Options for switching UK cement production sites to near zero CO_2 emission fuel: Technical and financial feasibility.

Summary Report

Feasibility Study for the Department for Business Energy and Industrial Strategy

A report funded by an SBRI Competition: TRN 1674/10/2018

Authors
Mineral Products Association
Gillingham House
38-44 Gillingham Street
London
SW1V 1VU

Cinar Ltd
11 Elvaston Place
London
SW7 5QG

VDZ gGmbH
Tannenstrasse 2
40476 Duesseldorf
Germany

October 2019

Table of Contents

Table of Figures

Table of Tables

1. Executive Summary

Mineral Interactive Computation Fluid Dynamic (MI-CFD) modelling shows that net zero fuel switching holds considerable promise for the environmental performance of cement manufacture, but technical limitations exist that require further work and investigation through physical demonstrations.

The methodology used in this study has allowed for the iterative development of preliminary optimum fuel switching scenarios. Previous empirical evidence and experience of MI-CFD in the cement sector provides a high degree of confidence in the modelling results. The benefits to this feasibility study in using MI-CFD is that the results provide robust evidence for the development of Phase 3 demonstration projects.

Against a base case of 100% coal fuelled cement plant, this study has modelled a fuel mix of 70% of the thermal input from biomass, 20% from hydrogen and 10% from plasma (electrification), across one scenario for the kiln and three different scenarios for the calciner (see Figure 1.1).

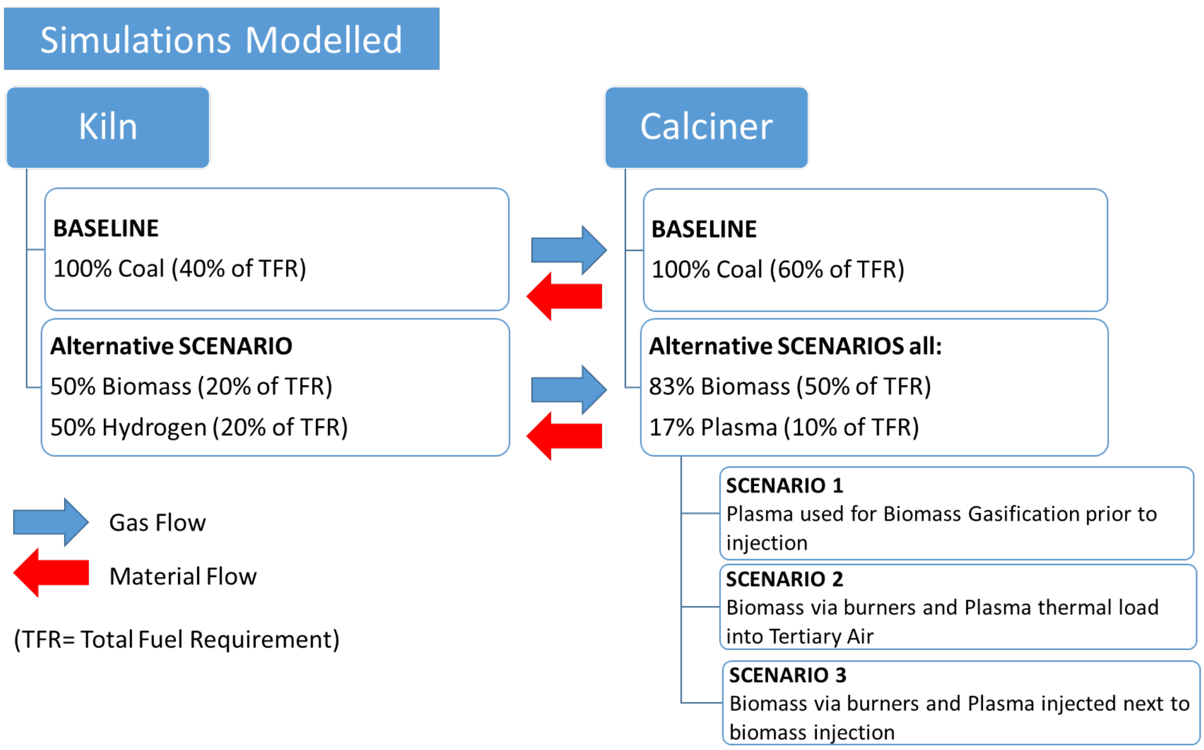

Figure 1.1: Scenarios modelled and compared to 100% coal fired baseline

Using a mix of 50% hydrogen and 50% biomass in the kiln and 83.3% biomass with 16.7% plasma in the Calciner leads to total elimination of all fossil fuel CO_2, leaving only process CO_2 from the breakdown of raw materials and CO_2 from biomass fuels (considered to be CO_2 neutral). To put this into context, if this fuel switching was deployed at all cement plants in the UK, the annual CO_2 saving would amount to over 2 million tonnes (excluding biomass emissions), equivalent to the CO_2

emissions from 266,000 households[1]. This suggests that when used in combination with carbon capture of the raw material CO_2 a net zero emitting cement kiln could be envisaged. It also suggests that where carbon capture is deployed on the raw material 'process CO_2' and the combustion CO_2, that a 'net negative' cement plant could be envisaged.

This fuel switching option, if deployed across all UK cement manufacturing sites at current cement production levels, would require over 1.2 million tonnes of biomass fuel (compared to 68k tonnes of 100% biomass fuels used in 2018). The key issues with biomass centre around securing long term sustainable supplies. Currently, the cement sector relies on waste biomass and part biomass fuels. The intention would be to source as much biomass from these waste sources as possible before considering the use of virgin biomass. Use of virgin biomass would introduce new issues around sustainability that the UK cement sector have not had to deal with to date in using only waste sources, which are inherently more sustainable having already been through at least one previous use before being utilised.

The results indicate that the elimination of fossil fuel CO_2 should be possible with no negative impact on clinker quality, kiln stability or build-up issues but some further work through demonstration is required to verify the modelling and to address the following:

- That the kiln burner can be optimised such that the higher flame temperature can be controlled to match that achieved using coal where the flame is confined to the centre of the kiln without touching the walls, in order to protect the refractory kiln lining. A demonstration would enable testing of burner design and location aimed at reducing the higher temperature regions and associated NOx emissions.
- Ensure that biomass fuel design is such that larger chips do not fall into the bed and negatively affect clinker quality. A specific fuel specification may be required for biomass fuel supplied to the main burner.
- Hot spots observed in the modelling near the calciner walls need to be minimised. The location of plasma injection in relation to the hot meal and biomass inlets needs to be investigated further. The correct positioning will improve the heat absorption via the calcination process in the near burner regions and reduce the hot spots observed.

Each issue identified above, can first be addressed through plant-specific modelling during the next phase of the project. The initial plant specific Baseline and Alternative simulation will then be expanded with optimisation by variations in the operating parameters (i.e. hydrogen injection velocity, rates of axial air, biomass injection location, meal inlet modification etc). Once the optimum parameters are selected it will be implemented through the physical demonstration which, in addition, will also provide the opportunities for various measurements to be collected and used to provide further assessment of modelling parameters and address

[1] Based on CCC analysis for the 5th carbon budget of CO_2 emissions for the average UK household (8.1 tonnes of CO_2 per year in 2014), https://www.theccc.org.uk/wp-content/uploads/2016/07/5CB-Infographic-FINAL-.pdf

specific issues. Finally, further optimisation via modelling can take place (thus avoiding more expensive physical tests/experiments) to eliminate any remaining issues.

If these issues could be addressed and overcome through the demonstration project, fuel switching would become a key part of the transition to net zero cement production:

- **Timing:** Both fuel switching and CCUS will require innovative technology updates to realise. However, cement manufacturers have considerable experience with fuel switching and some of the technologies that can aid this are currently available. Fuel switching could therefore be implemented in the near future. CCUS technology has the potential to be far more disruptive to the cement manufacturing process and is reliant on there being either options for utilising the captured CO_2 or the infrastructure to enable it to be transported for storage.
- **Net Zero:** In legislating for the UK to meet a target of net zero by 2050, every option for decarbonisation needs to be explored. Fuel switching might reduce the need for expensive CCUS by limiting it to the capture of process emissions only. However, if used to capture biomass CO_2 emissions, cement manufacture could become net negative and help to offset other harder to decarbonise sectors of the economy.
- **Technology:** Some CCUS technologies, such as the Calix technology that is being trialled in the LEILAC project or the calcium looping technology being trialled under CEMPCAP (see Table 2.2), may only capture process emissions. Therefore fuel switching will still be required to reach deep levels of decarbonisation. It is also possible that for some sites, CCUS is not an option because there isn't space on site for capture plant, planning permission for capture plant is unlikely to be granted or the logistics of transporting CO_2 from the site are incredibly difficult. The only way to lower emissions from these sites at all, may therefore be fuel switching.

A financial comparison to business as usual shows that net zero fuel switching costs are considerable and currently prohibitive under operating conditions today (see Table 1.1 and Table 1.2 below). However, this feasibility study gives plants the technical information to progress to the next stage of research and development. Eventual deployment of net zero fuel cement manufacture would be a world first innovation.

Table 1.1: Calculation of the total cost of clinker considering the application of additional technologies (±35 % uncertainty)

Additional cost of clinker due to fuel switch	
Additional CAPEX Hydrogen	0.105 €/$t_{clinker}$
Additional CAPEX Plasma	2.209 €/$t_{clinker}$
Additional Fixed OPEX	0.10 €/$t_{clinker}$
Additional Variable OPEX	19.33 €/$t_{clinker}$
Total cost of clinker for fuel switch	**21.74 €/$t_{clinker}$**

Table 1.2: Cost of possible CO2-savings (±35 % uncertainty)

Price of CO_2 per ton of produced clinker	
Total cost of clinker with additional technologies	21.74 €/$t_{clinker}$
CO_2 savings	310 kg_{CO2}/$t_{clinker}$
Cost of CO_2 savings	**70.1 €/t_{CO2}**

This feasibility study concludes with a programme of work to address the gaps in technical and techno-economic knowledge.

Acknowledgements: The authors would like to acknowledge the considerable 'in kind' contributions made to this project by Breedon, Cemex UK, Hanson, Tarmac and Aggregate Industries

2. Introduction

i. Industry Background

a. Cement in the UK

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 the society's most useful materials; no modern school, house, road, hospital or bridge could be built without it.

The cement industry contributes nearly a billion pounds annually to the UK economy. The UK has 11 manufacturing and two grinding and blending plants and produces around ten million tonnes of Portland cement a year, representing about 78% of the cement sold in the UK. An additional cement kiln produces specialist Calcium Aluminate cement, much of which is exported. Cement production was hit heavily by the 2008 recession and in 2009 production dropped to the lowest recorded since 1950 (Figure 2.1). Imports of cement to the UK have historically made up around 10% of the market. However, since 2006 imports have steadily increased and now make up 22% of the cement sales in the UK (Figure 2.2).

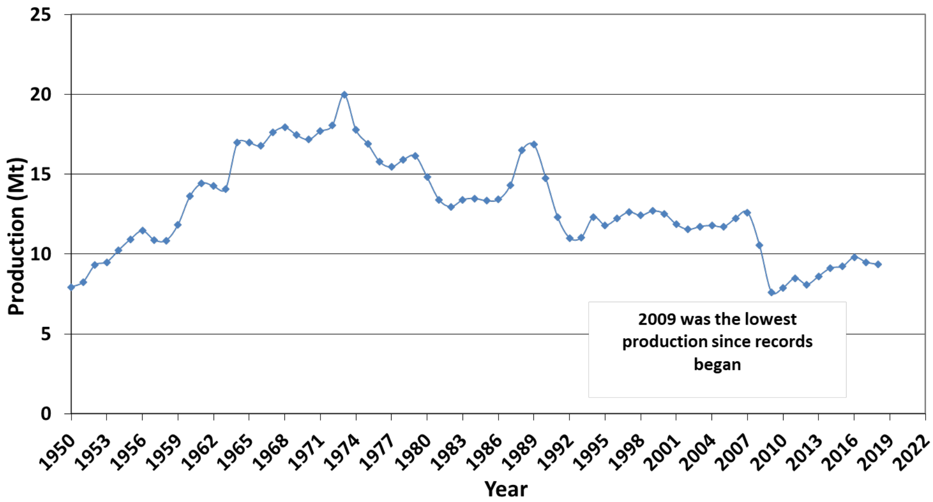

Figure 2.1: UK Cement Production 1950 to Present.

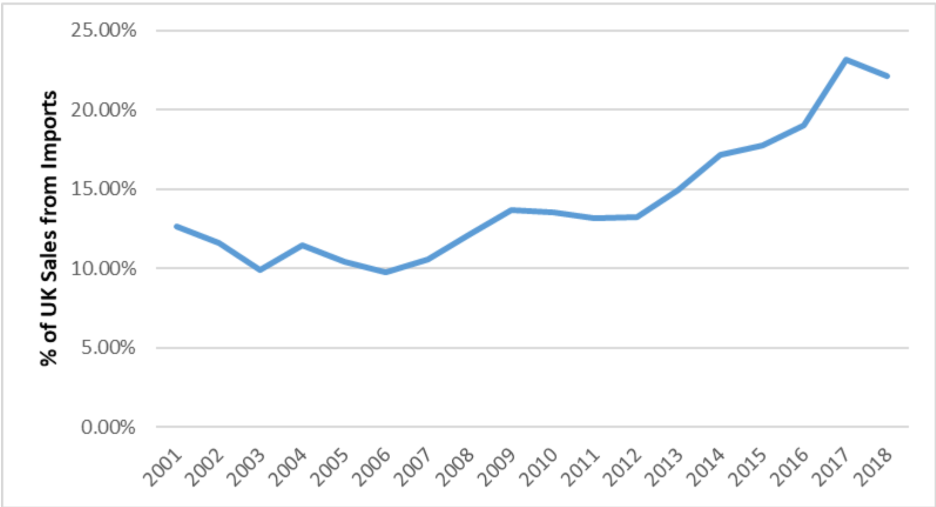

Figure 2.2: Proportion of UK Sales from Imported Cement 2001-2018

The entire UK Portland cement production capacity is operated by five major UK manufacturers, namely: CEMEX UK, Hanson Cement, Breedon Cement (A Breedon Group company), Lafarge Cement (a member of LafargeHolcim) and Tarmac (a CRH Company) (Figure 2.3).

	Company	Site
1	CEMEX Building the future™	Rugby
2		South Ferriby
3		Tilbury
4	Hanson HEIDELBERGCEMENTGroup	Ketton
5		Padeswood
6		Ribblesdale
7	BREEDON	Hope
8	LAFARGE CEMENT A member of LafargeHolcim	Cauldon
9		Cookstown
10	TARMAC A CRH COMPANY	Aberthaw
11		Dunbar
12		Tunstead
13		Barnstone

Key

Kiln sites

Grinding and blending sites

Grinding only sites

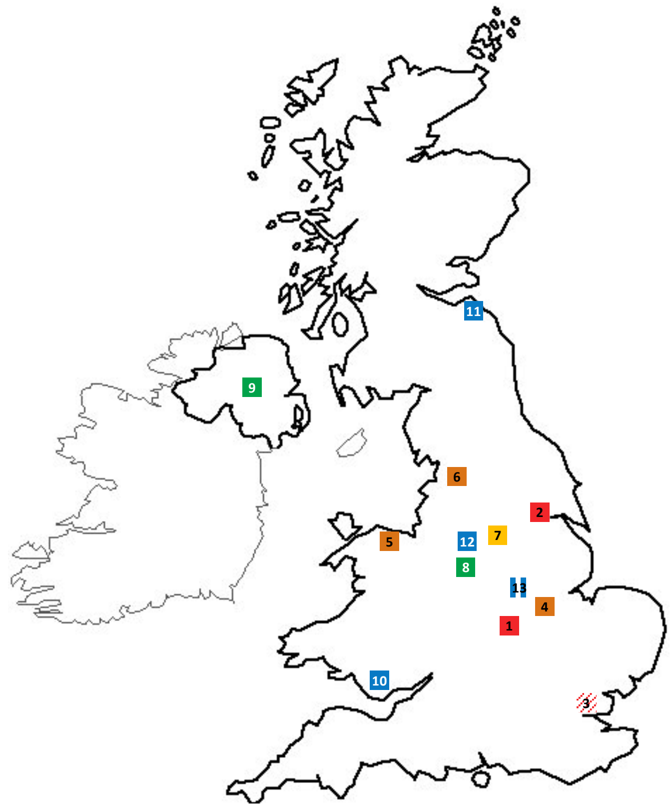

Figure 2.3: MPA Cement Member Kiln, Grinding and Grinding and Blending Sites

b. What is Cement?

Cement is a man-made powder that, when mixed with water and aggregates, produces concrete. The cement-making process (Figure 2.4) can be summarised in 3 basic steps (more detailed information is available in Table 2.1):

1. Raw material preparation
2. Clinker production in a kiln at a temperatures of 1,450°C
3. The grinding of clinker with other minerals to produce cement

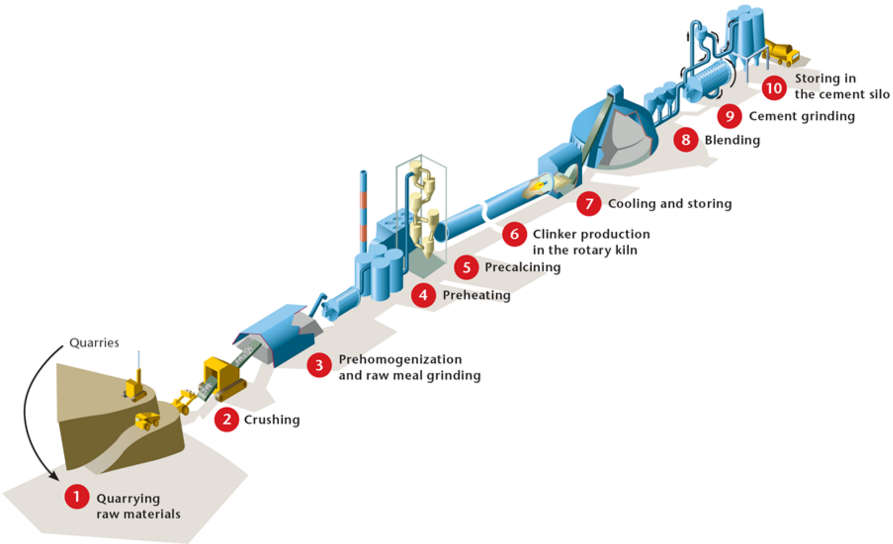

Figure 2.4: Cement manufacturing process [source: “Technology Roadmap: Low-Carbon transition in the Cement Industry”, International Energy Agency, Cement Sustainability Initiative, 2018].

Table 2.1: Cement manufacturing in more detail [source: “Technology Roadmap: Low-Carbon transition in the Cement Industry”, International Energy Agency, Cement Sustainability Initiative, 2018].

1. **Quarrying Raw Materials:** Naturally occurring calcareous deposits, such as limestone, marl or chalk, provide calcium carbonate, which is a key ingredient for cement. They are extracted by heavy duty machines from quarries, which are often located close to the cement plant. Small amounts of other materials, such as iron ore, bauxite, shale, clay or sand, may also be excavated from deposits to provide the extra iron oxide, alumina and silica needed in the chemical composition of the raw mix to meet the process and product performance requirements.
2. **Crushing:** The quarried materials are crushed, typically to less than 10 centimetres in size, and are transported to the cement plant.
3. **Preparing Raw Meal:** Raw materials are mixed to achieve the required chemical composition in a process called “prehomogenisation”. The crushed material is then milled to produce a fine powder called “raw meal”. The chemistry of the raw materials and raw meal is monitored and controlled, to ensure consistent and high quality of cement.
4. **Preheating and co-processing:** A preheater is a series of vertical cyclones through which the raw meal is passed. During this process, the raw meal comes into contact with swirling hot kiln exhaust gases moving in the opposite direction. Thermal energy is recovered from the hot flue gases in these cyclones, and the raw meal is preheated before it enters the kiln. The chemical reactions therefore occur quickly and efficiently. Depending on the raw material moisture content, a kiln may have up to six stages of cyclones with increasing heat recovery at each stage. The raw meal temperature is raised to over 900°C.

Cement production can co-process wastes and by-products generated from other industries and municipalities, as materials for the raw mix or as fuels for pyro-processing. Wastes and by-products vary widely in nature and moisture composition. They may need sorting, shredding and drying before feeding into the cement kiln.

5. **Precalcining:** Calcination is the decomposition of limestone into lime. It takes place in a "precalciner" in most processes. This is a combustion chamber at the bottom of the preheater above the kiln and is partly in the kiln. Here, the chemical decomposition of limestone into lime and CO_2 typically emits 60-70% of the total CO_2 emissions. Fuel combustion generates the rest of the carbon emissions. Approximately 65% of all fuel is burnt in this step of the process, in plants with precalciner technology.
6. **Producing Clinker in the Rotary Kiln:** The precalcined meal then enters the kiln. Fuel is fired directly into the kiln to reach temperatures of up to 1 450°C. As the kiln rotates (about three to five times per minute), the material slides and falls through progressively hotter zones towards the flame. The intense heat causes chemical and physical reactions that partially melt the meal into clinker. The reactions in the kiln include completion of the calcination of limestone that has not taken place in the precalciner and emission of CO_2 from other CO_2 combined minerals. The CO_2 released from the raw materials during production is referred to as "process CO_2 emissions".
7. **Cooling and Storing:** Hot clinker from the kiln is cooled from over 1 000°C to 100°C rapidly on a grate cooler, which blows incoming combustion air onto the clinker. The air blowers use electricity and heated blown air circulation to improve thermal efficiency. A typical cement plant will have clinker storage between clinker production and the cement grinding process. Clinker may be loaded onto transportation, and can then be traded or further processed into cement.
8. **Blending:** Clinker is mixed with other mineral components to make cement. All cement types contain around 4-5% gypsum to control the setting time of the cement. Slag, fly ash, limestone or other materials can be interground or blended to replace part of the clinker. This produces blended cement.
9. **Cement grinding:** The cooled clinker and gypsum mixture is ground into a grey powder, known as Portland cement (PC), or ground with other mineral components to make blended cement. Ball mills have traditionally been used for grinding, although roller presses and vertical mills are often used in modern plants due to their greater energy efficiency.

Over time UK cement producers have invested heavily in upgrading kilns to improve energy efficiency. Historically cement was produced using a wet process whereby raw materials were fed into the kiln in the form of a slurry. This required considerable energy to drive off moisture before the sintering process could begin. Today in the UK there are no longer any wet process kilns but two main types of kiln remain; semi-dry (3 sites) and dry (8 sites). Within this there are variations in terms of whether or not the kiln has a pre-calciner and if so how many stages it has and whether or not there is a pre-heater and the number of stages it has. Unlike the historic wet process kilns, modern cement manufacture utilises waste gases to preheat raw materials and improve energy efficiency.

c. Cement Standards

All cements produced in the EU have to meet standard EN 197-1 “Cement: Composition, specifications and conformity criteria for common cements”. This standard exists to ensure that cement produced across Europe is harmonised and of the correct quality for use in construction to ensure all homes, buildings and infrastructure are safe and durable.

The standard sets out 27 different cement types that can be produced. These are broadly categorised as CEM I, CEM II, CEM III, CEM IV and CEM V with the categorisation depending on the type of constituents they contain. Different cement types have different properties and therefore suit different applications. They also have different CO_2 profiles[2].

d. Lowering Emissions

The manufacture of cement is an energy and CO_2 intensive process with around 70% of total emissions arising from the chemical decomposition of limestone (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 2.5) through investment in newer more efficient plant and fuel switching to biomass fuels. In 2018 a wide range of waste biomass and part biomass fuels contributed 17% to the total thermal input.

[2] More information is available in an MPA Factsheet, “Factsheet 18, Embodied CO_2e emissions of UK cement, additions and cementitious material”, 2019 update, https://cement.mineralproducts.org/documents/Factsheet_18.pdf

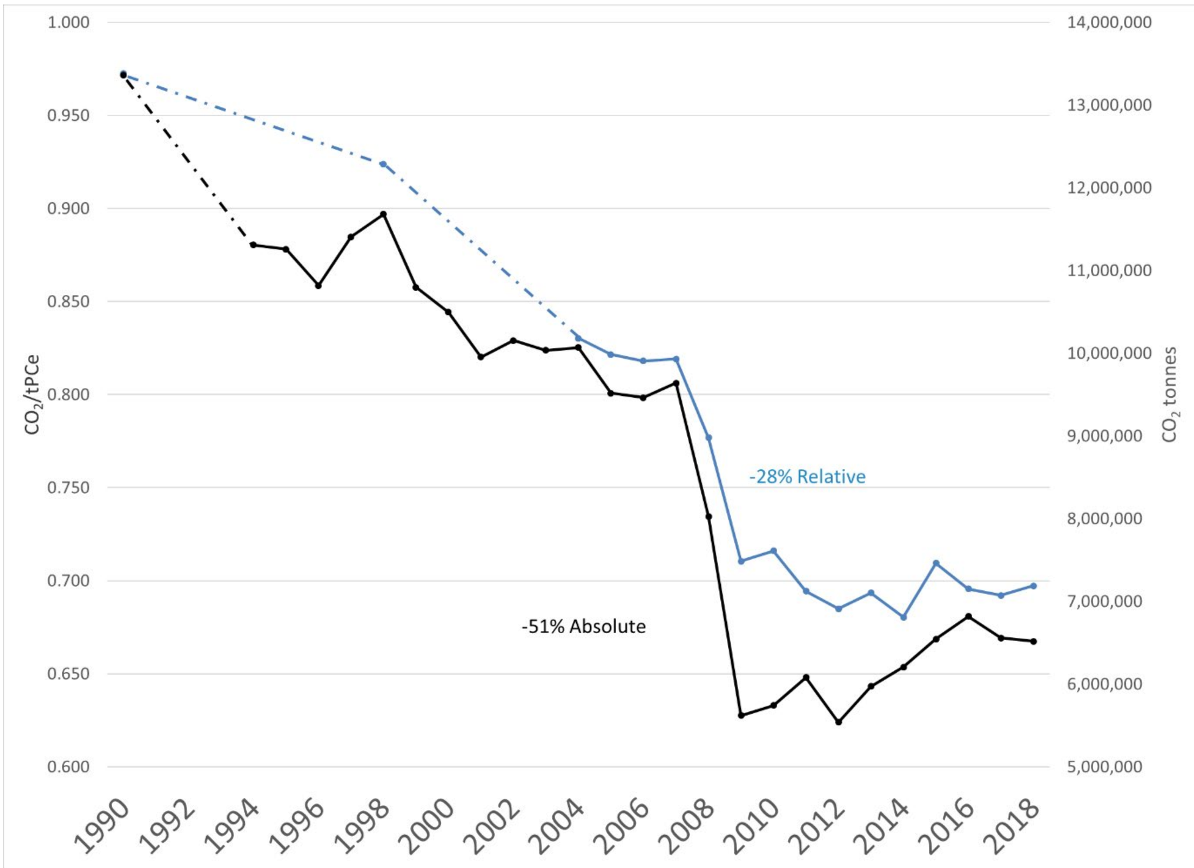

Figure 2.5: Reduction in Absolute and Relative Emissions from UK Cement Manufacture 1990 - 2018

In 2013 the Mineral Products Association (MPA)[3] published a roadmap setting out how emissions could be reduced by 80% compared to 1990[4] and the conditions under which that may be achieved. It concluded that in addition to incremental energy efficiency, there are three key technologies to decarbonising cement manufacture:

1. Use of greater cementitious additions in the product
2. Fuel switching to low carbon fuels (e.g. biomass).
3. Carbon Capture and Utilisation/Storage (CCUS)

This conclusion was validated in the UK Government cement roadmap[5] that was published in 2015, which MPA was also involved in producing.

[3] The Mineral Products Association is the trade association for the aggregates, asphalt, cement, concrete, dimension stone, lime, mortar and silica sand industries.
[4] MPA Cement Greenhouse Gas Reduction Strategy, 2013, https://cement.mineralproducts.org/documents/MPA_Cement_2050_Strategy.pdf
[5] "Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050; Cement", March 2015, Department for Energy and Climate Change and Department for Business, Innovation and Skills (now a combined Department for Energy and Industrial Strategy), https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/416674/Cement_Report.pdf

As the roadmaps outline there are a range of technologies needed to deeply decarbonise UK cement production. The cement industry are involved in further developing these technologies as set out in Table 2.2.

Table 2.2: UK Involvement in decarbonisation research and development.

1. **Use of greater cementitious additions.**
   MPA has initiated test work to demonstrate the capabilities of low carbon multi-component cements for the UK market. The results from this work will be used to modify the concrete application standard BS8500 so that the new cements can be confidently and safely used by specifiers and engineers. The work comprises of:
   a. Design and optimise a range of new low carbon multi-component cements for the UK cement industry; These cements are based on using additions of limestone with either Ground Granulated Blast Furnace Slag (GGBS) from steel manufacture or Pulverised Fuel Ash (PFA) from coal fired power generation. The aim is to reduce reliance on high quantities of GGBS and PFA, supplies of which are reducing.
   b. Demonstrate that low carbon multi-component cements are fit for purpose in a wide range of UK applications through extensive laboratory testing followed by a full-scale demonstration in the field via an engineered concrete structure;
   c. Influence relevant industry standards and guidance documents so that low carbon multi-component cements can be specified in practice;
   d. Provide the shared evidence base for rapid deployment of low carbon multi-component cements in the UK market by communicating the results to all UK cement manufacturers;
   e. Execute a communication plan for the UK construction industry on the benefits of specifying low carbon multi-component cements in construction projects (e.g. conferences, external seminars) to ensure early uptake of these low carbon materials.

   The cements produced will have CO_2 profiles between 39% and 41% lower than the highest clinker containing Portland cement CEM I.

2. **Carbon Capture and Use/Storage (CCUS)**
   There is considerable work being undertaken in the European cement industry on CCUS that UK cement producers are involved in:
   a. European Cement Research Academy (ECRA) Oxyfuel project. This project started in 2007 and several phases have been completed including a literature study, a study on oxyfuel and post combustion technology and laboratory scale/ small scale research. Two candidate sites have been identified for demonstration of the technology, but project costs are estimated to be around €90 million. Industry has pledged a considerable sum but further funding is required before the demonstration can be built. The constraints of EU funding programmes appear to be the most significant limiting factor.
   b. Norcem Brevik cement plant in Norway. This Government supported €11.7 million project that started in 2013 is testing four post-combustion capture technologies:

- Amine technology (liquid)
- Amine technology (solid)
- Membrane technology
- Calcium looping

c. LEILAC (Low Emissions Intensity Lime and Cement): This project started in 2016 and is due to run to the end of 2020. It is funded by consortium partners and Horizon 2020. The aim is to develop and test a pilot plant using Calix technology, a Direct Separation Reactor. This type of kiln re-engineers current calciners so that the raw meal is indirectly heated via a special steel vessel. It enables pure CO_2 process emissions to be captured with the combustion exhaust gases kept separate.

d. CEMCAP (CO_2 capture from cement production) is investigating four different CO_2 capture technologies and their integration into a cement plant:
   - Oxyfuel
   - Chilled ammonia process
   - Membrane-assisted liquefaction
   - Calcium looping

e. SCARLET (Scale up of Calcium Looping Technology) was a three year research project that ran from 2014 to 2017 and was funded by the EU 7th Framework programme. The aim was to obtain reliable information and tools for the scale-up of the Calcium Carbonate Looping process.

ii. Fuel Switching Versus Other Decarbonisation Options

A key challenge for cement manufacture is that fuel switching alone will not result in full decarbonisation because process emissions will remain. CCUS is a major part of the answer but CCUS is not yet proven at the industrial scale in cement production and unlikely to be cost effectively deployed for several years, if not decades. It also relies on there being a national transport and storage infrastructure that in the UK currently doesn’t exist. There are therefore a number of reasons why fuel switching is advantageous to consider now, whether or not CCUS is deployed at scale later on.

a. Timing

Both fuel switching and CCUS will require innovative technology updates to realise. However, cement manufacturers have considerable experience with fuel switching and some of the technologies that can aid this are currently available, albeit they may not yet have been trialled in cement production. It may also be possible to implement these technologies in a phased way that can help spread the capital cost. Fuel switching, at least to some extent could therefore be implemented in the near future with the support of the right policy framework. CCUS technology has the potential to be far more disruptive to the cement manufacturing process and is reliant on there being either options for utilising the captured CO_2 or the infrastructure to enable it to be transported for storage.

b. Net Zero

In legislating for the UK to meet a target of net zero by 2050, every option for decarbonisation needs to be explored. There is nothing to prevent sites fuel switching first and then deploying CCUS at a later date. The advantage is that in capturing biomass CO_2 emissions, cement manufacture could become net negative and help to offset other harder to decarbonise sectors of the economy. However, this could be costly and the correct policy support to enable this would need to be in place.

c. Technology

Some CCUS technologies, such as the Calix technology that is being trialled in the LEILAC project or the calcium looping technology being trialled under CEMPCAP (see Table 2.2), may only capture process emissions. Therefore, fuel switching will still be required in combination with these technologies to reach deep levels of decarbonisation. It is also possible that for some sites, CCUS is not an option because there isn't space on site for capture plant, planning permission for capture plant is unlikely to be granted or the logistics of transporting CO_2 from the site are incredibly difficult. The only way to lower emissions from these sites may therefore be fuel switching.

iii. Historic and Current Fuel Use

a. History of Fuel Use in UK Cement Manufacture

Historically cement manufacture has relied on fossil fuels such as coal and petcoke. 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.

Figure 2.6 shows how the amount and composition of waste derived fuels has changed over the period 1998 to 2018.

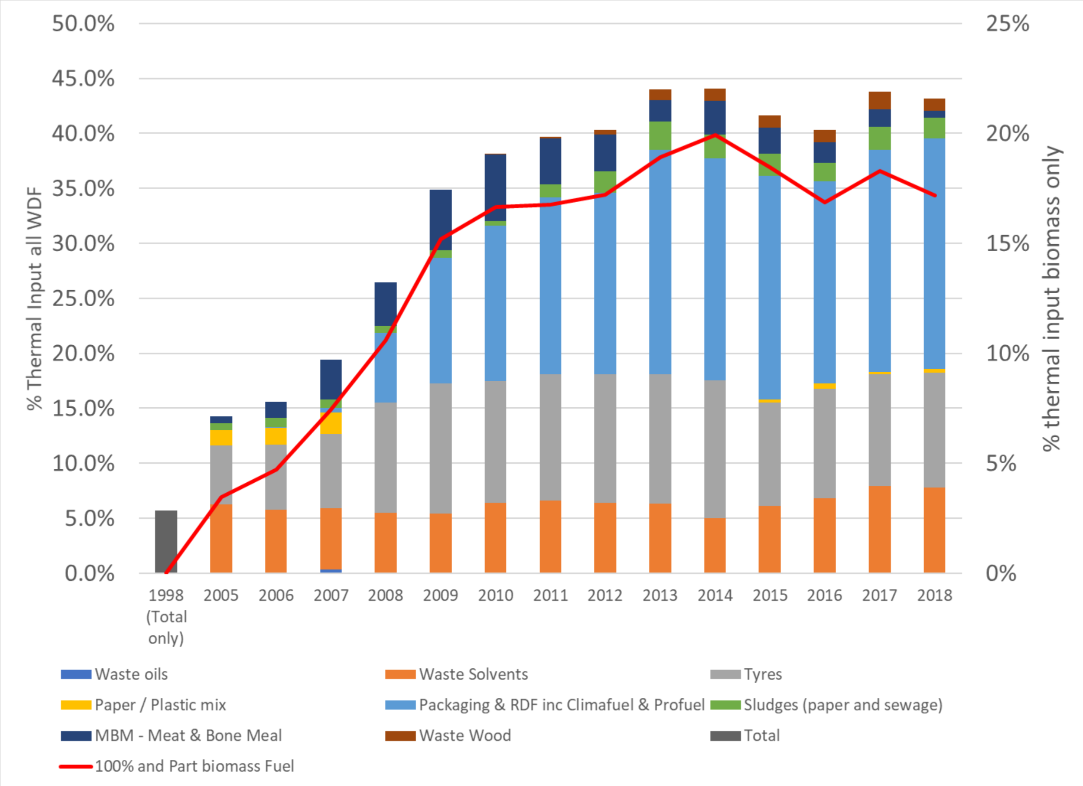

Figure 2.6: Waste Derived Fuel use in UK cement manufacture 1998-2018

b. Fuel Use Today

Figure 2.6 shows how the use of waste derived fuels increased considerably to almost 45% of the thermal input in 2014. The thermal input from biomass, shown in Figure 2.6 by the red line, reached a peak of 20% in 2014 but in 2016 this had reduced to 16.7%. Although it increased slightly in 2017 a reduction to 17% was seen in 2018. The main reason given by UK cement producers for this reduction is that incentives offered to other sectors are preventing them from competing on the market effectively for limited biomass resources. In particular, there has been a considerable reduction in the use of Meat and Bone Meal (MBM) by cement manufacturers since the introduction of the non-domestic RHI in 2011. In 2011 UK cement producers used 68kt of MBM, in 2016 MBM use was less than half that, at only 30kt and in 2018 usage was only 9kt.

c. Fuel Switching: It’s not just about energy

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’. As a result of waste used as raw material and ash from co-processed waste derived fuel, 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[6].

iv. Opportunities for Zero Carbon Fuel Cement Production

a. Candidate Energy Sources for Net Zero Carbon Combustion

Currently 17% of the thermal input to UK cement manufacture comes from (waste) biomass fuels. It is clear from this that if the sector is to move to net zero carbon combustion that secure sources of biomass or reliance on new untested fuels and/or technologies are required.

The assumptions made in this study are:

1. Waste derived fuels from non-biomass sources carry a carbon emission factor even though they have already been put to use in society i.e. as packaging, lubricants or solvents.
2. Waste derived fuels from biomass sources e.g. paper, processed sewage pellets, meat and bone meal carry a zero carbon factor.
3. Waste derived fuels with a biomass and non-biomass fraction e.g. tyres, carry a carbon factor proportional to the non-biomass fraction.

This section briefly explores the possibilities associated with candidate energy sources that could contribute to a net zero combustion emission kiln.

b. Electrification

The UK ambition is emissions from the power sector to be close to zero by 2050. Power sector emissions have fallen 49% since 1990 through, largely subsidised, switching from coal to gas and renewable power. The UK Government intention, as set out in the Clean Growth Strategy, is to phase out unabated coal generation by 2025, deliver new nuclear capacity through the building of Hinkley Point C and continue to invest to reduce the cost of renewables (see Figure 2.7).

[6] "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

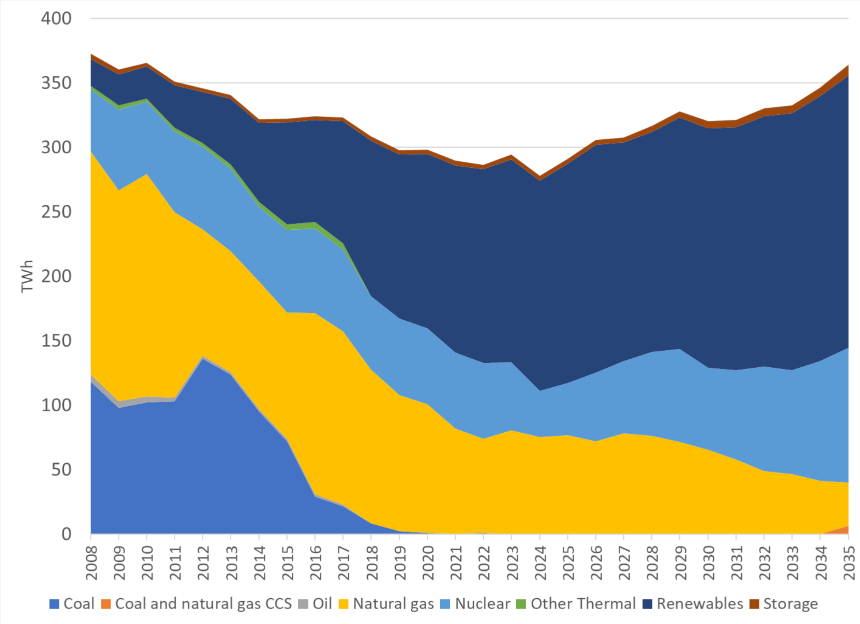

Figure 2.7: Projection to 2035 of UK Electricity Generation by Source[7]

Electrification could therefore provide a good opportunity to move to zero carbon combustion if the technologies and secure supplies are available to enable this.

c. Biomass

As noted above, waste biomass already makes up 17% of the thermal input into UK kilns. Higher levels of waste derived fuel use have been possible (even 100% for short periods) but significantly higher use of biomass has not yet been tested.

The advantage of using biomass fuels are that emissions from their use attract a carbon price of €0/tCO_2 in schemes such as the EU Emissions Trading System.

The key issues with biomass centre around securing long term sustainable supplies. Currently, the cement sector relies on waste biomass and part biomass fuels. Increasing use of biomass may require the use of virgin biomass. This introduces new issues around sustainability that the UK cement sector have not had to deal with to date in using only waste sources, which are inherently more sustainable having already been through at least one previous use before being utilised.

Reports such as the CCC report on biomass[8] recognise that biomass resources are limited and there are many different activities and sectors competing for these resources including power generation, heating of buildings and industry (for energy and as a raw material for some sectors). The growing of biomass for fuel must compete with farming applications including land use for crop production. However, the report highlighted that the best use of biomass is where it “maximises the removal and minimises the release of carbon into the atmosphere”. This could be

---

[7] Source: BEIS 2018 Updated Energy and Emissions Projections, Annex J Total electricity generation by source, https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2018

[8] CCC, “Biomass in a Low Carbon Economy”, 2018, https://www.theccc.org.uk/publication/biomass-in-a-low-carbon-economy/

achieved using biomass in cement manufacture with the addition of IBECCUS (Industrial Bioenergy Carbon Capture and Utilisation/Storage). Furthermore, the use of biomass in cement manufacture ensures that its mineral content is also recycled into the cement product (co-processing).

There are also technical constraints to using high levels of biomass including their lower calorific value, high moisture content, trace elements and chlorine content, which could disrupt the manufacturing process.

d. Hydrogen

The use of hydrogen has risen up the agenda in the UK considerably in recent years and there are a number of workstreams going on both privately and with Government funding looking at whether the natural gas network could be used to support hydrogen, what the implications are at different levels of hydrogen use and what changes might be required to appliances to enable its use.

If large volumes of hydrogen can be produced using low carbon methods (e.g. using renewable electricity or using CCUS) it may be an option for cement manufacturers. However, it has never been tested so it is unknown how it might impact on cement manufacturing process.

Although hydrogen wouldn't contribute any mineral or metal content to cement manufacture, if it could be used in combination with biomass fuels the fuel mix could be optimised.

3. Methodology

In undertaking this feasibility study, the following steps have been taken:

1. Literature has been reviewed and analysed for any information on fuel switching in the cement industry or use of novel combustion techniques that might be of relevance to this study and help define the most appropriate technologies for the sector and their relative importance/share of fuel switching (see section 5).
2. A reference plant has been outlined. This will be used as a reference for comparison of results of the fuel switching scenarios. The plant is not exactly representative of a specific UK cement plant but the intention is that it closely resembles as many plants as possible to ensure the results from the feasibility study are broadly applicable to any UK cement plant with only minor adjustments required in any future work (see section 6).
3. Biomass fuel specification and fuel mix was determined based on what is known today about how these fuels interact in the kiln and their availability. The most appropriate design for a plasma burner was determined (see section 7).
4. A number of scenarios were defined to test the feasibility and implications for the product and its production, of reaching a zero carbon or near zero carbon fuel cement plant (see section 8).
5. Mineral Interactive Computational Fluid Dynamics (MI-CFD) was used to model the different scenarios and for each one establish a detailed insight of the kiln operation for temperatures, NOx, CO, gas species and clinker

composition compared to operation of the reference plant. This was followed by kiln optimisation simulations, to identify the required improvements and assess the risks and limitations for a kiln operating under 100% carbon neutral combustion conditions. Note that in reality there was an iterative process between step 3 and step 4 to determine the most appropriate fuel mix/operating conditions and then optimise these (see section 9).

6. An optimal fuel mix option was drawn from the MI-CFD modelling and assessed for the impact it would have on clinker quality and techno-economic considerations (see sections 10, 11 and 13). This optimal fuel mix is used to determine the stages of further experimental investigation and demonstration.

4. Project Partners

i. 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.

One of the key roles of MPA within this project was to project manage the study, contribute with technical and commercial oversight using its network of members, provide UK specific data, interpret results, summarise the outcomes and to communicate the results to UK cement manufacturers and the concrete supply chain. The widespread dissemination of the results will help ensure all manufacturers have access to the information to inform any decision making on fuel switching.

ii. 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 200 projects, dealing with various combustion, emissions and process issues. The acquisition of 2 engineers with significant cement industry experience has enabled CINAR to more readily relate and produce workable solutions for our customers with a unique tool PKD-MI-CFD (process knowledge driven, mineral interactive computational fluid dynamics). CINAR has become the only company worldwide, which is able to offer AFR, Process, Emissions and Clinker Quality assessments to add value to our normal MI-CFD work.

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.

iii. 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. Among VDZ's customers are leading cement companies in many parts of the world. Recent projects focus on energy saving, fuel substitution, kiln optimisation, increasing grinding efficiency, environmental performance and finally quality improvement of clinker and cement. VDZ can offer its services along the value chain of cement and concrete production, from the raw materials to concrete and even the recycling of concrete structures.

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. ECRA understands itself as part of a network which comprises various research facilities such as universities, federal institutes and the research centres of cement companies or equipment suppliers.

5. Literature Review and Environmental and Safety Considerations

i. Literature Review

This section provides a high level summary of the key points.

a. Hydrogen (H_2)

The nature of hydrogen and natural gas combustion is quite similar. Methane (CH_4, natural gas) is the closest carbonaceous fuel to hydrogen as it has fewer bonds compared to the other fossil fuels. The main differences are the radiation properties of a hydrogen flame and the flame size, which is smaller in hydrogen combustion.

Nevertheless, the burning process and the heat formation are still different when the hydrogen is combusted. Technically, due to its highly flammable characteristics, safety precautions must be taken to avoid dangers that may arise from hydrogen usage. Dilution with other gases may be a solution.

Steam dilution will be effective for NO_x reduction in the process. Additionally, it lowers the reactivity of hydrogen, and the relatively low steam content may prevent light-back (flame flash-back). The combination of steam injection and hydrogen can provide efficient combustion[9].

NO_x formation can be another limitation as the temperature will be very high in a clinker kiln, when it is fired with hydrogen fuel. Even though hydrogen allows for cleaner combustion, NO_x emissions will probably increase. The newly designed Toyota burner could be considered for use in a rotary kiln[10,11].

One other aspect which is still unclear is the hydrogen flames low radiated heat. The low heat radiation could disturb the clinker burning process and must be thoroughly investigated. Mixing hydrogen with other materials/elements could be a solution to increase heat radiation (flame colouring). Clinker dust or calcined kiln inlet dust could be considered[12].

For safety reasons the chemical reactions of the hydrogen combustion demand a certain amount of activation energy to get started. The Chevron experiment also showed a temperature increase when the hydrogen is burned, mainly due to its high adiabatic flame temperature[13]. For this reason it is also important to take into account the hydrogen fuels high ignition temperature. The kiln start-up will be problematic due to this, as the auto-ignition temperature of hydrogen fuel is relatively high at 585°C. This makes it difficult to ignite a hydrogen/air mixture with heat alone and without some additional ignition sources like natural gas. Such a mixture can increase the reliability and the safety of the combustion.

The change of the clinker burning process into hydrogen combustion could be possible. It certainly needs further research in order to adopt the system, modify the conventional equipment and update the process parameters.

b. Electrification

Thermal plasma torches are distinguished by high temperature and enthalpy and therefore offer an attractive option for introduction in the cement industry, which has never yet trialled this technology. Their power density is especially high, as much as 100 times higher than conventional furnaces and various plasma torches have been developed with power ranging from tens of kW to several MW to fit the variety of requirements set by the steel and waste treatment industries[14].

---

[9] Sebastian,Gökea; Marc,Fürib; Gilles,Bourqueb; Bernhar,Bobuscha; Katharina,Göckelera; Oliver,Krügera; Sebastian,Schimeka; Steffen,Terhaara; Christian Oliver,Paschereita. Influence of steam dilution on the combustion of natural gas and hydrogen in premixed and rich-quench-lean combustors

[10] Sampson,J.. „Gasworld“ Toyota Motor Corporation. Available: https://www.gasworld.com/toyota-develops-worlds-first-hydrogen-burner/2015852.article: November 2018

[11] Toyota Motor Company Media Site. WORLD’S FIRST GENERAL-PURPOSE INDUSTRIAL HYDROGEN BURNER. 2018

[12] ECRA - Europeran Cement Research Academy. Carbon Capture Technology - Options and Potentials for the Cement Industry. Düsseldorf: 2007

[13] Cliff Lowe,Nick Brancaccio, Dan Batten, Chris Leung, Dick Waibel. Technology Assessment of Hydrogen Firing of Process Heaters. 2011

[14] Ananthapadmanabhan, P.V.; Venkatramani, N.. Suryanarayana, C.. Thermal Plasma Processing. Non-equilibrium Processing of Materials 1999, S. 121-149

Plasma technology has begun to emerge as a commercial tool in several industries such as steelmaking, precious metal recovery, and waste incineration. Research in the United States is also underway on the use of plasma torches for soil stabilisation with investigation of higher power levels with different types of soils, varying moisture content, and at different depths. Major research programmes for the study of the basic science of plasma heating and development and the implementation of models and prototypes for different applications are being conducted around the world (Australia, Canada, France, Japan, Russia, South Africa, Switzerland and United States)[15].

Plasma arc technology appears to have overcome most of the limitations associated with thermal stabilisation techniques using fossil fuels and electric heat sources. The higher temperatures, if controlled correctly, as well as greater flexibility and “simplicity” of the plasma torch potentially make it a more attractive option in the cement industry than the conventional torch using fossil fuels. This is especially the case in the light of CO_2 reduction incentives. The plasma torch potentially offers two to three times the heating value of fossil fuels[15].

A study that has been conducted within the framework of the “CemZero” project has concluded that electrification of the production process using the plasma burning technique, is technically feasible but needs to be verified in larger scale tests. In addition, the production cost in an electrified process is expected to be double that of today’s technology but could remain competitive when compared to other options aimed at radical emission reduction[16].

The future potential of a wider application of plasma techniques in industry depends on improvement of the characteristics of plasma torches. The biggest challenge to overcome is extension of the lifetime of the anode and cathode. The wearing of these electrodes is influenced by the thermal stress. Further research will focus on increasing the lifespan of the electrodes, as well as increasing the continuous service of plasma torches to many hundreds and even thousands of hours and upgrading thermal efficiency. In addition, the application of working gases of different chemical composition can be studied, taking into account the specific features of clinker production.

c. Biomass

Biomass based fuels have been used in the European cement industry for many years and their usage, in combination with conventional fuels or other alternative fuels, can be considered state of the art, availability and economic viability provided.

The most widely used, sewage sludge and meat and bone meal is considered 100% (or close to 100%) CO_2-neutral. Other alternative fuels such as industrial or domestic wastes contain varying proportions of biogenic material from 10% to 50%. While high shares of up to 100% alternative fuels covering the thermal energy demand can be achieved during normal cement plant operation, a usage of 70% to possibly more

---

[15] Purdue ECT Team. Plasma Arc Torch Technology Stabilization and Ground Improvement. 2007

[16] Wilhelmsson, Bodil; Kollberg, Claes; Larsson, Johan; Eriksson, Jan; Eriksson, Magnus. A feasibility study evaluating ways to reach sustainable cement production via the use of electricity. CemZero 2018

than 80% of pure biomass fuels needs further investigation. According to the experience of the cement industry, a replacement of conventional and other alternative fuels may be achieved if the necessary thermal input can be met. This may be facilitated by the application of oxygen enrichment (see below).

In addition to their fuel properties, the ash contents of the fuels contribute to the formation of the clinker phases. Therefore, as with the utilisation of all fuels, biomass fuels have the added value of acting as an alternative raw material.

1) *Oxygen Enrichment*

Clinker burning in an oxygen enriched environment has been investigated since the 1960s. It brings certain advantages to the production process. In the context of fuel usage, it enables the burning of alternative fuels with lower calorific values enabling a better fuel devolatilisation, ignition and burn-out. Furthermore, production increases and/or reductions of thermal energy demand due to reduced flue gas losses have been observed. However, due to the higher flame temperature as well as the presence of high oxygen content, there is the possibility of an increased NOx formation in the main burner.

Regarding the replacement of the current fuel mix utilised in the UK's cement industry, oxygen enrichment may facilitate the usage of a higher share of low calorific biomass fuels.

ii. Environmental and Safety Considerations

a. Hydrogen

The hazards associated with hydrogen are similar to those associated with other fuels, and they differ where physical characteristics differ. If applied correctly, hydrogen may provide clean energy for industrial uses. However, as a combustible gas, precautions must be taken in its application. The safe storage and transportation of hydrogen as well as risks relating to hydrogen leakage have all been considered.

The key environmental consideration associated with the use of hydrogen is the formation of Nitrogen oxides (NOx). The high gas temperatures demanded by the production process of up to 2,000°C at the main burner result in the formation of nitrogen oxides by the reaction of nitrogen and oxygen contained in the combustion air (thermal NO_x) as well as nitrogenous compounds with oxygen (fuel NO_x). The burning of hydrogen as a fuel would not result in any fuel NO_x but thermal NO_x could be an issue. In the last decades, the cement industry has introduced measures to reduce NO_x emissions by primary and secondary abatement measures. It is anticipated that the same techniques should be applicable with the proposed fuel switch.

b. Biomass

Biomass, especially sewage sludge can contain a variety of harmful substances. The main pollutants and some examples of the respective sources are provided in Table 5.1.

Table 5.1: Compilation of pollutants in sewage sludge

Pollutant	From domestic use	From combined sewage systems	From industrial discharges
Pathogens	Human metabolism	Animal faeces	Meat industry
Environmentally relevant elements	Pb from paints Cu from pipe corrosion	Pb, Cd, Zn from rain water drainage Zn, Cu from roof corrosion Pb from oils	Various
Persistent organic pollutants	Paints, solvents, pharmaceuticals, timber treatment, cosmetics, detergents	Oil, pesticides, tar, road de-icing, rain, combustion	Various

Mercury can also increase with the use of biomass compared to traditional fuels such as coal. However, the increase in mercury contained in fuel will not necessarily result in increased mercury emissions because there are ways of mitigating these emissions including through careful selection of raw materials and the application of an effective dust removal system when raw mills are not operating.

Risks associated with collection and transport of sewage sludge have been considered. It must be noted that the UK cement industry has been using these waste biomass fuels for a number of years and has systems and processes in place to manage the associated risks.

6. Reference Plant

To enable the feasibility study modelling, a reference plant was defined. Assumptions were made around typical plant and equipment dimensions, using a reference plant. The described reference plant has been developed by VDZ in order to simulate BAT technology for cement kilns. To enable comparison of results with other decarbonisation technologies it was decided to keep the reference plant similar to one used for carbon capture studies, e.g. by ECRA (European Cement Research Academy) in order to develop a design for an Oxyfuel cement kiln and to investigate its impact on the clinker burning process. This enables the results from this study to be compared with results from other decarbonisation projects across Europe. This might enable future modelling of fuel switching combined with CCUS, for example.

i. Location

The reference cement kiln is assumed to be situated inland, with the following ambient conditions:

- Air temperature: 15°C
- Air pressure: 1.013 bar
- Relative humidity: 60%

ii. Structure

The reference plant relies on the Best Available Technique (BAT) standard as defined in the European BREF-Document (Best Available Technique Reference) for the manufacture of cement[17]. The plant structure for the reference case, based on a dry kiln process, consists of a five stage cyclone preheater, calciner (also called precalciner) with tertiary air duct, rotary kiln and grate cooler, as illustrated in Figure 6.1. This process model has been built by VDZ (in this document referred to as the VDZ process model).

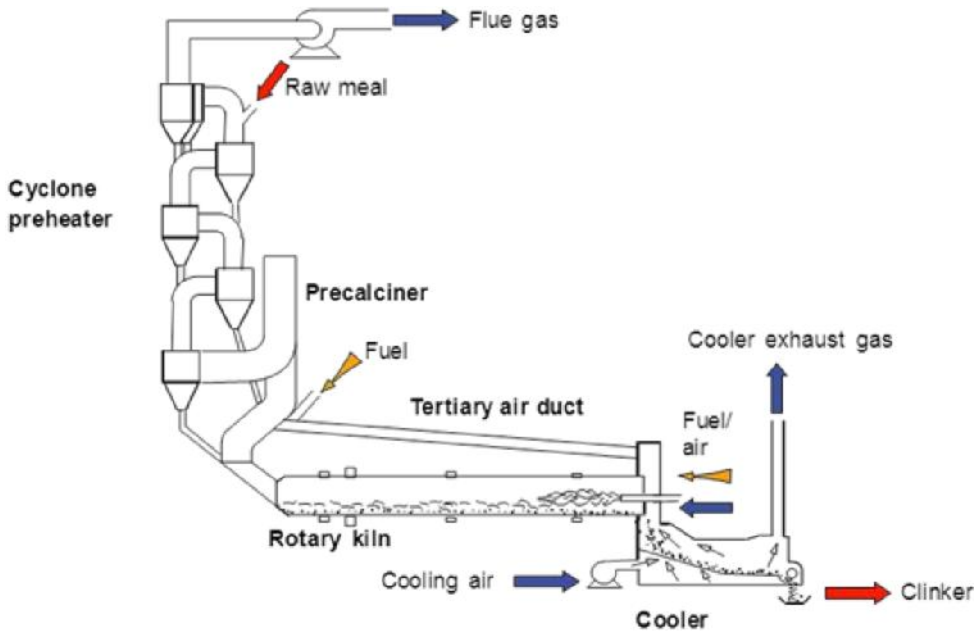

Figure 6.1: BAT cement kiln

iii. Key Parameters

The BAT cement kiln has a clinker capacity of 3,000 tonnes per day (t/d) (raw meal/clinker factor 1.6), which is a representative size for a European cement kiln (see

Table 6.1). In the reference kiln a bypass is excluded since this is not required in an ideal kiln. This corresponds to a yearly clinker production of 1 Mt (equivalent to a run time of >330 days per year) or a cement production of 1.18 Mt per year (clinker/cement factor 0.850 for UK).

Table 6.1: Production characteristics of a BAT cement kiln

Parameter	Value
Production capacity	1 Mtclk/y (3,000 tclinker/d)

[17] European Commission (Ed.); Schorcht,Frauke; Kourti,Ioanna; Scalet,Bianca Maria; Roudier,Serge; Delgado Sancho,Luis. Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide. Luxembourg: Publications Office of the European Union 2013

Parameter	Value
Cement production	1.18 Mtcement/y
Raw meal/clinker factor	1.6
Fuel applied	100% coal
Specific CO_2 emissions	850 $kgCO_2$/tclinker
Specific total electricity demand	97 kWh/tcement
Kiln expected run time	>330 days

7. Fuel Specification and Plasma Burner Design

i. Coal Fuel Specification for Coal Fired Baseline

The reference plant is assumed to run on 100% coal. Table 7.1 shows the specification used for coal.

Table 7.1: Coal specification for Base Case

Proximate Analysis	As Fired
Volatiles	38.00
Fixed C	45.00
Moisture	0.50
Ash	16.50
TOTAL	100.00
C	69.00
H	4.00
S	0.50
N	0.48
O	7.30
Moisture	0.50
Ash	16.50
TOTAL	100.00
Net Calorific Value (MJ/kg)	27.15
Density (kg/m3)	1200

ii. Biomass Fuel Specification

In view of the experience of the cement industry and availability of biomass, the firing of wood chips, Meat and Bone Meal (MBM) and dried pulverised sewage sludge (PSP) in the kiln and the calciner is the probably the most realistic future use of biomass in the sector. Hence, for this feasibility study, only these biomass-based fuels are considered for demonstrating the net zero carbon fuel utilisation in cement kilns.

With limited biomass availability, it may not be possible to run the kiln and calciner with biomass alone and additional energy input from other non-fossil fuel sources will be required. The other sources identified for thermal input are hydrogen as a fuel and heat input from plasma burners.

iii. Use of Hydrogen

Hydrogen can be commercially produced using electrolysis whereas its by-product, ‘oxygen’ can be used to combust separated hydrogen as well as biomass.

The use of pure oxygen, produced from an electrolyser, can replace a large amount of nitrogen from air as an oxidant. This will substantially reduce the volume of combustion products, thereby compensating for use of low CV biomass which would increase the volume of combustion gases drawn by the ID (induced draft) fan. Hence, it will be possible to maintain the clinker production rate which is mainly controlled by ID fan capacity – drawing gases (by volume) from clinker cooler to preheater tower.

iv. Plasma Burner Design

Field experience shows that the generation of ‘hot’ plasma, produces heat which is adequate for sintering or ash fusing for waste treatment or production of clinker in small scale experiments. Once developed for the cement kiln/calciner, the plasma burner has the advantage of being an independent heat source not affected by oxidising conditions (i.e. typical flow stratification problems observed in the kiln/calciner where fuel and oxidant remain unmixed for an extended duration) and characteristics of biomass fuels. Under these conditions, the production of tars and other undesirable compounds of the syngas, produced from partial oxidation of solid fuels, are eliminated.

After carefully considering all options and the technical barriers for plasma generation for cement manufacture, it was decided to base the plasma burner design on simple and small-scale plasma burners, i.e. those which are in operation to ignite low-grade coals in power stations. The power rating of these plasma burners varies between 50-200 kW. In particular, for the feasibility study, a well-tested industrial scale 200 kW rated plasma burner was selected, as recommended by Dr. Alexandr Ustimenko, – who at present heads the R&D plasma test facility at the Institute of Combustion Problems, Almaty, Kazakhstan.

8. Scenarios Modelled

The overall fuel mix tested across the kiln (40% of thermal energy) and calciner (60% of the thermal energy) was 70% (of the thermal input) from biomass, 20% hydrogen and 10% plasma. A single scenario was modelled for the kiln and this was combined with three different scenarios modelled for the calciner (see Figure 8.1 and Table 8.1 for details of the scenarios).

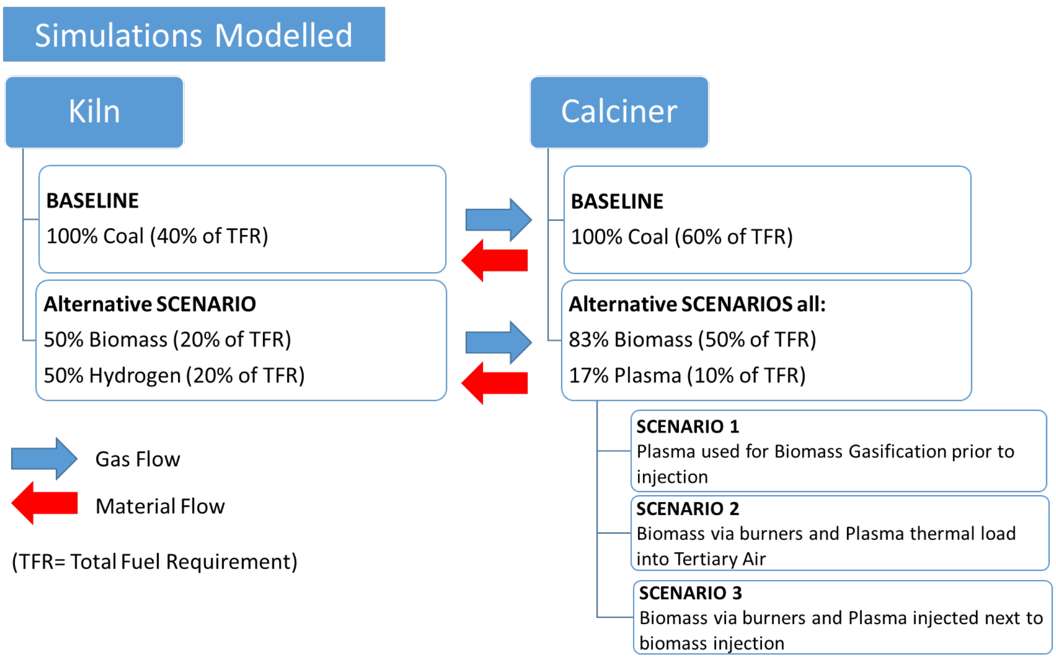

Figure 8.1: Scenarios modelled and compared to 100% coal fired baseline

Table 8.1: Outline of the scenarios modelled

Kiln	Fuel Mix	Calciner	Fuel Mix	Details
Kiln coal fired baseline	100% coal	Calciner coal fired baseline	100% coal	
Kiln biomass and hydrogen scenario	50% biomass, 50% Hydrogen	Calciner Scenario 1 (plasma biogas)	83.3% biomass, 16.7% plasma	Plasma burner is used to produce gas (42% CO, 37%H_2 and 21%N_2) by gasification of biomass which is then introduced at 1000°C.
		Calciner Scenario 2 (biomass (B/m) burners plus plasma injected in Tertiary Air (TA))	83.3% biomass, 16.7% plasma	Biomass is injected via 4 burners and used with plasma to increase the enthalpy of the Tertiary Air from 950°C to 1350°C(TA).
		Calciner Scenario 3 (B/m burners and plasma injected near burners)	83.3% biomass, 16.7% plasma	Biomass as in scenario 2. Thermal energy from plasma is used to heat air injected via 5 injection locations next to each burner plus one in the riser duct. Increases the temperature to 1165°C.

These simulation scenarios were selected considering various combinations of fuels/technologies, the availability/scarcity of fuels, the level of development of each technology (as revealed through the literature review and described above) and their practical ease of implementation. As biomass is currently fired in both kilns and calciners at various rates it was selected to be used as the main fuel. As hydrogen and plasma are not yet used widely in the cement industry, it was decided not to try to use all 3 options in both kiln and calciner as this adds considerable complexity and could make isolating the results of each technology more difficult. Instead hydrogen was selected for use only in the kiln (as gas combustion is already available in many kiln main burners) and plasma was selected for use only in the calciner.

While kiln fuel can be supplied only from the main burner in a co-current flow pattern with rest of the gases, there is potential in the calciner to use a variety of injection locations. This enabled several locations to be used for biomass injection in order to increase its mixing with the available oxygen and thus increase its burnout.

Plasma energy is an unknown for cement manufacture and therefore presents a more challenging technology. As a result, it was selected to contribute a smaller fraction of the heat required in the calciner and several different options for its use were proposed. The first was the use of several small plasma burners at five locations which use gas from biomass gasification. The second alternative uses solid biomass injected via burners with the plasma energy being used to increase the enthalpy of the TA upon entering the calciner. The third alternative places plasma torches at several locations close to the biomass burners, which would introduce air with higher enthalpy in the system in the near burner regions to help improve the burnout of the injected biomass.

For each scenario the following parameters were assessed through the modelling:

- Aerodynamics
- Biomass Combustion (burnout)
- Temperature
- Oxygen, Carbon Dioxide and Water
- Process

9. Modelling Results

i. CO_2 Reduction Achieved

Using a mix of 50% hydrogen and 50% biomass in the kiln and 83.3% biomass with 16.7% plasma in the Calciner leads to elimination of all fossil fuel CO_2, leaving only process CO_2 from the breakdown of raw materials. Furthermore, the use of hydrogen and plasma technologies reduces total CO_2 (raw material CO_2 plus fuel CO_2 including that from biomass fuels) by around 14%.

Table 9.1 shows the CO_2 reductions that are possible for each of the scenarios (note that the kiln scenario is the same across all the calciner scenarios and is shown in the “kiln fuel” row of the table).

Table 9.1: CO_2 Reduction for the Simulated Scenarios.

CO_2 source	**Fossil CO_2, biomass CO_2 or raw material CO_2 (process emissions)**	**Coal Fired Baseline**	**Calciner Scenario 1 Plasma biogas**	**Calciner Scenario 2 B/m burners + plasma injected in TA**	**Cacliner Scenario 3 B/m burners + Plasma air near burners**
		kgCO_2/kg clinker			
Kiln Fuel	Fossil	0.118	0.000	0.000	0.000
	Biomass	0.000	0.054	0.054	0.054
Calciner Fuel	Fossil	0.176	0.000	0.000	0.000
	Biomass	0.000	0.140	0.137	0.137
Raw Material	Raw Material	0.438	0.438	0.438	0.438
	CO_2 reduction on fuel and raw material CO_2		40.2%	40.2%	40.2%
	Total CO_2 reduction (including raw material and biomass CO_2)		13.7%	14.1%	14.1%
	Scenario fuel mix CO_2 reduction vs. Coal fired baseline		100%	100%	100%

ii. Other Parameters Modelled

a. Kiln Model

- **Aerodynamics:** High velocities are observed in front of the main burner, developing a stronger recirculation zone above the burner, which is observed to enhance the secondary air mixing compared to coal fired baseline.

- **Biomass Combustion/ Burnout:** The hydrogen burns quickly and assists the ignition of biomass which has bigger sized particles than coal micron particles.
- **Temperature:** The temperatures are increased at the front of the burner.
- **Oxygen, Carbon Dioxide and Water:** Replacing half of the fuel by hydrogen leads to reduced mass flow of CO_2 as expected. As the flowrate of secondary air reduced so did the exit kiln gases. The new exit composition of the kiln gases corresponds to much less CO_2 mass flow; 40% of CO_2 is reduced of the total 5.29kg/s CO_2 exhaust of the coal fired baseline (or 54% of the kiln fuel generation CO_2)
- **Process:** The clinker formation processes show a similar behaviour as the coal fired baseline.

b. Calciner Scenarios

- **Aerodynamics:** The decrease of kiln gases results in lower kiln riser velocities. (This is not seen as a significant problem as the kiln riser could be modified in order to maintain the required magnitude of the velocities).
- **Biomass Combustion/ Burnout:** Scenario 3 with Biomass via burners and plasma injected air, although 99% burnout was achieved had lower calcination level.
- **Temperature:** There would be necessary optimisation of the locations of the plasma (thermal input) to be introduced near the meal inlets. In such a way the heat would be absorbed for the endothermic reactions and would create conditions very similar to those of Base Scenario conditions.
- **Oxygen, Carbon Dioxide and Water:** The heat provided from the plasma increases the thermal load without adding any CO_2 in the system. Scenario 2 with Biomass via burners and plasma in TA where solid biomass was fired, lead to a reduction of 15% of the total CO_2 emitted from the Calciner or a 22% of the Calciner fuel CO_2 generation.
- **Process:** The NOx has significantly increased due to the higher nitrogen content in biomass fuels compared to coal.

10. The Optimum Fuel Mix

The modelling results show that a fuel mix of 70% biomass, 20% hydrogen and 10% plasma can successfully eliminate fossil fuel CO_2 emissions from cement manufacture. The optimum configuration for this fuel mix is described below for the kiln and calciner.

i. Kiln

In the optimal case scenario it is assumed that 40% of the overall thermal energy is supplied from the main burner (and 60% from the calciner). The modelling of kiln fuel switching shows that a fuel mix of 50% biomass and 50% hydrogen is realistic and applicable using biomass fuels of wood, meat and bone meal (MBM), and processed sewage pellets (PSP) with a moisture content less than 10%. If a plant is already using alternative fuels it may be possible to use a specially designed fuel to improve energy efficiency, in the existing burner.

In reality, it is expected that the flame temperature will be at the higher range of the requirement at the main firing, therefore burner adjustments will play a key role to control this and keep it within limits. The flame shape and length play a key role in order to have better control over the NOx emissions and also to protect the refractory lining inside the rotary kiln.

ii. Calciner

Three scenarios were modelled for the calciner (all based on 83.3% biomass and 16.7% plasma).

Scenario 1 used the plasma energy to gasify biomass and the resulting hot gas was the energy input. This option was ruled out for further investigation because the CO_2 reduction is lower than that achieved via the other options. Furthermore, it is far more complex and would require higher CAPEX.

Scenario 2 is technically possible and requires only a few modifications to existing kilns. This scenario has a good distribution of the biomass in the calciner as the tertiary air (TA) flow is creating a strong swirl. The reduction of the TA is compensated by the higher velocities of the flow which has increased temperature through the plasma input as “heat”. The heat provided from the plasma increases the thermal load without adding any CO_2 in the system.

Scenario 3 is interesting but preheating the axial air of the biomass burners is challenging and would need considerable testing especially on the refractories, since combustion in the burner must be avoided.

Scenario 2 has 4 biomass burners at the calciner. This gives a good fuel distribution in the calciner, which is important for NOx reduction. This installation assumes that the biomass can be transported in air convening lines to the calciner.

The trend for present installations are Step-Combustors® (Polysius) and the Pyrorotor® (KHD), which allow the burning of 3D material with diameters >30 mm. In this case when a retrofit is considered, an increase of the temperature of the TA via electric heating (i.e. resistance heating, microwave heating, plasma arc, etc.) could be a realistic optimal case scenario. This is not only an advantage in terms of installation, but also having the plasma burner at the TA duct would reduce the thermal load at the calciner side. Heating up the tertiary air (TA) electrically from 950°C to 1,350°C in the above mentioned pre-combustors could give the desired electric heat input of 10% of the total thermal energy.

It must be mentioned that the development of plasma burners are not yet advanced enough that one burner could deliver the required heat (10.9 MW). Efficient plasma burners (>70% efficiency) can be presently built up to 1 MW. For the practical use of the plasma burners not only the electric power at the burner floor is required, but also cooling water needs to be at the burner floor. In this case a cooling system must be built also that up to 30% of the plasma energy can be dissipated.

In an optimal scenario dielectric heating (microwave system) can be an alternative to the plasma burner. In any case the location of the heat input must be well adjusted to the plant set up.

Electrification technology is developed but needs to be adapted to the plant infrastructure.

11. Issues Identified for Further Investigation

MI-CFD predictions demonstrate that overall, the existing kilns and calciners can be adapted to operate under conditions whereby no thermal input from conventional fossil fuels is employed. The results and subsequent predictions indicate that this should be possible with no negative impact on clinker quality, kiln stability or build-up issues but some further work through demonstration is required to confirm this. In particular, a phase 3 demonstration is required to address the following:

- The modelling has shown that the hydrogen will develop a short and intensive flame. Further work is required to determine how best to optimise the kiln burner such that the higher flame temperature can be controlled to make it similar to that achieved through the use of coal. In particular, this means ensuring that the flame is confined to the centre of the kiln without touching the walls, in order to protect the refractory kiln lining. A demonstration with flame thermography would enable testing of burner design and location aimed at reducing the higher temperature regions and associated NOx emissions and ensuring a good burnout of the fuel and no overheating of the burning zone.
- Further investigation is required to determine if an existing burner can be retrofitted for the use of Hydrogen or if a new innovative burner is required.
- Ensure that biomass fuel design is such that larger chips do not fall into the bed and negatively affect clinker quality. A specific fuel specification may be required for biomass fuel supplied to the main burner i.e. particle size distribution to be minimised.
- Hot spots observed in the modelling near the calciner walls need to be minimised. The location of plasma injection in relation to the hot meal and biomass inlets needs to be investigated further. The correct positioning will improve the heat absorption via the calcination process in the near burner regions and reduce the hot spots observed.
- How to split the biomass material flow between a number of burners, which will be challenging.
- Further work is required to investigate the use of plasma burners:
    - The best location for the placement of the plasma burners needs to be determined. This might be limited by the space available on site.
    - Multiple plasma burners (electric power is 1 MW per torch) might cause infrastructural difficulties because of the huge increase in power demand.
    - The choice of plasma gas (ambient air, steam, CO_2, argon, or hydrogen) will be made according to availability and local cost.
    - Concerns related to the lifetime of electrodes (especially the anode). Presently the life expectancy is approximately 500 hours, which may cause significant problems for a continuous production process. Larger plasma burners must be used if the process is to be completely electric

and the removal of a burner for regular maintenance will cause disturbances of the process.
  - Plasma burner inefficiency has to be investigated as they require a water-cooling system in order to minimize the wear on the electrodes. Depending on the burner power capacity, the efficiency loss at the thermal output can be up to 50%. The inefficiency drops down to 25-30% at bigger burners with MW-scale power capacities. Empirical evidence in cement kiln applications is needed.

12. Product Safety Assessment

As set out in the introduction (section 2.i.d), cement manufacture recycles the mineral and metal content of fuels as well as utilising their energy content. Any change in fuel mix will affect the properties of the clinker produced. For this study, it is the increase in biomass that will have the greatest effect since hydrogen and plasma have no mineral ash content.

This study investigated the impact on clinker quality of the following three scenarios:

1. 100% coal fired baseline: BAT reference plant scenario with 100% coal firing as the baseline case. All thermal input is covered by coal with a fuel split between calciner and main burner of 60:40.
2. Fuel Switching Scenario used for this feasibility study: 70% biomass fuel firing, 20% hydrogen and 10% plasma. In the main scenario 70% of the thermal energy demand is covered by biomass fuels, i.e. wood, processed sewage pellets (PSP) and meat and bone meal (MBM). Due to different demands regarding the firing location, two different fuel qualities for wood with differing moisture content and net calorific values (NCV) were considered.
3. Full biomass use (the worst case scenario for clinker quality considerations): Impact of 100% biomass fuel firing. In addition to the fuel distribution for the fuel switching scenario, the maximum case of 100% biomass firing was investigated to determine the highest possible impact of biomass fuels on clinker quality. Therefore, the fuels' mass flows were increased, keeping their proportional share in the fuel input into the production process.

In comparison to the coal fired baseline, the fuel switching scenario with 70% biomass fuels as well as the maximum case for 100% biomass fuel use lead to higher lime saturation factor (LSF). The clinker will therefore have slightly higher alite (C_3S) content. The C_3S content of the clinker may shift to the alumina-ferrite phase (C_4AF) with a slight reduction in early reactivity.

Regardless of the share of biomass fuels, phosphate (P_2O_5) input to the burning process and eventually its share in clinker composition will increase to 0.5–0.7 molar %. This is still within an acceptable range below 1 molar % provided that a good homogeneity of material in the kiln is secured.

The suggested fuel switching scenario as well as the investigated case for 100% biomass fuel usage will increase the content of trace elements due to a higher intake with wood and PSP, except for arsenic. The expected trace element concentrations are below the given reference values for clinker and far below the concentrations where an effect on clinker quality may be expected. For a more comprehensive representation the figures for the three scenarios modelled for product quality are compared with the reference plant values of the raw meal (Table 12.1).

Table 12.1: Comparison of input materials compositions (raw meal +ash) and moduli for three product quality scenarios (composition in m-%, dry)

Unit	**Raw meal + ash** (Coal fired Baseline)	**Raw meal + ash** (Fuel switching scenario)	**Raw meal + ash** (100% biomass)	**Raw meal reference plant**
SiO_2	21.83	21.55	21.58	21.09
Al_2O_3	5.45	5.12	5.15	4.97
TiO_2	0.12	0.09	0.09	0.09
P_2O_5	0.08	0.51	0.69	0.06
Fe_2O_3	3.07	3.11	3.14	3.00
Mn_2O_3	0.08	0.08	0.08	0.08
CaO	66.39	66.09	66.22	66.06
MgO	1.12	1.56	1.12	1.09
SO_3	0.59	0.56	0.57	0.52
K_2O	0.85	0.88	0.88	0.84
Na_2O	.190	0.21	0.23	0.18
LSF	95.47	97.27	96.62	98.79
SR	2.56	2.62	2.60	2.65
AR	1.78	1.65	1.64	1.66
Trace element concentration (dry, in ppm)				**reference values for clinker**[1]
Cr	41.37	46.89	50.03	150
Cu	26.09	40.48	47.17	100
As	7.13	5.98	6.12	40
Cd	0.43	0.57	0.63	1,5
Zn	66.92	170.90	213.53	–
Pb	28.41	33.26	37.77	100
Ni	25.04	22.05	22.81	100

[1] Ministry of Environment and Nature Conservation, Agriculture and Consumer Protection of North Rhine-Westphalia (ed.), *Leitfaden zur energetischen Verwertung von Abfällen in Zement-, Kalk- und Kraftwerken in Nordrhein-Westfalen.* 2005

13. Techno-Economic Assessment

i. Analysis of Capital Costs

All costs are estimated for the reference plant (set out in Section 6) which is a 5-stage preheater kiln system with 3000t of clinker output per day. The thermal power input from the main burner is estimated to be between 100–120 MW.

a. Hydrogen

This analysis mainly covers the capital costs. Operational costs will be limited with some additional maintenance expenses in order to control any hydrogen leakages in the transport pipeline.

Table 13.1 shows the rough estimation of capital costs when the fuel is switched to hydrogen.

Table 13.1: Estimation of capital costs for fuel switching to hydrogen

Equipment	Estimated costs
New hydrogen burner	£200,000
New hydrogen storage tank	£100,000
Renovation of the pipeline	£50,000
Total CAPEX	**£350,000**

b. Plasma Burner

The analysis of cost related to plasma covers capital as well as operating costs with a certain discrepancy, as the calculation is based on the experience from related industries, such as steel and waste incineration industries.

The thermal power input derived from the burning is estimated to deliver the values of 100–120 MW, 10% or 10–12 MW of which is expected to be covered by the plasma technology.

The general structure of the plasma torch system consists of the following parts: plasma torch, thyristor-based DC power supply, control and instrumentation system, process or shield gas supply, and cooling water system. Therefore, the costs presented below reflect the system dimensioned for the reference plant.

Capital costs are subject to a generalised rough estimation. Commercial projects in the steel industry for car manufacturing demonstrated the economic viability and expedience of such system implementation[18]. As stated by the plasma torch producer, the pay-back of the system can be expected within 1–3 years depending on the power rate and usage intensity. For the cement industry, no statements of a potential pay-back can be made, yet it should be noted that the positive CO_2 impact that such a production will have, could play a decisive role.

Table 13.2: Estimated calculation of the plasma torch system

Equipment	Units	Estimated Costs
Plasma torch [2 MW]	5	£5,000,000–£8,000,000
Control and instrumentation	1	£300,000

[18] Westinghouse Plasma Corporation. *Plasma Torches for Foundry & Ironmaking Applications*. 2013

Cooling water system	1	£50,000

While talking about costs of the plasma torch system, other aspects also need to be considered, in particular infrastructural development, additional supply of gases and spare parts, e.g. electrodes.

Table 13.3: Estimated calculation of the capital costs directly related to the plasma torch system

Part of system	Units
Civil modifications (supports, beams, buildings)	£1,000,000–£2,000,000
Electrical modifications (transformers, cables, switchgears)	

Table 13.4: Estimated calculation of the operational costs directly related to the plasma torch system

Part of system OPEX estimation	Estimated Costs
Electrical energy supply for 10MW (>7500 hrs/year)	£2,000,000–£3,000,000
Expandable materials (electrodes, etc.)	£100,000–£200,000
Gas supply (depending on gas)	£50,000–£500,000
Shield gas	£50,000
Maintenance (manpower)	£50,000

ii. Cost Comparison with the Base Case

This section provides a summary comparison of both capex and opex costs of fuel switching with the base case. Note that the cost estimates presented look primarily at hydrogen and plasma with the use of biomass representing a possible saving. However, it should be noted that to reach high levels of biomass replacement, some investment would be required, and higher operating costs may also be expected.

Table 13.5: Calculation of the total cost of clinker considering the application of additional technologies (±35 % uncertainty)

Additional cost of clinker due to fuel switch	
Additional CAPEX Hydrogen	0.105 €/$t_{clinker}$
Additional CAPEX Plasma	2.209 €/$t_{clinker}$
Additional Fixed OPEX	0.10 €/$t_{clinker}$
Additional Variable OPEX	19.33 €/$t_{clinker}$
Total cost of clinker for fuel switch	**21.74 €/$t_{clinker}$**

Table 13.6: Cost of possible CO_2-savings with strong hydrogen price dependency (±35 % uncertainty)

Price of CO_2 per ton of produced clinker	
Hydrogen avg. price	29.7 €/GJ
Hydrogen low price (H1 case)	20.1 €/GJ
Hydrogen high price (H2 case)	39.9 €/GJ
Additional costs of fuel switch per t clinker	21.74 €/$t_{clinker}$
Additional costs of fuel switch per t clinker (case H1)	*15.4 €/$t_{clinker}$*
Additional costs of fuel switch per t clinker (case H2)	*28.5 €/$t_{clinker}$*
CO_2 savings	310 kg_{CO2}/t clinker
Cost of CO_2 savings	**70.1 €/t_{CO2}**
Cost of CO_2 savings (case H1)	***49.7 €/t_{CO2}***
Cost of CO_2 savings (case H2)	***91.9 €/t_{CO2}***

14. Non-Technical Considerations

In addition to the technical feasibility, the UK cement businesses will need to consider the commercial, operational and practical feasibility of a Net Zero fuel mix. Assuming the technical considerations for a Net Zero fuelled UK cement kiln can be addressed, issues remain for widespread deployment. The principal non-technical issues are outlined in Table 14.1.

Table 14.1: Non-technical considerations for net zero fuel mix deployment.

Subject	Consideration
Risk of carbon leakage	At present the cost of carbon placed on UK cement manufacturing is higher than many other countries, due to the combined effect of the EU Emissions Trading System carbon price and the indirect carbon costs associated with the UK's Carbon Price Support. Circumstantial evidence suggests that the resulting higher UK production costs have at least contributed to the loss of UK cement production to other countries, 'carbon leakage'. UK cement imports have risen from their traditional 10% level prior to the introduction of the Carbon Price Support to the 23% level they are today. Whilst a direct cause and effect is inconclusive the import trend places into context the fragility of domestic production and its ability/inability to absorb the costs associated with the deployment of very costly novel technology. So the first non-technical consideration for the deployment of a Net Zero fuel mix is that the cost model, support framework and associated context should ensure that there is no 'carbon leakage' as a consequence of any new or existing measures that seek to alter the business model for cement manufacture.

Cost drivers; Carbon price, taxes and levies	Economic instruments can be used to encourage changes in behaviour. These can take the form of direct costs e.g. the EU ETS carbon price. Carbon costs, taxes and duties can be used as drivers/levers to push or pull the technology deployment. If cost drivers are being used to drive the industry toward a Net Zero fuel mix then the longevity of those costs, the predictability of the costs level, the cumulative effect of direct costs, taxes and levies and to what extent the costs are mitigated by other measures will be important decision making considerations for deployment.
Availability of support, funding and equalisation measures	If, as expected, the costs of a Net Zero fuelled cement kiln place the adopter plant at a disadvantage to other UK or international plants then there will need to be a mechanism for equalising the competitive position. Equalisation measures for the adopter plant could include, but are not limited to; tax reliefs, State Aid support, grants, loans, free allocation.
Fossil fuel costs	The relative costs of fuels will play a major part in the commercial desirability to fuel switch. Coal is a very good fuel for cement manufacture because of its energy and raw material value where the combustion ash cementitious properties add to the cement chemistry. The prevailing coal price influences the cost effectiveness of investment in new waste derived fuel, waste biomass, biomass or novel fuel technologies.
Net zero power and fuel	The costs of carbon neutral energy sources can be considerable. Renewable electricity switching has assisted in increasing the electricity price in the UK by 166% in 20 years[19]. The future demand for electricity will be considerable, the Committee on Climate Change forecast that the power demand will be 594 TWh in 2050[20] (twice the consumption of 2017) as personal transport, domestic heating and industrial/commercial activities move to greater use of electricity. So in addition to the power demand of plasma burning/microwave technology which could considerably increase the operational costs of production we may therefore assume that similar levels of cost increase could be associated with the provision of low carbon or Net Zero fuels. Imperial College's Sustainable Gas Institute has estimated the retail price of decarbonised hydrogen of 4.9 to 18.4 p/kWh (average 9.3 p/kWh)[21] depending on the decarbonisation technology. For comparison, the price of coal in 2018 was

[19] Department for Business, Energy and Industrial Strategy, "International Industrial Energy Prices", Table 5.3.1, https://www.gov.uk/government/statistical-data-sets/international-industrial-energy-prices
[20] Committee on Climate Change, "Net Zero Technical Report", May 2019, https://www.theccc.org.uk/publication/net-zero-technical-report/
[21] These prices include costs for gas generation, transportation, storage, and assumptions regarding tax, profit and other additional costs. Source Imperial College London, Sustainable Gas Institute, 2017

	1.081 p/kWh excluding Climate Change Levy[22]. The wide price range clearly has an influence over the cost comparison vs decarbonised electricity or natural gas as lower carbon alternatives to coal. This suggests that in order to provide industrial consumers with the certainty that they would need to invest in breakthrough technologies such as hydrogen that it may be beneficial to have some kind of price control on the hydrogen market in its infancy to improve its competitiveness against other fuels.
Marginal abatement costs curve	As this feasibility study has demonstrated the capital and operating costs of a novel Net Zero fuel mix are considerable, as such the likelihood of deployment can only be judged in comparison with other low carbon abatement opportunities and their relative costs. Further work will be necessary to assess where on the Marginal Abatement Cost Curve (MACC) a Net Zero fuel mix sits especially when comparing to carbon capture which has the potential to abate most residual CO_2 in the fuel mix at the same time as addressing raw material CO_2.
UK future energy mix and power demand	There are some significant elements relating to a Net Zero fuel mix that are outside the control of the cement producers. Electricity demand will almost certainly increase for a low carbon cement plant. Carbon capture, plasma or microwave technology will all add to the electricity demand of the cement plant which will potentially increase the cost of production and emphasise indirect CO_2 and renewable costs considerations. A consideration on the future investment of a Net Zero fuel mix will be the UK energy mix and whether or not the UK invests in more hydrogen relative to increased power generation and supply infrastructure.
Low carbon energy source infrastructure	For large scale power demand increases that are forecast by the Committee on Climate Change thought will need to be given to local supply infrastructure for the Net Zero fuel mix adopter plants. This might include hydrogen pipework or additional power supply connections.
Biomass availability and sustainability	The UK Committee on Climate Change have stated[23] that by 2050 there will be supply constraints on biomass, with potential demand likely to exceed sustainable supply. However, there may be opportunities that exist with 'second use biomass' sources in order to supply the needs of UK cement production. If all UK cement plants switched to using 70% biomass, at current production levels over 1.2 million tonnes of biomass would be required. To put this into context, the sector currently uses 68,000 tonnes of 100% biomass

[22] Department for Business, Energy and Industrial Strategy, "Prices of fuels purchased by manufacturing industry", https://www.gov.uk/government/statistical-data-sets/prices-of-fuels-purchased-by-manufacturing-industry

[23] Committee on Climate Change (CCC) "Biomass in a Low-Carbon Economy", November 2018, https://www.theccc.org.uk/publication/biomass-in-a-low-carbon-economy/

	fuels (all wastes). Initial data mining of the Environment Agency's waste records suggests that additional waste biomass could be available to cement producers but physico-chemical quality considerations will be important to consider further. Recovery and recycling practices will influence the cost of waste biomass available for co-processed recovery and recycling in cement kilns. Waste biomass i.e. biomass that is mostly cellulose that has already gone through a 'first use' as packaging or other uses has sustainability credentials that are much better than, for example, biomass fuel crops where planting rates may not allow the sequestration to keep pace with the emissions released during combustion the so called, carbon debt payback period. First use/natural biomass often attracts attention because of its sustainability criteria associated with deforestation, poor biodiversity of land managed for fuels or for timber with fuel biomass as a by-product. As such the adopter plant would need to consider secure sources of the right quality waste biomass to reduce the environmental impact of a Net Zero fuel switch.

15. Conclusions

This feasibility study set out to test the feasibility of using a plasma burner, hydrogen and biomass fuels with additional oxygen with the aim of determining if a combination of fuel switching technologies could move cement manufacture to as close as possible to 100% zero carbon fuels with no impact on cement product quality and without the need to undertake significant modification to existing kiln and calciner configuration. Doing so required an extensive literature search, modelling and expert interpretation.

Here we summarise the conclusions for each of the net zero fuels, the product formulation and the deployment potential.

i. Plasma burners

The literature search draws knowledge from the incineration sector for the use of plasma burners to illustrate the potential to reach high temperature low carbon heat with a renewable power source. It highlights that plasma technology in cement production has not been globally tested or demonstrated. Having discounted the addition of a gasifier unit where the plasma is used to burn biomass with the hot gases fed into the calciner, the modelling demonstrates that it is possible to use plasma torches to apply heat to the calciner with two principle options:

1. Thermal energy from plasma is used to heat air injected via 5 injection locations next to each burner plus one in the riser duct.
2. Heat the tertiary air to provide a hot gas for the calcination reaction

The assessment team have concluded that both of these options are ultimately possible but the direct application to the calciner carries potentially the highest disruption risk to the system. Heating the tertiary air appears to provide a workable first step solution, especially for the demonstration of plasma technology in cement production.

Plasma offers options but further work is necessary to establish the most appropriate intervention point, plasma gas and a deeper understanding of the operational performance and reliability.

The initial cost assessment suggests that a 10% plasma thermal replacement of the total fuel requirement would require capital expenditure in the order of £4.6m to £8.4m with operating costs which may double.

Other costs with the modification will need to be considered. Regulatory costs associated with permit changes and other permissions as well as additional modelling and assessments associated with process safety. Further work is needed to determine the most cost-effective scale of plasma torch use and the detailed CAPEX and OPEX costs.

At a demonstration scale the assessment team have concluded that a 1MW plasma torch is large enough to generate measurable results yet small enough not to be too intrusive in the calciner.

Key areas for further work:

- 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 burners and relationship with calciner meal inlets and degree of calcination assessment
- Kiln riser velocities and aerodynamics

ii. Hydrogen

As identified in the literature study the physical and chemical properties of hydrogen present entirely new challenges to cement production. The assessment team have concluded that hydrogen is most suitable for the main burner of the kiln where its high heat generation can be used to address some of the calorific limitations associated with high levels of biomass. Conversely, a hydrogen flame alone does not suit the formation of clinker due to its high heat, high flame speed, low heat radiation and short flame, the modelling has illustrated that combined use with biomass can help overcome some of the combustion characteristics.

The high flame temperature requires a modification to the kiln burner in order to have a flame similar to coal where the flame is centred in the kiln and doesn't touch the kiln walls. The new burner design would aim to reduce the hot spots and avoid additional creation of thermal NOx.

A full renovation of the burner with associated hydrogen storage and pipework modifications could result in a minimum CAPEX of £350,000.

Given the unique characteristics of hydrogen there will need to be considerable environmental permitting, COMAH consideration, HAZOP, ATEX explosion risk assessment and the resulting additional control measures. It is anticipated that a Phase 3 trial could explore these aspects in more detail.

Key areas for further work:

- Hydrogen delivery to the burner
- Storage and handling / Safety assessments
- Hydrogen compatible prototype burner design
- Empirical assessment of NOx formation
- Empirical observation of flame radiation performance, especially temperature profile at the front of the burner
- Kiln wall hot spot minimisation
- Gas flow rate observations
- Assessment of the potential for kiln start up on hydrogen
- Clinker formation evaluation.
- Whole life CO_2 assessment of hydrogen use in cement manufacture
- Retrofit compatibility assessment

iii. 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. However, a variety of biomass fuels are possible and each have their pros and cons.

In conclusion this presents the following potential problems:

- Higher moisture in the biomass reduces the energy input per tonne of material
- Biomass particle size distribution can be wider than the coal counterfactual
- Potential for increased NOx formation where biomass contains a higher nitrogen content than the coal base case.
- High velocities in front of the main burner when used in conjunction with hydrogen, developing a stronger recirculation zone above the burner.

Oxygen enrichment can be used to offset quality (low CV) characteristics with the biomass but ideally the use of oxygen should be avoided due to its high cost.

The assessment team have assumed a high-quality biomass fuel in the modelling; a fuel that is not currently abundant in the UK. Trials will need to be performed on a bespoke fuel design to assess if the kiln performance can match that of a coal fired baseline when very high levels of biomass are introduced.

The MI-CFD simulations in this study show some particles falling into the raw material bed of the kiln. The particle size distribution of the fuel will need to be optimised to address this.

Key areas for further work:

- Optimised biomass fuel design
- Assessment of availability and supply constraints to widely deploy the biomass fuel
- Main burner 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 and empirical observations any further work in this area should include clinker quality and minerology tests as well as an overall techno-economic assessment of potential scale up.

iv. Overall feasibility conclusions

The assessment team set out to answer whether a ‘net zero’ fuel mix for UK cement production is possible. The ‘problem’ has been researched and experience drawn from parallel industries. In a series of iterative modelling simulations possible solutions have been identified which would give the cement kiln the outline engineering concept for a net zero fuel mix with options for further adaptation, optimisation and flexibility. The assessment team has identified several gaps in the current knowledge and recommended a scope of work to address those gaps. Given the lack of global experience with the novel ‘net zero’ fuel mix the most effective way to fill the knowledge gaps is to carry out further site-specific assessments and physical trials. If successful and fully deployed in a cost-effective manner, the net zero fuel mix could replace the current UK cement industry fuel mix with a saving of 2.15 million tonnes of CO_2 (based on the 2018 industry emissions). To put this into context, if this fuel switching was deployed at all cement plants in the UK, the annual CO_2 saving would be equivalent to the CO_2 emissions from 266,000 households[1]. Full deployment across EU28 would leverage CO_2 saving of around 40 million tonnes CO_2.

16. Phase 3 Project Plan

To address the knowledge gaps identified in the feasibility assessment the following project plan has been identified. The work has been sub-divided into 3 workstreams covering general background and a kiln and calciner trial respectively. There are a number of work packages within each workstream. The three tables below provide information on the key work packages within each of these workstreams.

Workstream A - General items and biomass fuel design

Work package number	Work package name	Brief description of work package, including key tasks
WPA1	Project Management	Overall project management including organising of meetings for project team and steering committee, budgeting, timesheet processing, scheduling of work to ensure the project remains on time, quarterly reporting and writing of the final report.
WPA2	Legal Planning	Identification of areas of the project that could be affected by Competition Law, ensure safeguards are in place to ensure no breaches of competition law and produce contracts for sub-contractor work.

Workstream B – Hydrogen/Biomass Kiln trial

Work package number	Work package name	Brief description of work package, including key tasks
WPB1	Pre-trial planning and assessment	Identification of planning requirements for trial and any planning applications required. Update of environmental permits via variations. Identification of any COMAH requirements and assess if necessary. Conduct HAZOP review. Identify if any ATEX explosivity testing is required. Undertake site design, plant audit/ assessment and base case study to enable comparison of trial results.
WPB2	Design/ Manufacture of a new biomass fuel	Produce a specification for biomass fuel for cement manufacture considering ideal particle size, calorific value and moisture content. Identify fuel suppliers and find best value for money method to produce the fuel required for the trials.
WPB3	Computational Modelling	Construction of plant specific computational grids and modelling to determine ideal conditions/design for the trial.
WPB4	Engineering Design	Using results from WPB2 determine and then design modifications required to the plant for the trial.
WPB5	Pre-trial preparations	Develop methodology for the trial including production of a trial method statement and a standard operating procedure. Produce a schedule for the construction work. Identify and undertake any staff training required. Develop a template trial report.

WPB6	Construction	Undertake any modifications required to existing plant, construct and test trial equipment/plant.
WPB7	Trial and product assessment	Undertake the trial according to the standard operating procedure, assess and report at each stage of the trial and undertake clinker and cement quality assessment.
WPB8	Analysis of results and scale up	Analyse trial results and produce a technical report of trial results. Assess risks and barriers to further scale up of the trials and undertake a cost assessment.
WPB9	Communication/ dissemination	Industry workshops to help to provide feedback and gain input to the trial. Design of material to disseminate results publicly. Follow up discussions with equipment suppliers to show what may be needed in future and assess any further R&D needs.
WPB10	Decommissioning/ deconstruction	Decommissioning of trial equipment and deconstruction.

Workstream C – Plasma/Biomass Calciner trial

Work package number	Work package name	Brief description of work package, including key tasks
WPC1	Pre-trial planning and assessment	Identification of planning requirements for trial and any planning applications required. Update of environmental permits via variations. Identification of any COMAH requirements and assess if necessary. Conduct HAZOP review. Identify if any ATEX explosivity testing is required. Undertake site design, plant audit/ assessment and base case study to enable comparison of trial results.
WPC2	Design/ Manufacture of a new biomass fuel	Produce a specification for biomass fuel for cement manufacture considering ideal particle size, calorific value and moisture content. Identify fuel suppliers and find best value for money method to produce the fuel required for the trials.
WPC3	Computational modelling	Construction of plant specific computational grids and modelling to determine ideal conditions/design for the trial.
WPC4	Engineering design	Using results from WPB2 determine and then design modifications required to the plant for the trial.
WPC5	Pre-trial preparations	Develop methodology for the trial including production of a trial method statement and a

		standard operating procedure. Produce a schedule for the construction work. Identify and undertake any staff training required. Develop a template trial report.
WPC6	Construction	Undertake any modifications required to existing plant, construct and test trial equipment/plant.
WPC7	Trial and product assessment	Undertake the trial according to the standard operating procedure, assess and report at each stage of the trial and undertake clinker and cement quality assessment.
WPC8	Analysis of results and scale up	Analyse trial results and produce a technical report of trial results. Assess risks and barriers to further scale up of the trials and undertake a cost assessment.
WPC9	Communication/ dissemination	Industry workshops to help to provide feedback and gain input to the trial. Design of material to disseminate results publicly. Follow up discussions with equipment suppliers to show what may be needed in future and assess any further R&D needs.
WPC10	Decommissioning/ deconstruction	Decommissioning of trial equipment and deconstruction.