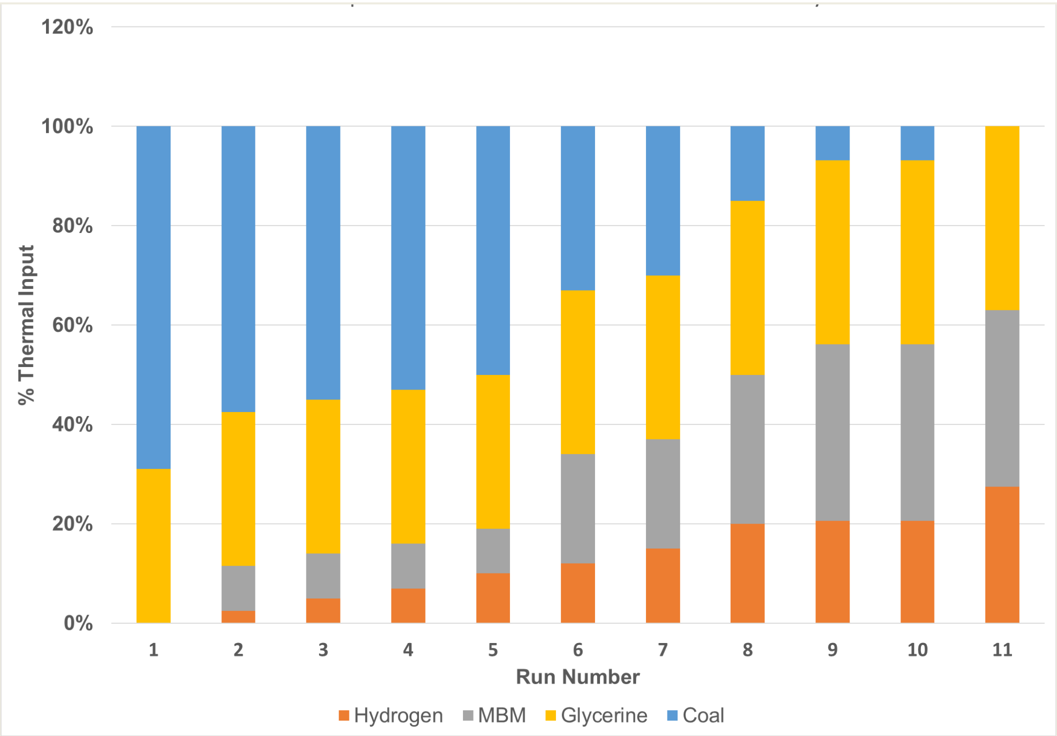

Figure 4.6: Thermal input from each fuel across the original 11 planned runs over 5 days.

At the beginning of each trial day the kiln would be burning a coal only flame to aid in creating the most stable conditions to begin the trial. The kiln controller would then introduce MBM and glycerine to the flame and allow conditions to settle before beginning to introduce hydrogen.

To determine the impact, if any, on the clinker produced, samples were taken throughout the duration of the trial.

4.9. Trial and product assessment

VDZ undertook a technical audit as part of the trial to evaluate:

1. The effect on the thermal energy consumption of the kiln line
2. The effect on emissions
3. The effect on the behaviour (temperature and shape) of the flame
4. The effect on the temperature profile and build-up formation in the kiln
5. The effect on clinker and cement quality

To comprehensively evaluate the performance of the kiln line at the time net zero was reached, a baseline for comparison was set. The kiln operating condition immediately prior to fuel switching trial was used as the baseline. At this point the plant was firing pulverised coal, MBM and glycerine in the main kiln burner. In addition, the plant was feeding coal and SRF in the calciner. The characteristics of the baseline are shown in Table 4.2 below.

One clinker and one cement sample were taken under baseline operating conditions. Three clinker and three cement samples were taken during the trial. All clinker and cement samples were compared and analysed in VDZs laboratories.

Table 4.2: Energy demand and fuel-based CO_2 emissions for the baseline.

Fuel	**Fuel Feed**	**Low Calorific Value**	**Thermal Power**	**CO_2 Emission Factor**	**Fossil CO_2 Emission**
	t fuel/h	**GJ/t fuel**	**GJ/h**	**kg CO_2/GJ**	**kg CO_2/h**
Main Burner					
Pulverised Coal	2.22	24.16	53.64	95.4	5117
MBM	0.75	19.38	14.54	0	0
Glycerine	3.175	15	47.63	0	0
Calciner					
SRF	8	16.50	132.00	88.6	11695
Pulverised Coal	1.54	24.16	37.21	95.4	3549

4.9.1. Energy consumption

The thermal energy consumption of the kiln decreased from 115.8 GJ/h in the baseline to 111.6 GJ/h during the trial, which corresponds to a reduction of approximately 4%. The reduction of the thermal energy consumption of the whole kiln line followed the same trend (from 285 to 274 GJ/h, or also approximately 4%). However, this potential thermal energy saving may not be attributable to the use of a net zero fuel mix but rather to the reduction of the kiln feed in the same proportion (~4%). A cautious approach was taken to the kiln feed rate to give more flexibility to respond to the changing conditions. Thus, the hydrogen-rich net zero fuel mix apparently had a neutral impact on the thermal energy consumption of the kiln line, or in other words, no thermal energy efficiency gains or losses have been noticed.

4.9.2. CO_2 emissions

As already expected, the fuel-based CO_2 emissions of the kiln could be significantly reduced when firing a net zero fuel mix (from approximately 5120 kg/h in baseline to 0 kg/h during the trial). This means that around 28% of the whole fuel-based CO_2 emissions of the kiln line could be avoided compared to the baseline set out in Table 4.2. As there were no thermal energy efficiency gains, the reduction in the CO_2 emissions is exclusively related to the utilization of fossil CO_2 free fuels in the main kiln burner (biomass and hydrogen).

Considering the thermal energy consumption and fuel mix of the kiln at Ribblesdale with its normal fuel mix of pulverised coal and Cemfuel in the main kiln burner (see Table 4.3), the CO_2 emissions avoided using the trial net zero fuel mix are greater than 40% of the whole fuel-based CO_2 emissions of the kiln line.

Table 4.3: Energy demand and fuel-based CO_2 emissions for the usual operation of the Ribblesdale plant.

Fuel	**Fuel Feed**	**Low Calorific Value**	**Thermal Power**	**CO_2 Emission Factor**	**Fossil CO_2 Emission**
	t fuel/h	**GJ/t fuel**	**GJ/h**	**kg CO_2/GJ**	**kg CO_2/h**
Main Burner					
Pulverised Coal	2.40	24.16	57.98	95.4	5532
MBM	0	19.38	0	0	0
Cemfuel	2.57	22.50	57.83	85	4915
Calciner					
SRF	8	16.50	132.00	88.6	11695
Pulverised Coal	1.54	24.16	37.21	95.4	3549

4.9.3. Other emissions

The amount of carbon monoxide (CO) at the kiln inlet doubled (from 10 ppm to approximately 21 ppm). Since the clinker sample did not show any signs of reduced burning conditions, the rise of CO formation is most probably related to a lack of

Oxygen (O_2) during the combustion process. This hypothesis can be confirmed by the level of O_2 observed at the kiln inlet, which on average was lower during the trial than in the baseline (3.9 vol.% and 4.6 vol.% respectively). This could be explained to a certain extent by the reduction of primary air. In comparison to coal, glycerine and hydrogen do not require air as a conveying medium to reach the burner tip. Thus, the substitution of coal by hydrogen and glycerine lowers the amount of primary air and, consequently, the quantity of O_2 available for the combustion process. In addition, the combustion of hydrogen requires less air than coal. This fact only reinforces the conclusion that the amount of air in the kiln was reduced; otherwise, the rise of O_2 concentration at the kiln inlet would have been observed.

Simultaneously, an increase of Nitrous Oxides (NOx) measured at the kiln inlet was observed with the use of a net zero fuel mix (from 857 ppm in the baseline to an average value of 1215 ppm and a peak value of around 1560 ppm during the trial). This apparently indicates that the flame was hotter during the trial, which could have promoted the formation of more thermal NOx. Usually, the level of O_2 at the kiln inlet and NOx formation are closely related to each other and follow the same trend when the kiln is hot. However, despite the O_2 reduction during the trial compared to the baseline, the level of NOx rose. This might be explained by higher peak temperatures in the flame when hydrogen was burned compared to coal.

Another explanation for the higher NOx and CO values observed during the trial is that given both NOx and CO are measured on a dry basis, both the reduction of CO_2 concentration of the kiln gases and a lower amount of air being pulled into the kiln can together artificially increase the NOx and CO values measured. Thus, a clear conclusion on NOx formation with a hydrogen-rich flame compared to coal cannot be drawn with the available data.

Although the stack Sulphur Dioxide (SO_2) and Ammonia (NH_3) emissions differ significantly between the baseline and the hydrogen trial period, this is predominantly due to the operating cycles of the wet gas scrubber and no relevant conclusions can be drawn in this case.

4.9.4. Flame shape and temperature

The flame was monitored in the control room with aid of a thermo-camera installed in the kiln hood, whose working principle relies on infrared technology and delivers a real-time imaging with temperature measurement (Figure 4.7 and Figure 4.8). Care must be taken if the comparisons of flame peak temperature and flame shape are made through the observation of real-time imaging (or screenshots) based on different temperature scales. An apparently brighter image of the flame or of the kiln environment might be misleading if the temperature scale is not properly considered.

There was no significant change in the flame shape or in the peak temperature when the kiln was operated at net zero compared to the baseline. This observation was also confirmed by the results of the analysis of the clinker samples taken during the trial (see section 4.9.6). A plume of approximately the same size was still visible in both operation scenarios. This demonstrates that firing hydrogen did not pull the flame closer to the burner tip, which could cause serious damage to the burner in the short to medium-term.

Figure 4.7: Flame shape and temperature (baseline).

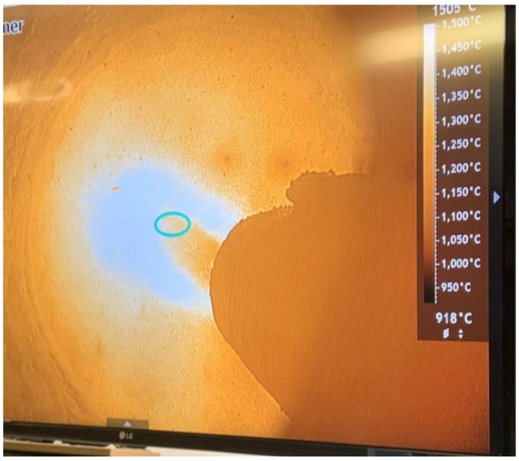

Figure 4.8: Flame shape and temperature at net zero.

The MI-CFD modelling simulations (see section 4.4) had indicated that feeding hydrogen at high thermal substitution rates would quickly consume the available oxygen and slowdown the burnout of MBM, which would have to travel further to mix with available oxygen. This would increase the overall flame length and consequently change the temperature profile in the kiln. Despite making sense from the theoretical point of view, this expected phenomenon was not observed during the trial. Flame shape was not observed to change compared to the baseline, or at least, not to a point to provoke any noticeable effect on clinker quality or on the images captured by the thermo-camera.

4.9.5. Temperature profile and build-up formation in the kiln

The location and evolution over time of coating formation in the kiln is closely related to flame properties and to kiln operation. However, coating formation has its own inertia, and the effects of changing flame properties take time before they can be observed with the kiln shell scanner. During the trial there were no changes of note on coating formation (Figure 4.9 and Figure 4.10 show no significant change in the colour banding along the shell of the kiln between the baseline and the trial).

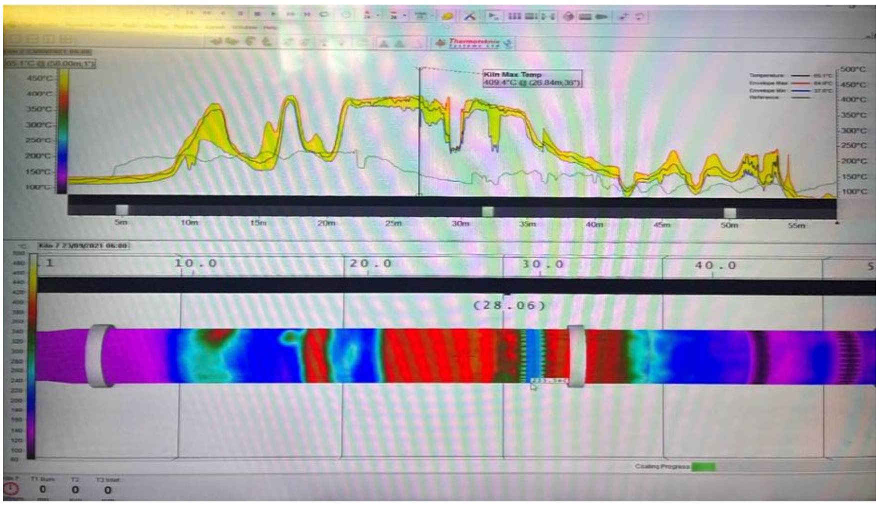

Figure 4.9: Kiln shell scan at 6:00 AM (baseline).

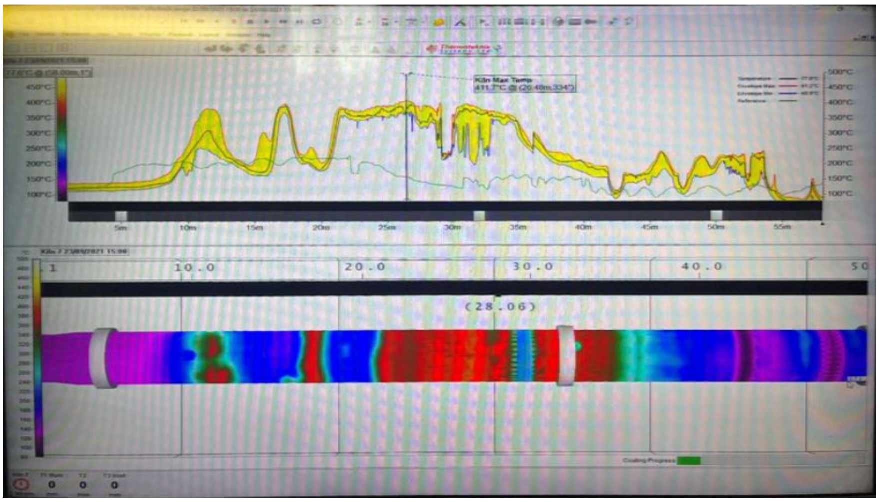

Figure 4.10: Kiln shell scan at 3:00 PM (trial).

4.9.6. Impacts on clinker and cement quality

A number of different tests were performed on the clinker. Optical microscopy was used to study sections under reflected light before and after etching. Chemical analysis of the main compounds was carried out with x-ray fluorescence analysis (XRF) on a fused bead and with infrared spectroscopy (IR) for CO_2 and water. Trace element contents were investigated by XRF on a pressed pellet. Additionally, the ferrous iron content and the free lime content was analysed by wet chemical methods.

The mineralogical composition of the clinker sample was examined with x-ray diffraction analysis (XRD). The clinker powder sample was analysed within a diffraction angular range of 5 – 65° 2 Theta. The x-ray diffraction pattern was evaluated quantitatively with the Rietveld refinement method. For a better differentiation of the minor phases in the XRD pattern, a methanol/salicylic acid digestion was carried out, and the residue was examined by means of XRD as well.

The physical properties (water demand, setting behaviour, strength development) were tested according to EN 196 standards. The heat of hydration was measured via isothermal heat flow calorimetry (TAM Air). Additional investigations on the mineralogy of the cements were carried out similar to the clinker.

Clinker chemical analysis: Table 4.4 summarises the chemical composition of the main constituents of the clinker samples. Samples 1-3 were taken during the final trial and sample 4 was the baseline taken before the trial. All clinker samples are quite similar, showing a typical intermediate chemical composition for Portland cement clinker.

Table 4.4: Chemical composition of the clinker samples.

Parameter	**Unit**	**Clinker 1**	**Clinker 2**	**Clinker 3**	**Clinker 4 (REF)**
Carbon dioxide	%	0,10	0,09	0,11	0,18
Water	%	0,18	0,17	0,14	0,26
Loss on ignition	%	0,28	0,27	0,25	0,44
Silicon dioxide	%	21,50	21,55	21,20	21,31
Aluminium oxide	%	5,27	5,31	5,21	5,27
Titanium dioxide	%	0,26	0,26	0,26	0,27
Phosphorus pentoxide	%	0,18	0,18	0,19	0,20
Ferric oxide	%	2,44	2,44	2,42	2,40
Manganese oxide	%	0,06	0,06	0,06	0,05
Magnesium oxide	%	2,22	2,21	2,23	2,47
Calcium oxide	%	65,04	64,79	65,47	64,75
Sulphate as SO3	%	1,16	1,33	1,22	1,42
Potassium oxide	%	0,55	0,62	0,58	0,52
Sodium oxide	%	0,31	0,31	0,31	0,28
Na2O equivalent	%	0,67	0,72	0,69	0,62
C3S	%	62,27	60,23	66,61	61,75
C2S	%	15,32	16,96	11,07	15,17
C3A	%	9,92	10,02	9,78	10,00
C4AF	%	7,51	7,51	7,44	7,38
LSF	%	97,5	96,8	99,5	97,6
Silica ratio	-	2,79	2,78	2,78	2,78
Alumina ratio	-	2,16	2,17	2,15	2,20
Degree of sulphurisation	%	135	142	135	176
FeO	%	0,027	0,036	0,036	0,047
Free lime	%	1,08	1,17	1,47	1,36

Clinker mineralogical analysis: The XRD patterns of the clinker samples is shown in Figure 4.11. All three clinker samples taken during the trial showed very similar phase composition. However, the mineralogical compositions showed slight deviations from the chemical analysis[8]. The reference clinker taken under the base conditions showed a phase composition close to the chemical analysis and seemed to be burnt to a slightly lower extent.

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[8] Differences were found in the alite content with XRD showing 65-66% by mass in clinker 1 and 2 which was higher than that found through the chemical analysis (60-62% by mass). The belite content of clinker 3 was higher in the XRD compared to the chemical analysis. Tricalcium aluminate (C_3A) appeared mainly in the cubic modification, but the contents found by XRD are lower than the calculated results. Some remaining Mayenite contents as well as some ingress of alumina as foreign atoms in the Ca-silicates should be responsible for these observations. The free lime contents also deviated from that of the chemical analysis.

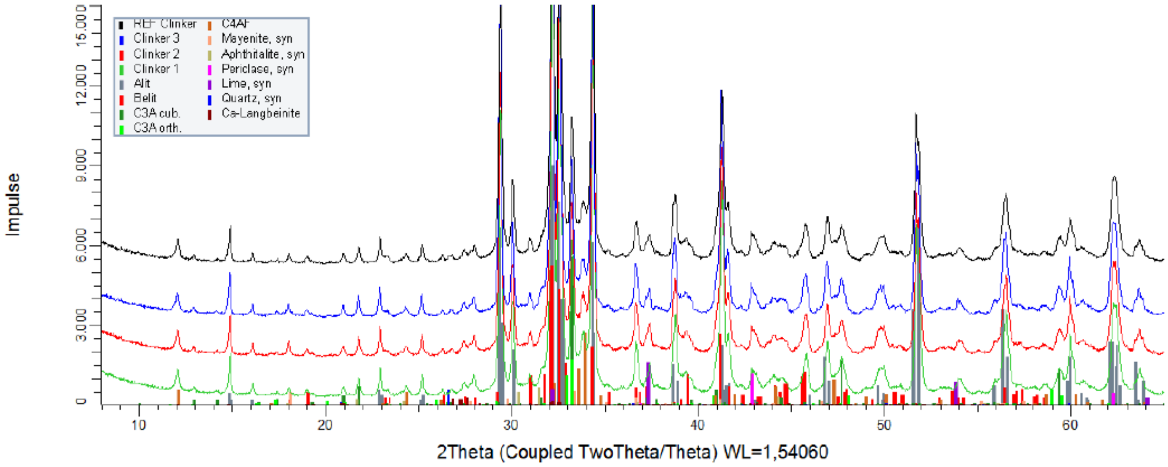

Figure 4.11: X-ray diffraction pattern of clinker samples, with phase indication.

Clinker microscopy: Using optical microscopy for the analysis of the unetched polished sections, alkali sulphates could be identified in the clinker samples as dark grey phases finely intergrown with ground mass phases (Figure 4.12a, b, c) and in pores (Figure 4.12a). After etching, the following clinker phases could be differentiated in the clinker samples:

- alite (xenomorphic to idiomorphic, light grey crystals with dark edges)
- belite (round, light grey crystals)
- tricalcium aluminate (C_3A, dark grey phase in the ground mass)
- ferrite (C_4AF; white phase in the ground mass)
- free lime (round, dark grey crystals with dark edges)

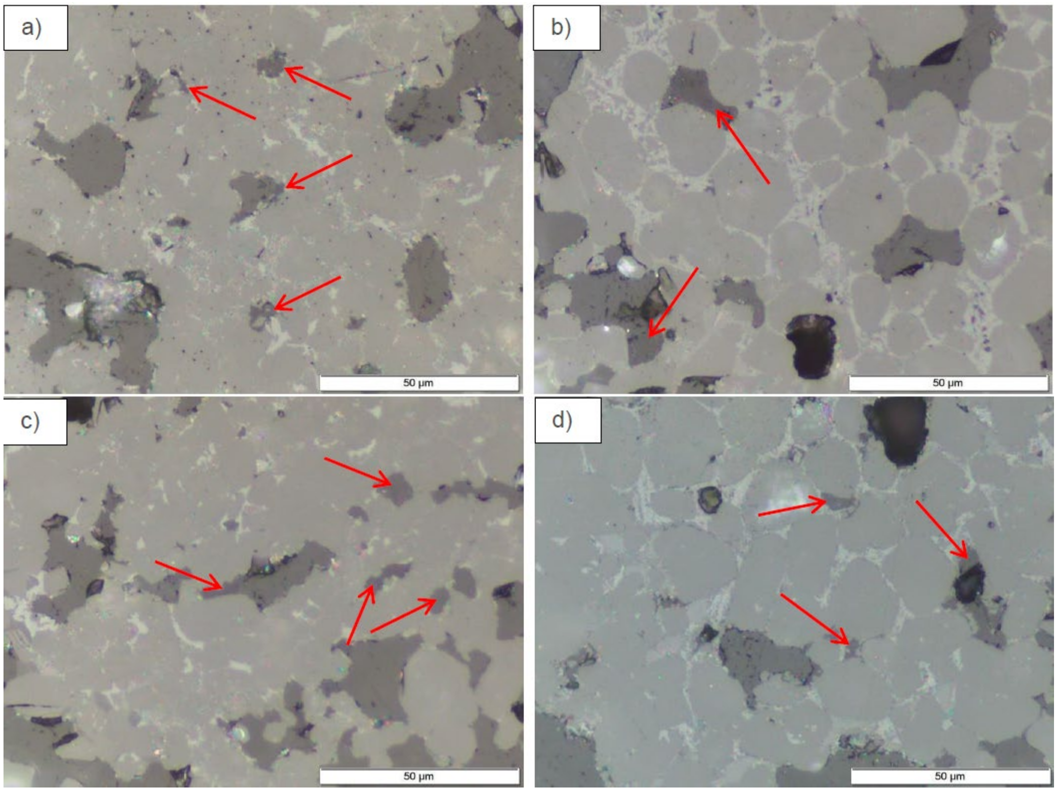

Figure 4.12: Alkali sulphates (red arrows) in the microstructure of the clinker samples, unetched: a). Clinker 1; b). Clinker 2; c). Clinker 3; d). Clinker 4 ref.

The microstructural features of all four analysed clinker samples were very similar. All had high burning degrees, comparable amounts of belite and free lime clusters, small alite sizes indicating high reactivity, characteristics showing a short to intermediately long precooling zone and intermediate cooling rates in the clinker cooler. No sample showed any signs for reducing burning conditions.

Three of the samples (clinkers 1, 2 and 4 Ref) sporadically contained mixed clusters of belite and free lime, probably caused by concentrations of P_2O_3 from meat and bone meal used as fuel.

Only small variations might indicate the tendency towards a slightly shorter sintering zone and a slightly higher heating rate in the clinker samples 1, 2 and 3 than in clinker 4 Ref. The former is indicated by a higher overall porosity, the latter by slightly smaller alite crystals (12.9 – 13.7 µm vs. 15.2 µm). However, the observations might be in the range of usual fluctuations in the kiln and should not be interpreted based on such a limited number of samples.

No significant impact of the use of hydrogen on the main kiln burner on the clinker quality could be verified based on the microscopical investigations.

Cement analysis: During the trial, three independent CEM I samples were taken which were produced from the test clinker represented by the clinker samples 1 to 3. It must be considered that there is no strict correlation of clinker and cement samples, so for example, cement A does not strictly represent clinker sample 1.

A fourth CEM I sample was investigated representing clinker from the common kiln operation status without using hydrogen as fuel. Again, there was no strict correlation between cement D and clinker sample 4.

All cement samples were tested on their physical performance. The results for water demand, stiffening behaviour, strength development and measurements on heat of hydration (isothermal heat flow calorimetry) are listed in Table 4.5.

Table 4.5: Physical properties of the cement samples (CEM I)

Parameter	**Unit**	**Cement A**	**Cement B**	**Cement C**	**Cement D (REF)**
Water demand	%	29.0	28.5	29	27.5
Initial setting time	min	145	130	145	115
Final setting time	min	185	165	185	160
compressive strength 2 days 7 days 28 days	MPa	35.8 53.4 69.2	34.7 51.3 67.5	34.6 52.2 67.5	31.9 47.0 60.8
Heat of Hydration	J/g	314	312	308	303

All three cement samples representing the clinker production with hydrogen showed very homogenous results and could be evaluated as Portland cement of type CEM I 52.5 R. All of them had a higher strength performance than the reference cement but had nearly the same level of heat of hydration. That indicates that there might be some differences in the product fineness which was not tested.

Additional XRD analyses were performed to ensure that there were no significant changes in the clinker. Figure 4.13 compares the XRD diffraction pattern of the cement samples. It became obvious that there were some differences in the dosage/dehydration of the sulphate carriers (gypsum) which also may cause some of the observed strength effects, as well as some differences in water demand and setting behaviour.

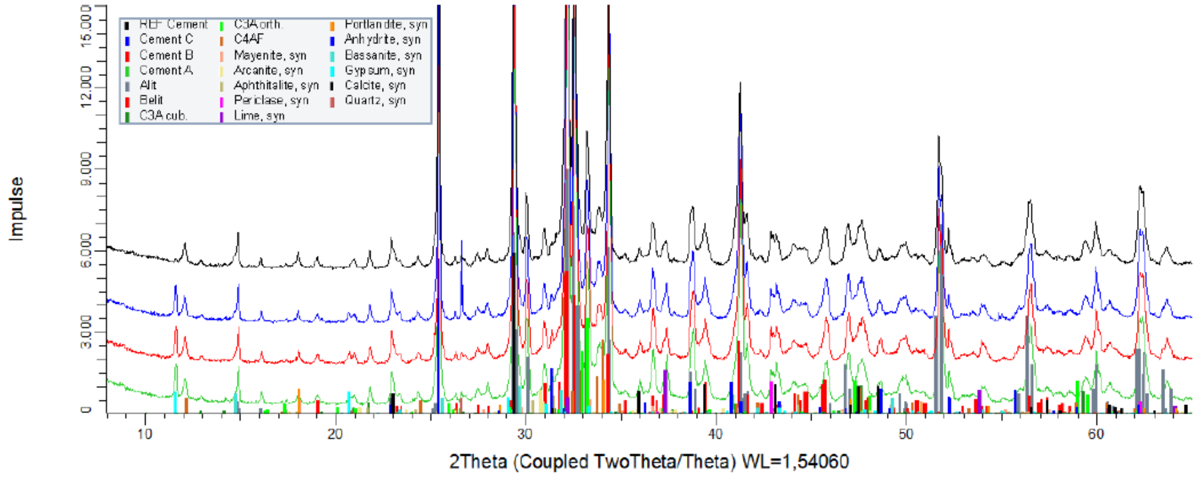

Figure 4.13: X-ray diffraction pattern of cement samples, with phase indication.

In conclusion, the cement samples representing the test phase with hydrogen usage were at least on the same performance level as the reference cement. The systematic increase of performance apparently observed in the available samples cannot be validated without having a greater number of samples available for further analyses.

4.10. Scale up: techno-economic barriers and challenges

In the last few decades, fuel switching has been one of the most discussed decarbonisation levers in the cement industry. The decarbonisation potential of completely switching from traditional fossil fuels to pure biomass is significant.

From the technical point of view, replacing traditional fossil fuels by pure biomass in the kiln or in the calciner needs to be differentiated. Pure biomass is frequently characterized by a low calorific value (10 to 18 GJ/t fuel) compared to traditional fossil fuels (e.g., hard coal, natural gas or petcoke). Such apparent drawback is less relevant in the calciner, where lower process temperatures are required. However, alite formation and the production of high-quality clinker demands higher temperatures in the kiln. Typically, the minimum average calorific value of the fuel mix fired in the main kiln burner should lie in the range of 18 to 22 GJ/t fuel mix. Based on this principle, the lack of thermal energy supplied by low calorific fuels (like pure biomass) in the main kiln burner must be compensated by firing fuels with a high calorific value (presently with traditional fossil fuels but also alternative fossil fuels and/or fossil/biomass mixed fuels to a lower extent). Thus, the real technical challenge to reach net zero CO_2 emissions in the main kiln burner lies in finding an innovative alternative fuel that combined with high rates of pure biomass may deliver the necessary energy to the process without generating fossil CO_2 emissions, jeopardizing clinker quality or harming the environment. In summary, such a fuel should meet the following technical requirements:

- CO_2 free
- High calorific value (similar or higher than traditional fossil fuels)
- Enable the formation of a flame adequate to the clinker burning process (shape, heat transfer, peak temperature)
- Avoid the generation of emission pollutants that are difficult to control/abate to levels below the emission limits set by the authorities
- Adequate fuel homogeneity, chlorine and sulphur contents (maximize kiln operation stability)
- Avoid/minimize the presence of harmful elements (heavy metals and organics)
- Enable transport, handling and storage complying with health and safety regulations

The trial performed in Ribblesdale has proven that hydrogen can be fired in the kiln and has the potential to meet all the technical requirements stated above. However, some questions related to carbon load, health and safety at the plant and adequate flame characteristics still remain uncertain with the scale up of the technology.

If costs could be reduced and a net zero fuel mix of hydrogen and biomass were deployed across the sector to make up 40% of the thermal energy to the kiln system (i.e., 100% net zero fuel on the main kiln burner), as demonstrated in this trial, this would reduce the annual CO_2 emissions of the sector by around 875ktCO_2 (based on 2019 levels of production). This represents a reduction of 13% of total CO_2 emissions (fuel and process emissions) across the sector. However, some challenges remain, as set out below.

The availability of renewable (green) hydrogen in the market is presently low, if not non-existent, as water electrolysis would have to exclusively rely on the use of renewable electricity. Blue hydrogen availability is slightly higher, but this would require a pipeline from the supplier, or it could be produced on site, but then carbon capture and storage (CCS) would be required, along with a CO_2 pipeline to storage. Even with CCS, some CO_2 emissions are expected to occur as capture is never 100% efficient and leakages could occur.

The scarcity of low and zero carbon hydrogen is, and will be in the near future, the main techno-economic barrier to reaching the net zero ambition. Other low-carbon approaches can be followed in the meantime. Electricity-based hydrogen production, whatever the electricity source (low-carbon hydrogen) might be a temporary alternative to renewable hydrogen, but how close it will be to net zero will depend on the degree of decarbonisation of the power sector. If available at a competitive cost, the use of low-carbon hydrogen would give cement plants the opportunity to partially decrease fuel-based CO_2 emissions, gain experience in handling and firing hydrogen, optimize its utilization and, thus, prepare for a wider and smarter use of renewable-hydrogen in the future. A water electrolyser could be installed on-site as an alternative to hydrogen supply offsite. Water electrolysis also has the advantage of producing oxygen which can further optimise the burning conditions. A careful assessment of CAPEX and OPEX should be performed in this case. In addition, water supply with the required quality and quantity as well as the existence of an electrical infrastructure onsite that is able to supply the required higher power demand would be required. Both can be strong barriers to the installation of a water electrolyser onsite. Therefore, the optimization of hydrogen utilization is fundamental, whatever hydrogen production route is chosen/ available (purchased or generated onsite).

The availability of biomass should also not be taken for granted. The scarcity of biomass with the desired quality and at competitive prices might also be a barrier to the wider deployment of this technology, particularly as competition for limited biomass resources increases across the economy.

No challenges are expected in terms of equipment required at the cement plant for the reception, handling and firing of biomass (liquid or solid) or hydrogen. The novelty lies exclusively on the use of hydrogen, as firing proportions of biomass is already state-of-the-art in cement plants. The trial at Ribblesdale has proven that the technology exists and apparently works well. Hydrogen was supplied to site in road tube trailers and delivered to the kiln via a series of pressure reducing skids, pipework and a lance (specially built for this purpose) inserted in the main kiln burner. The flame generated from the combustion of glycerine and MBM combined with hydrogen in certain proportions had no negative effects on the clinker burning process. However, such successful achievement has to be interpreted with some reservation, as biomass combined with hydrogen was fired for a relatively short period of time (a few hours). Possible negative effects of firing such fuel mix for several months on a continuous basis are difficult to predict, especially concerning the condition of the main kiln burner, coating formation and thermal stress of the kiln refractory lining. In addition, scaling-up the use of hydrogen and scaling down biomass will change the flame characteristics, especially the flame radiation and formation. No clear statement can emerge from the trial results with respect to firing very high rates of hydrogen in the main kiln burner (e.g., close to 100% of the energy supply) or the use of other biomass sources.

Presently, no other cement plant has experience concerning the health and safety issues for the reception, handling, storage and firing of hydrogen besides Ribblesdale. Scaling-up the technology will involve training plant staff in new safety procedures and local regulations applied to the utilisation of hydrogen. Risks are apparently manageable but need to be carefully assessed, especially in the burner platform and hydrogen storage area.

4.11. Cost assessment and benchmarking with other decarbonisation technologies

One of the objectives of this demonstration was to evaluate the economic viability of utilising a net zero carbon fuel mix rich in hydrogen as a potential decarbonisation lever and perform a preliminary economic benchmarking of this technology against other technologies available to the sector for decarbonisation. For the cement sector, carbon capture is the only other technology that could bring about a step change reduction in CO_2 emissions and therefore has been used as a comparator for the assessment. Figure 4.14 shows the potential carbon capture technologies for use in cement production.

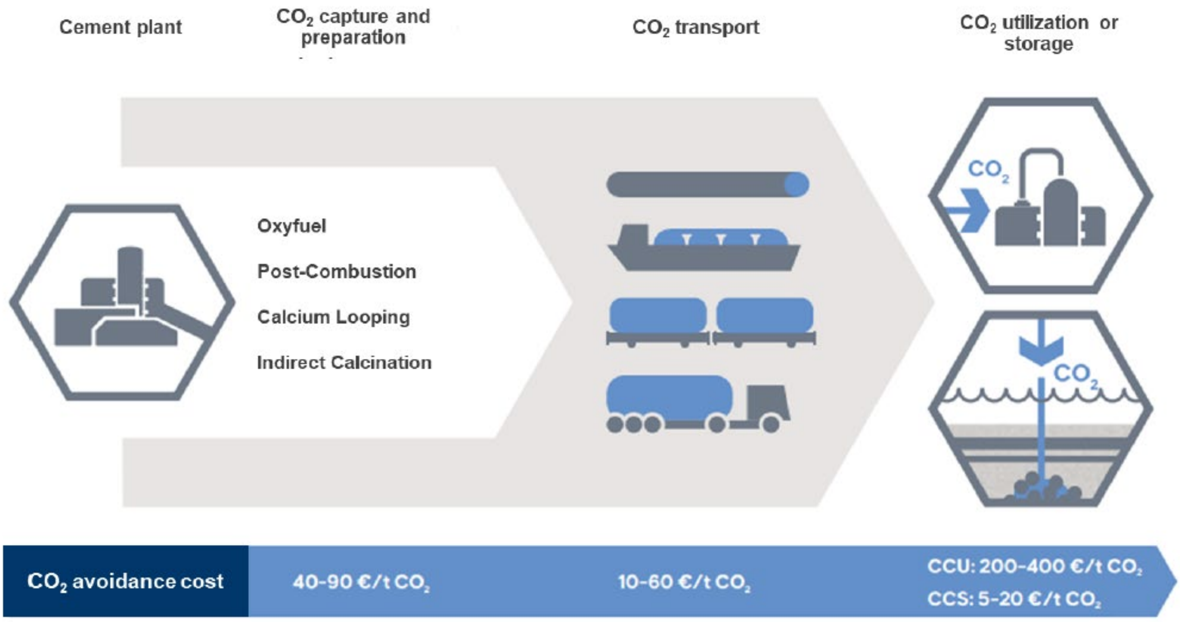

Figure 4.14: CO_2 capture technologies in cement clinker production[9].

The information related to net zero carbon fuel mix utilisation was provided by Hanson. Information on CCS is based on several research projects conducted by VDZ and/or is already available in the literature. The economic Key Performance Indicator (KPI) chosen for the benchmarking is the "*Cost of CO_2 Avoided (CAC)*". This KPI compares the cost of clinker and the clinker specific CO_2 emissions of a cement plant "*with*" and "*without*" implementation of the CO_2 reduction lever under assessment (CCS or net zero carbon fuel mix). As a reference, a plant without any CO_2 reduction technology has been used. The following formula applies to the calculation of CAC:

$$CAC = \frac{COC_{with\ lever} - COC_{without\ lever}}{e_{clk;without\ lever} - e_{clk;with\ lever}} \left[\frac{€}{t_{CO2}}\right]$$

The clinker specific CO_2 emission of the cement plant (e_{clk}) includes process emissions, fuel emissions and emissions from electricity. In the case of a "*net zero carbon fuel mix*", the following is assumed:

- Thermal energy consumption of the plant remains constant (there are no efficiency gains)
- No extra power consumption is required compared to reference (same power emissions)
- Kiln capacity is not affected and remains constant (same process emissions)

The cost of clinker (*COC*) is evaluated by summing up the contributions of CAPEX (C_{inv}) and the variable OPEX costs. The CAPEX cost includes all the costs allocated to engineering, consulting, materials and equipment, plant staff and project

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[9] Verein Deutscher Zementwerke, VDZ – Dekarbonisierung von Zement und Beton – Minderungspfade und Handlungsstrategien, Dusseldorf, 2020

management, sub-contracting (e.g., erection, mechanical assembly, automation, civil and electrical works, etc.) and legal and regulatory expenses. It is converted into a yearly constant annualized cash flow. Moreover, it is assumed that the kiln line, the hydrogen facility and the CO_2 capture and conditioning processes have an economic lifetime of 25 years. The industrial facilities to unload, store and transport biomass are state-of-the-art in cement plants. It is therefore assumed that such facilities already exist in the plant, but some capital has to be invested to make some modifications or adaptations.

The OPEX cost includes fuel (C_{fuel}), raw meal ($C_{raw\ meal}$), electricity ($C_{electricity}$) and other operation and maintenance costs ($C_{O\&M}$) for a tonne of clinker produced. It is assumed that the cement plant pays a fixed rental fee for the skid system required to unload the hydrogen tank trucks (accounted for in $C_{O\&M}$).

The *COC* can be calculated with the following equation:

$$COC = C_{inv} + C_{fuel} + C_{raw\ meal} + C_{electricity} + C_{O\&M} \quad \left[\frac{€}{t_{clk}}\right]$$

The cement plant used as a reference in the economic appraisal is based on the Best Available Technique (BAT) cement plant, which is described in the European BREF Document for the manufacture of cement[10]. The cement manufacturing process relies on the dry kiln process, which consists of a five-stage preheater, a calciner with tertiary air duct, a rotary kiln and a grate cooler. The same reference cement plant has been used to benchmark different CCS technologies (Figure 4.14). The general assumptions applied in the economic appraisal concerning the reference cement plant are presented in Table 4.6.

Table 4.6: Technical data and assumptions valid for all scenarios.

Plant technical data	**Unit**	**Reference cement plant**
Clinker production	tclinker/day	3000
Thermal energy consumption (performance test)	MJ/tclinker	3000
Direct CO2 emissions (fuel+process emissions)	kgCO2/tclinker	813 (271+ 536)
Thermal energy split (burner+calciner)	%	(40% + 60%)
Type of fuel (reference scenario)	-	100% coal
Coal emission factor	kgCO2/GJ	90

The most relevant economic data required for the calculation of CAC is summarized in Table 4.7.

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[10] Production of Cement, Lime and Magnesium Oxide | Eippcb (europa.eu)

Table 4.7: Relevant economic data.

		Value	**Comments**
CAPEX (Cinv)	€	~1,000,000	Hydrogen facility engineered and constructed from scratch (from the unloading skid system to the main kiln burner).
CAPEX (Cinv)	€/t clinker	~0.10	From hydrogen facilities (25 years lifetime)
Coal (100%) (C*fuel*+C*O&M*)	€/t clinker	13.3	Assumption of 120 €/tcoal including Cfuel and CO&M
Fuel mix (C*fuel*++C*O&M*)	€/t clinker	80.7	Includes hydrogen cost, transport and environmental charges. Thermal energy split: 84% coal and 16% H_2 of total energy consumption (or 40% H_2 + 60% coal in the main kiln burner)
Electricity (Δ*Celecricity*)	Δ €/tclinker	0	Assumed that potential savings in the electricity consumption by shifting from coal to a fuel mix made of coal and hydrogen are negligible.
Discounted cash flow rate	%	8	Assumption also taken for CCS technologies
Economic lifetime	years	25	-

A "*Cost of CO_2 Avoided (CAC)*" of 1559 €/t_{CO_2} was estimated based on the data depicted in Table 4.6 and Table 4.7. This is based on hydrogen composing 40% of the thermal input to the main burner compared to a reference based on 100% coal. The impact of increased use of biomass has not been factored in because it is already state of the art in cement manufacture (although not at the high proportions demonstrated in this trial), So this cost assessment is for the introduction of hydrogen as the innovative fuel. It becomes clear that CAC is strongly driven by the cost of the net zero carbon fuel mix and respective operation and maintenance cost, which includes fuel transport, taxes and charges. Hydrogen is responsible for about 87% of the fuel mix cost at the burner tip. The impact of CAPEX on the cost of clinker is negligible compared to OPEX.

Table 4.8: Economic assessment.

Parameter	**Unit**	**Δ**
COC with lever – COC without lever	€/t clinker	67.6
ΔCinv.	€/t clinker	0.10
Δ(Cfuel + CO&M)	€/t clinker	67.5
Δcraw meal	€/t clinker	0
Δcelectricity	€/t clinker	0
CO_2 reduction $(e_{clk;without\ lever} - e_{clk;with\ lever})$	tCO2/t clinker	0.0433
CAC	€/tCO2	1559

Presently the use of net zero carbon fuel mix rich in hydrogen is not economically attractive compared to CCS, even if renewable hydrogen could be available at the current price of grey-hydrogen. The CAC of CCS is currently uncertain but previous studies have shown that it should lie in the range of 55 to 170 €/tCO_2 under certain techno-economic boundary conditions (Figure 4.14) and covering the whole CO_2 value chain (from capture to storage). Assuming the use of the same type of biomass fired in the trial, the cost of hydrogen at the burner tip would have to be twelve times lower than the value reported by Hanson Ribblesdale in order to bring the CAC closer to 85 €/t_{CO2}.

4.12. Conclusions

The trial performed in the Ribblesdale plant demonstrated that the use of a net zero carbon fuel mix made of hydrogen and biomass in a cement rotary kiln is technically feasible and can significantly contribute towards the reduction of the CO_2 emissions without negatively affecting the clinker and cement quality. The necessary equipment is affordable and available in the market, which could facilitate a rapid dissemination of this technology. However, the barrier to firing a net zero carbon fuel mix rich in hydrogen is the cost. Presently the price charged by the hydrogen suppliers is unaffordable. The consequent negative impact on clinker cost makes the utilisation of this technology prohibitive.

The "*Cost of CO_2 Avoided (CAC)*" is mostly driven by the cost of hydrogen and it is not envisaged that hydrogen utilisation might be able to compete with CCS in the medium-term. If the cost of hydrogen at the burner tip could be brought to a twelfth of the value in this trial, the CAC could be reduced to closer to 85 €/t_{CO2}. Another possibility is to optimise the net zero carbon fuel mix to reduce the quantity of hydrogen required to fire high proportions of biomass whilst ensuring the required flame temperature for the clinker burning process. This would reduce the quantity of hydrogen required, and therefore the cost, but would require higher quantities of waste biomass, access to which is also challenging given its limited supply across the UK.

If costs could be reduced and a net zero fuel mix of hydrogen and biomass were deployed across the sector to make up 40% of the thermal energy to the kiln system (i.e., 100% net zero fuel on the main kiln burner), as demonstrated in this trial, this would reduce the annual CO_2 emissions of the sector by around 875ktCO_2 (based on 2019 levels of production). This represents a reduction of 13% of total CO_2 emissions (fuel and process emissions) across the sector.

5. Tarmac biomass/plasma trial

5.1. Introduction

The original intention of the biomass/plasma trial was to demonstrate the use of 1MW plasma torches placed in the tertiary air ducts of the calciner to generate heat along with the use of high proportions of biomass fuel. Although this size of plasma torch wouldn't meet the 10% of total kiln system thermal input that was set out in the feasibility study, larger torches are not yet developed for use. During the trial considerable challenges occurred:

- Sourcing 1MW plasma torches proved to be very difficult and beyond the budget available, so a much smaller torch (100kW) was sourced, and the trial scaled back to demonstrating the concept of using plasma to generate heat in a cement calciner environment
- Recovery of the construction sector after COVID resulted in UK shortages of cement and the site had to prioritise production over the trial
- Upgrades to the site during the last winter shutdown before the trial meant that the planned biomass calciner feed systems were no longer available
- The trial encountered problems with the plasma torch which meant that in the end it ran for only 30 minutes

The learnings from the work on this trial is presented here but due to the short length of time that the calciner was running with plasma energy, it was not possible to assess the impact of the fuel mix change on kiln operations or product quality or fully assess the cost associated with this.

5.2. Planning and assessments

Before starting the trial there were several assessments and permitting requirements that had to be fulfilled. A summary of these is provided here.

Environmental permit: A variation to the existing permit was required to allow the proof-of-concept trials with plasma arc technology in the cement kiln calciner supported by large proportions of biomass fuel. The use of biomass in the calciner was already approved under the Mineral Products Association code of practice for the use of waste derived fuels in cement kilns[11]. The use of plasma technology has not previously been trialled in cement production but in principle the torch would provide heat within the calciner to supplement the biomass fuels being used in the trial. As this is proof of concept, the energy input from the torch was limited to less than 1MW or less than 1% of the calciner energy requirements. In addition, the plasma torch was required to be:

- Supervised in its operation by the supplier
- Only used in "Normal" working hours (Monday to Friday 8:00 – 16:30)
- Limited to circa 100 hours or 11 days of total operation
- Be used under stable kiln operations.

Planning permission: There was no requirement for planning permission for this trial as the scale of the additional equipment required on site was relatively small and temporary in nature.

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[11] Mineral Products Association (MPA) Cement - representing the UK cement industry

5.3. Biomass selection

The calciner at the Tunstead site had in the past utilised a number of fuels including Tyre Chips, Solid Recovered Fuel (SRF), Coal and Wood Chips. There were a number of injection points available for fuel including:

1. Fuel Injection #1 – mechanical belt transport and gravity fed to calciner midpoint (used at the present time for Tyre Chips, and other lumpy fuels)
2. Fuel Injection #2 – Pneumatic transport to the calciner base, level with the Tertiary Air Duct (TAD). Used at the present time for SRF.
3. Fuel Injection #3 – Pneumatic Transport to the Kiln Riser. Used at the present time for fossil fuel.

Four Separate Storage/dosing systems are available, three of which are currently in use. The fourth storage/ dosing system used for MBM (Meat and Bone Meal) is located on site, however it would have required substantial work to return to service and the fuel injection point changed from the main kiln burner to the calciner vessel.

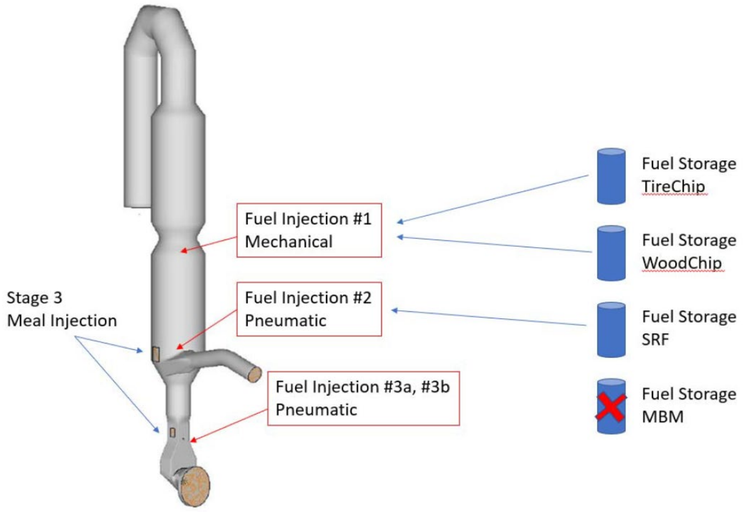

Figure 5.1: Schematic of the Tunstead calciner showing injection points available before the trial. MBM has storage facilities, but dosing is to the main kiln burner rather than the calciner.

A review of fuels available on the Market was completed by Sapphire (a Tarmac owned alternative fuel provider) and three potential fuels were identified. Wood Pellets, MBM, and PSP (Processed Sewage Pellets). All three fuels have high (>95%) biomass content and are available in the market today.

The wood pellets are a dry fuel (5% moisture), size 6mm by 10-25mm cylinders with 18,500 kcal/kg energy. MI-CFD Modelling was required to understand the possible process limitations related to dosing high amounts of pellet fuel at the calciner midpoint (see section 5.4).

MBM fuel was available locally, however the delivery system directed MBM to the kiln and not the calciner. Furthermore, the storage/delivery equipment had been out of operation for some years and required expenditure to bring it back into commission. MBM dosing was theoretically possible to Fuel Injection #3, following renovation of Fuel Storage MBM.

PSP was available however, due to the nature of the fuel, it was expected that significant modification to existing equipment would have been required. Such modification would exceed the budget available for the trial and so this fuel was not proposed for use.

Wood pellets (Figure 5.2) dosed at Fuel Injection #3 and #2 were deemed the best option for the trial. At a heating value of approximately 18GJ/t, the wood pellets would undergo full burnout within the calciner. However, MBM was included in MI-CFD modelling (see section 5.5) in the event that Wood Pellets alone were not able to achieve sufficiently high levels of biomass content. Due to the size of the installation available however it was expected only to have a limited impact on total biomass content in calciner fuel.

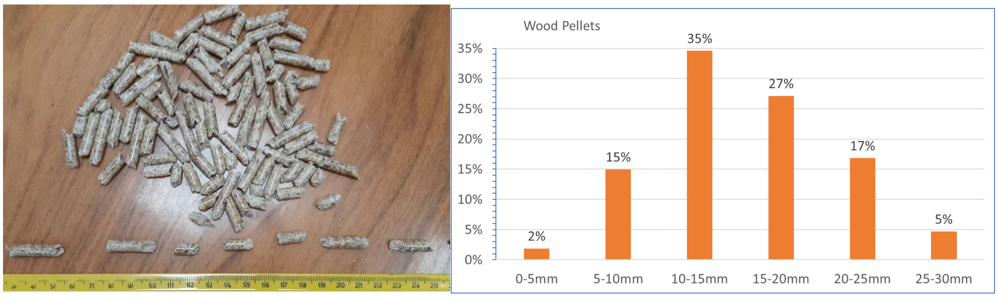

Figure 5.2: Photo of wood pellets proposed for use in the trial and their size distribution

Tests were then conducted in February and July 2021 to determine whether mechanical or pneumatic transport was most suitable for the wood pellets. The mechanical trial found that the wood pellets could be conveyed on the inclined belt and no blockages occurred in the transport system. Temporary modifications were required to the silo extraction system due to the improved flowability of the pellet material – however the material once loaded onto the belt did not prove problematic. Process stability was reasonable, and it was concluded that this transport line would be suitable for the wood pellet fuel at rates of up to 6tph. The pneumatic trial was unsuccessful due to conveying blockages within the transport line even at low tonnages.

5.4. Type of plasma torch

The plasma torch model PBR100 from PlasmaAir AG used in the trial was a water steam plasma torch with a power output of 100kW. From a conceptual point of view, it is a hot cathode burner using a tungsten based central cathode. In operation, the electric arc of the plasma torch is located within a short distance to the cathode, leading to a high temperature close to the metal's melting point. The anode, which also acts as the nozzle of the plasma torch, is made from a copper tungsten alloy. The two electrodes are water-cooled to prevent overheating and failure of the material. The plasma torch model PBR100 was optimized for the operation of water steam as the plasma source. Due to small quantities of oxygen, which are present in the water steam gas, the cathode has to be protected by a small gas stream of Argon. In addition, during the trial the plasma torch was placed into a water-cooled jacket made of stainless steel in order to protect the installation from the high temperatures (around 1000 °C) of the gases in the kiln riser duct.

5.5. MI-CFD modelling

Once the biomass fuels had been selected, Cinar used their process knowledge driven, mineral interactive computational fluid dynamics (MI-CFD modelling) to model a range of scenarios to determine the optimum plant trial conditions and understand the impact of moving to a net zero carbon fuelled calciner.

Figure 5.3 shows the scenarios that were modelled (MBM was included in the modelling in the event that Wood Pellets alone were not able to achieve sufficiently high levels of biomass content). The base case is shown in Case 1 and Case 1a. This represents operation of the calciner prior to the trial. It shows the use of tyre chips and SRF with the SRF having different injection points in Case 1 and Case 1a.

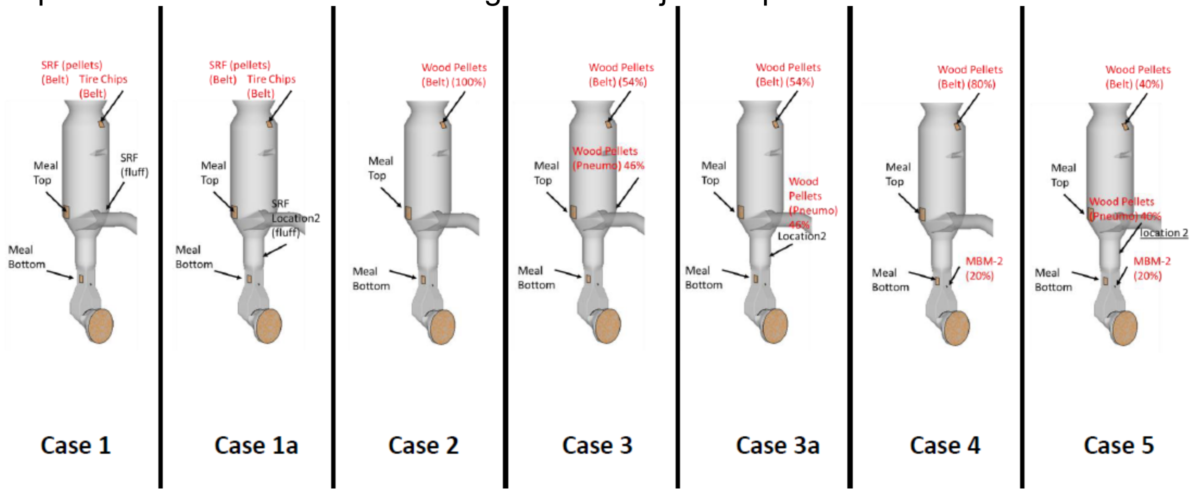

Figure 5.3: Scenarios modelled included a base case (representing operation of the calciner before the trial) and Cases 2-5 using different injection points for wood pellets and MBM.

The results of the exit calciner values for each case are shown in Table 5.1. The modelling found that the wood chips are well suspended even when introduced gravitationally. Additionally, using pneumatic injection at location 2 (i.e., cases 3a and 5) heat is released at the lower part of the calciner, increasing temperatures and improving the calcination rate therein. At the same time the top meal inlet (with a higher mass ratio than the bottom) receives initially less heat, thus, resulting in a net reduction of the total meal calcination (Loss on Ignition, LOI, increased).

Table 5.1: Exit calciner values for each case modelled.

		Case 1	Case 1a	Case 2	Case 3	Case 3a	Case 4	Case 5
Temperature	[°C]	878	882	886	880	881	882	883
Oxygen (O_2)	[% volume-dry]	2.27	2.25	3.12	3.37	3.42	3.11	3.42
Water (H_2O)	[% volume]	7.31	7.32	6.53	6.42	6.43	6.43	6.35
Wood pellet burnout	[%]	-	-	99.9	99.9	99.9	99.9	99.9
MBM burnout	[%]	-	-	-	-	-	98.2	99.0
Total fuel burnout	[%]	97.42	97.39	99.9	99.9	99.9	99.6	99.7
Meal loss on ignition (LOI)	[%]	6.02	6.26	5.29	5.25	5.47	5.31	6.01

Cinar also analysed what the impact of the plasma torch would be when combined with Case 3a above. This found that the plasma torch had a very small local impact as the larger volume flowrates of tertiary air and kiln gases quickly dissipated the heat and vapour from the torch. Some small variation was observed in calcination as more mixing was achieved with the tertiary air inlet. An example of the results from this analysis is shown in Figure 5.4.

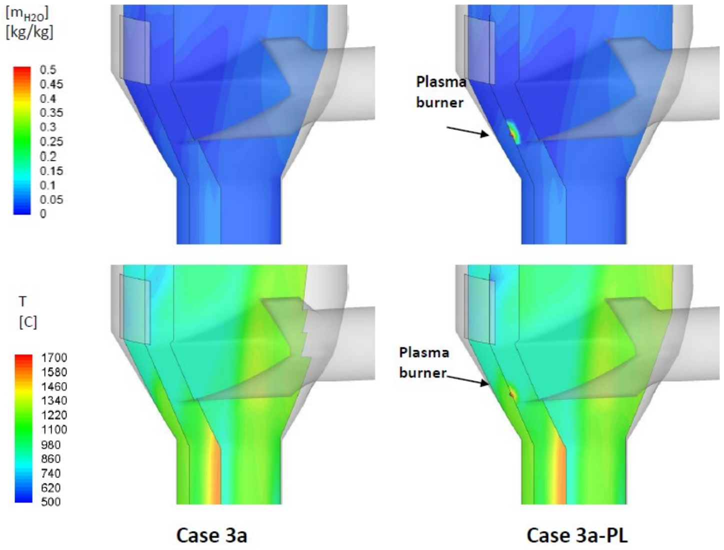

Figure 5.4: Comparison of water and temperature with and without the plasma torch, near the plasma injection point.

The modelling concluded that the wood pellets are well suspended with good burnout and that the small plasma torch sourced for the trial will have limited impact on the process.

5.6. Safety

The fuel switching trial was reviewed and planned in accordance with Tarmac internal procedures and standards in regard to safety. Within the Management of Change procedures at Tunstead plant, a Safe System of Work and Hazardous Energy Control Procedure was developed to ensure all risks were minimised or eliminated.

The Hazard and Operability study (HAZOP) was facilitated by an independent expert consultant in the field of safety and risk management, GEXCON. As part of the HAZOP plant technical experts reviewed all identified risk points in the proposed trial plan generating a number of actions for further review. The key risks identified were around the generation of dust, the potential for contact with electricity, the potential for employees or plant to be struck by moving vehicles and the potential for a fall from height while accessing cables for the trial. Actions proposed to mitigate these risks including ensuring all personnel had full personal protective equipment (PPE), barriers were erected to prevent vehicles entering the area used for the plasma torch, the generator was fenced off to limit access and only trained personnel with use of a fixed lanyard and safety harness were allowed access to cables at height. All these actions formed part of the plant specific risk assessment.

5.7. Plant modifications and enabling works

The plasma torch location was constrained by access within the existing plant structure, availability of plant resources (cooling water and power), and the physical design of the torch itself. The torch control equipment was constructed within a standard shipping container for ease of transport and placement on site.

Figure 5.5: Plasma torch control container.

The torch control equipment container was positioned at the base of the preheater tower. To minimise impact on plant infrastructure and reduce the risk of impacting the plant power supply, power to the torch was supplied by a standalone diesel generator. The generator was positioned beside the torch. Earthing considerations required additional care and attention (risk of impact of the high frequency DC voltage on plant equipment was identified as having a possible impact on plant operation).

Electrical supply ran from the container to the 28m level of the preheater tower at the location of the torch insertion point in the calciner. Cooling water supply ran in two separate circuits (internal torch cooling plus the external coil jacket cooling) from the container to the torch to the container heat exchanger.

A number of insertion locations for the plasma torch in the calciner were reviewed (see Figure 5.6) however position #3 was selected on the basis of access, MI-CFD Modelling and it being a possible future position of any larger scale torch installation. Location for the insertion point of the plasma torch was at the level of the intersection of the Tertiary Air Duct (TAD) and Main Calciner Lower Section.

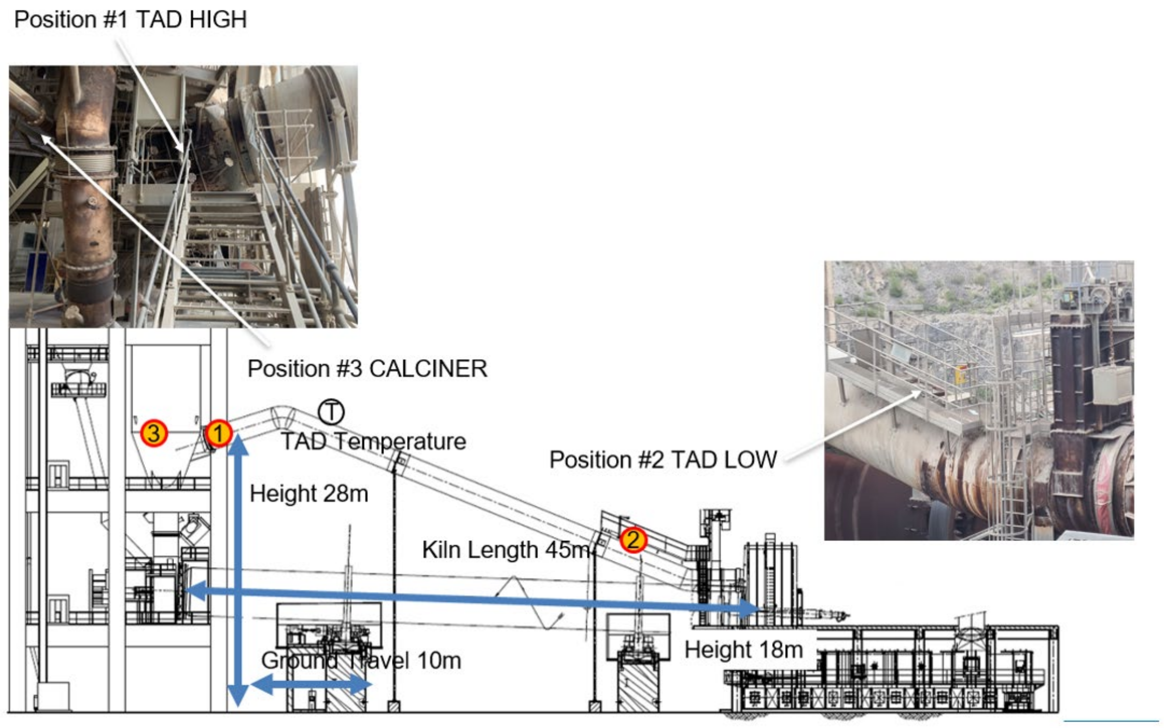

Figure 5.6: Schematic diagram showing potential locations for the plasma torch in the calciner (TAD = Tertiary Air Duct).

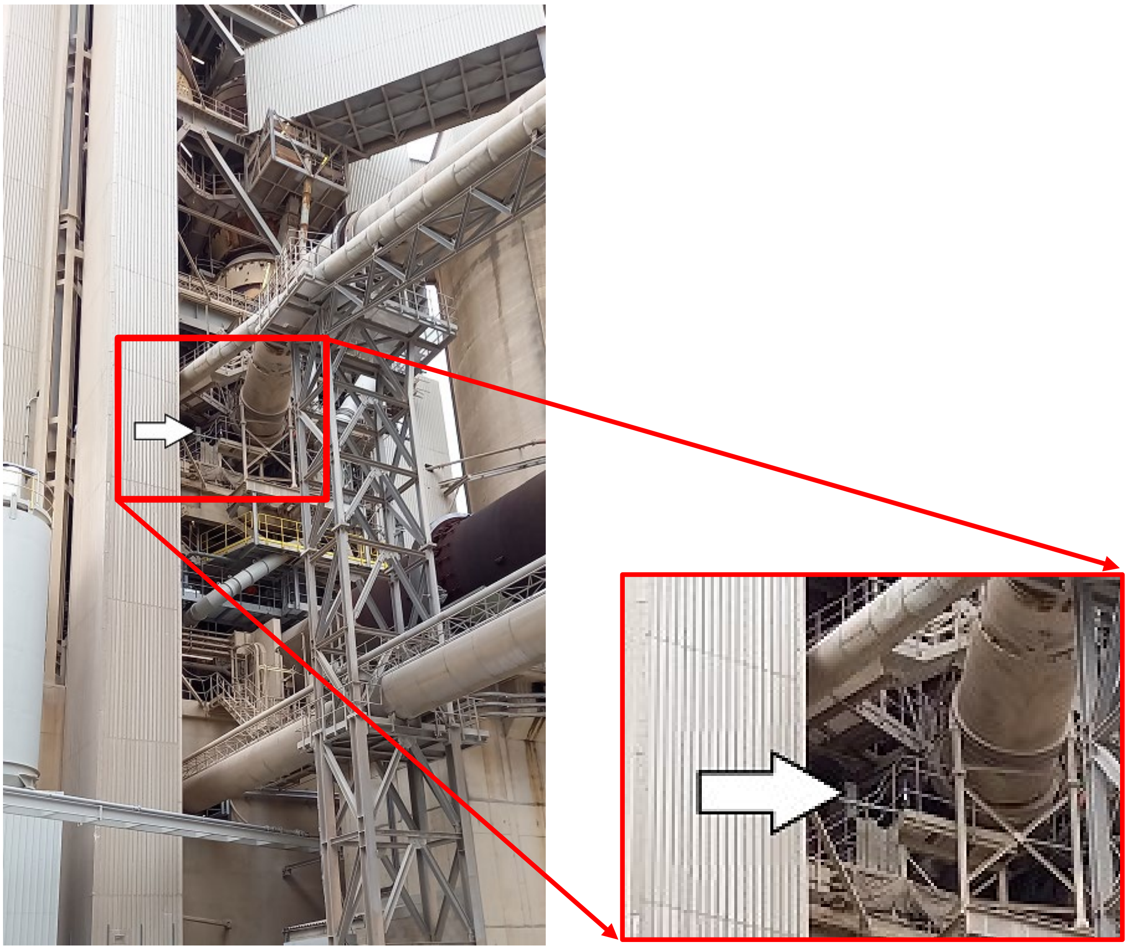

Figure 5.7: Plasma torch insertion point on calciner wall at the level of the Tertiary Air Duct.

Torch insertion was via a modified 10” pipe connection to the calciner wall. As the torch weighed approximately 50kg, additional lifting support was available in positioning the torch prior to insertion.

As part of the plant risk assessment, additional fixations were added to the torch / insertion point to allow energy isolation procedures to be followed and prevent the torch from being removed whilst in operation.

Due to the strict safety restrictions of the Tarmac Tunstead plant, several modifications had to be made prior to the plasma torch trial. Namely, at voltages above 110 V, no electrical plug connections were permitted. Beyond that, insulated cables had to be used, so that all components had to be hard wired: the evaporator, the cooling units, the heated tubes, the ignition unit, and the chiller. Also, the control cables of the cooling units had to be replaced. However, the power cables of the ignition unit and of the plasma torch did not have to be changed.

The torch was not integrated into the plant control system architecture and was manually controlled on site by technical support engineers from the torch supplier.

Due to the high temperatures expected within the body of the calciner vessel, additional cooling capacity was included with the torch assembly, consisting of a water-cooled jacket in addition to the cooling water within the torch body itself.

5.8. Use of the plasma torch in the trial

Prior to the main testing of the plasma torch inside the kiln riser duct, a preliminary functional check was performed. The test was conducted to assess the functionality of the plasma torch, the peripheral devices and the power supply. After successful ignition and validation of the functionality of all components, the plasma torch was placed into the riser duct for the trial (see Figure 5.8). The ignition procedure was then initiated. The Argon gas stream was adjusted and set to 1.20 Nm^3/h during the trial. The amount of water steam was increased from 1.8 kg/h during ignition to 3.5 kg/h to increase the power input from 100V and 235A to 260V and 205A. In this regard, the decrease of the current was caused by the current-voltage characteristics of electric arc plasma torches. After several minutes of stable operation, the amount of water steam was increased to 4.5 kg/h, so that a current of 255A with a voltage of 280V was reached, corresponding to a power input of over 70kW, which is less than 0.2% of the total heat input of the calciner. For the next steps the intention was to further increase the electrical power of the plasma torch, however, after testing at this operation setpoint the power supply of the plasma torch failed. In total the plasma torch was in operation for around 30 minutes.

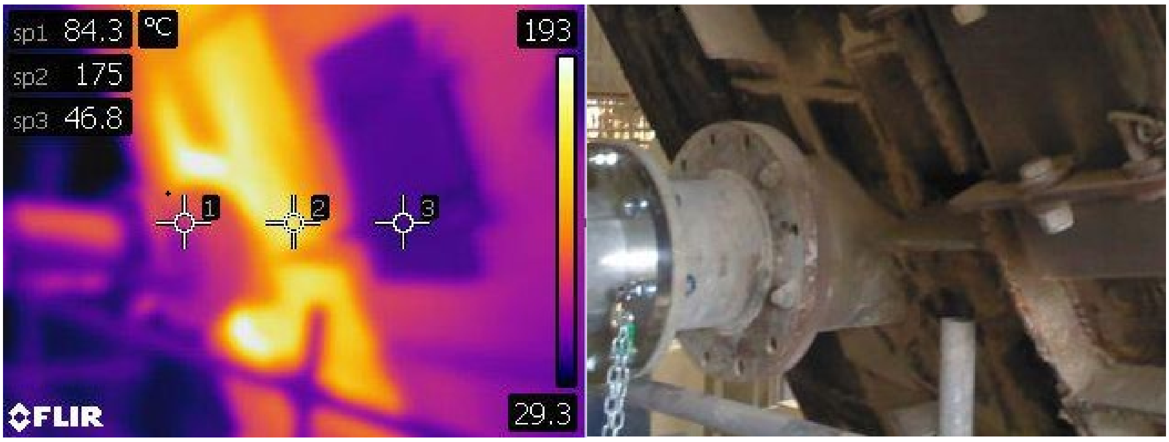

Figure 5.8: Thermal calciner wall scan and photo of the same area during torch operation.

5.9. Cause of failure

The cause of the failure was only able to be assessed when the plasma torch system was returned to the supplier in Germany. During the trial, a safety module was destroyed. In the event of an emergency shut-off, this module triggers a complete shutdown of the power electronics. Therefore, it was not possible to restart the electrical power supply of the plasma torch. The failure of the module was caused by the feed-voltage of 415V. As a consequence, for the supply of 230V components, the value of the secondary-side voltage of the transformer reached a value higher than 250V, which possibly led to failure of the module.

Figure 5.9 shows an image of the torch tip after removal from the calciner.

Figure 5.9: Torch tip after removal from the calciner.

5.10. Conclusions

The plasma torch was successfully designed, modified to comply with the technical electrical requirements of Tarmac and commissioned onsite. The plasma torch was operated in the kiln riser duct for around 30 minutes before its safety module was overloaded and subsequently destroyed. The low heat input of the plasma torch and the relatively short operation period could not provide the necessary experimental data to validate the technology, properly assess its impacts on the clinker manufacturing process, evaluate the feasibility of a technological scale up and perform a fair benchmarking assessment against suitable carbon capture technologies for decarbonisation of the cement industry. However, the barriers encountered in this trial around the electronics when using only a very low powered torch indicate that scale up to much larger torches would be challenging for the sector.

6. Development Plan

The phase 2 feasibility study identified that theoretically it should be possible to produce cement using net zero carbon fuels but identified several technical barriers and uncertainties. This phase 3 demonstration project investigated these technical barriers further. The hydrogen/biomass trial has shown that modifications to existing burners can be made cost effectively to enable the introduction of hydrogen and confirmed that the use of hydrogen can work well with high proportions of biomass so that the main kiln burner can be operated using 100% zero carbon fuels. If hydrogen/biomass could be deployed across the UK sector, there is the potential to save around 875ktCO_2 per year.

The trial of the use of plasma was less successful and few conclusions could be drawn other than noting the challenges faced even when testing a relatively low powered plasma torch in the cement calciner. The sourcing of biomass was limited to what was available on the market at a reasonable cost and which did not require major change to the fuel storage and delivery systems currently at the respective sites.

In terms of next steps for cement fuel switching, the failure of the plasma trial has cast doubt on whether the use of plasma is worthwhile developing further in the sector. However, the efficiency of plasma technology to generate heat means that consideration should be given to repeating the trial with another 100kW torch to see if the issues of using it in the calciner can be overcome. If successful, this could be scaled up to using a more highly powered torch to test the impact on the calciner and the clinker produced. However, high electricity prices remain a barrier to greater electrification of cement production. An alternative option to decarbonise the calciner, which requires lower temperatures than the main kiln burner, could be the use of 100% biomass fuels without the aid of energy from plasma. This would be worth exploring as a next step providing a secure supply of cost competitive waste biomass fuel at the required specification can be accessed.

The use of hydrogen was highly successful. The next steps for the cement sector should be to optimise the use of waste biomass sources combined with hydrogen at the main kiln burner focussing on bringing the rate of hydrogen to a minimum whilst ensuring the required flame temperature for the clinker burning process. The deployment of hydrogen at scale across the sector is very much tied to UK plans for increasing hydrogen production and scaling up the infrastructure to enable its delivery. The high quantities of hydrogen needed in cement manufacture would require pipeline infrastructure rather than delivery by tube trailer. However, reducing the use of hydrogen through optimisation may increase the opportunity for onsite electrolysis to produce smaller quantities of hydrogen and remove barriers associated with electricity price (if renewable energy could be generated onsite) and transport. This would also require a good supply of water in sufficient quantities and at the right specification but could be further investigated.

There is far greater potential for the scale up of biomass fuel use across the sector. Use of biomass fuels is a key lever to the long-term decarbonisation of the cement sector. In 2020, the MPA published the "*UK Concrete and Cement Industry*

Roadmap to Beyond net Zero"[12] which set out how fuel switching away from coal to source 70% of the thermal input from waste biomass, could reduce emissions in 2050 by 16% compared to 2018. However, over the last 10 years biomass use has only increased 1% overall and 100% biomass fuels has decreased from 6.5% of the thermal input to only 3.6% in 2019. The reason for this is that policies including Contracts for Difference, Renewables Obligation, the Renewable Heat Incentive (now replaced with its successor scheme, the Green Gas Support Scheme) are diverting waste to energy generation, Combined Heat and Power (CHP) and Anaerobic Digestion (AD), with directly fired operations like cement being unable to access such incentives.

In future the greenhouse gas savings associated with use of waste biomass fuels in the cement sector will be even greater if emissions from biomass fuels are captured using BECCUS (BioEnergy Carbon Capture Utilisation or Storage). Given the high proportion of unavoidable process emissions generated in the production of cement (around 70% of emissions arise when the raw materials are heated to volcanic temperatures), whatever happens with fuel switching, carbon capture is also required. Combining carbon capture with the use of biomass fuels is a way of generating negative emissions and ensuring every possible CO_2 benefit is extracted from limited biomass resources.

For the cement sector to utilise waste biomass, policy barriers must be removed so that cement producers can compete for limited waste on a level playing field with other consumers.

In summary, the key remaining barriers to deployment of a net zero fuel mix following this demonstration are:

- Hydrogen: obtaining a secure supply of cost competitive zero carbon hydrogen. Optimising the net zero carbon fuel mix to use other biomass sources combined with a lower proportion of hydrogen at the main kiln burner to reduce the use of hydrogen to a minimum while ensuring the required flame temperature for the clinker burning process.
- Plasma: development of plasma technology to be of sufficient power and energy and further testing in the cement manufacturing environment
- Biomass: obtaining a secure supply of waste biomass and testing the use of 100% biomass fuel in the calciner.

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[12] Decarbonising UK Concrete and Cement (thisisukconcrete.co.uk)