Department for
Business, Energy
& Industrial Strategy

FLY ASH AND BLAST FURNACE SLAG FOR CEMENT MANUFACTURING

BEIS research paper no. 19

September 2017

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Date: 7 April 2017

Project number: SISUK16401

Contents

Executive summary

The cement and concrete industry are heavily dependent on the production of clinker as key ingredient for cement production. The calcination and combustion processes required for this clinker production releases a substantial amount of CO_2. (Partial) substitution of clinker in cement production or (partial) substitution of cement in concrete production reduces these CO_2 emissions, especially if material is used which is seen as a waste of other processes, such as Fly Ash (FA) from coal power plants and Granulated Blast Furnace Slag (GBFS) from the iron and steel sector. These materials are currently used as cement or concrete additions in the UK, thereby reducing CO_2 emissions of the cement and concrete sector.

The sectors providing FA and GBFS are under transition caused by national and global developments, such as the Paris Agreement on Climate Change, the UK Climate Change Act and global over capacity of steel. These changes have a direct impact on the availability of FA and GBFS for the cement and concrete sector. This research has looked into the usage of FA and GBFS in the cement and concrete sector, the expected availability up to 2030 and the impact that more limited availability may have on the price of these materials.

FA is said to increase the strength and durability of concrete, making for a good cement addition. It also makes economic sense, as it is a cheaper material to use than clinker. The main application of FA is addition in cement and concrete production (about 2 Mt per year In the UK). There is a European standard for FA quality, of which the specifications are set in EN450. In the past there has been a substantial overproduction of FA, resulting in landfilling of significant amounts of FA (a few Mt per year in the UK). This has resulted in a significant stockpile (of around 50 Mt) of FA throughout the UK which could be utilised in the future. However, due to agglomeration and reduction of reactivity, older stockpiled FA is not as easily utilised as fresh FA. Based on the expert interviews undertaken, it is expected that only a small share of recovery of this stockpile is feasible. In the last few years, coal consumption in power plants has decreased substantially, resulting in a significant lower fresh FA availability. Currently, there is only a small volume of EN450 quality FA imported to the UK.

Based on a model developed within this research, the future availability of FA is modelled for both the UK and the world. This model is based on expected coal power production and demand in the cement and concrete industry in the UK and in the world. The model outcomes suggest that the availability of FA will continue to decline towards 2022, when all unabated coal power plants are expected to close. The demand will remain steady, resulting in a large shortage in FA availability. This shortage can possibly be compensated for by either recovering stockpiled FA or importing FA from other countries. The recovery of stockpiled FA highly depends on the recoverable amount of FA in stockpiles and is therefore uncertain. At an international scale, it is expected based on global production data of coal, that an oversupply of FA will remain towards 2030, which indicates that import could be a viable solution.

It has been indicated during stakeholder interviews that prices of FA have already increased between 85% and 100% in the period 2012-2016 due to lower FA availability. The future impact on the price of FA depends on the viability of recovery of stockpiled FA or increasing the import. Since both routes will induce extra costs for upgrading or transport, it is possible that prices will further increase. A price increase can also be expected if insufficient FA can be delivered by either, or both, of these routes.

GBFS is slag from the iron production in Basic Oxygen Furnaces. When this slag is actively cooled and ground, GBFS is produced, which can be utilised as a cement or concrete addition. GBFS is said to increase durability of concrete due to an increased setting time, which reduces the possibility of cracks. This increased setting time can be problematic in some applications of concrete. Precise data on the production and consumption of GBFS in the cement and concrete sectors were not readily available, but it is known that over the past years the production was in line with consumption (about 2 Mt per year). However, the UK primary steel production has declined significantly in the past two years, reducing the amount of available slag. It is known that there are rather small (less than 1 Mt in total) stockpiles of GBFS, mainly at the Redcar plant. In 2017 imports of GBFS from China started driven by a lower price and higher reactivity if this type of slag. A disadvantage of Chinese GBFS is its high aluminum content, which makes it necessary to mix it with local (lower aluminum content) GBFS to meet the cement quality standards.

The model developed within this research suggests a small shortage of GBFS in the UK in 2016 and the years after. However, this may change in the future, since UK blast furnaces are approaching their end of life and it is uncertain whether they will be rebuilt or replaced with electric arc furnaces. If they are closed, this will clearly reduce the availability of GBFS. At a global scale, the model indicates that there is an overproduction of GBFS, mainly in China. If the current import route from China or other countries can be extended, future shortages in the UK might be avoided. To address possible future shortages it is important to further develop these opportunities. Based on the expected changes in demand and availability, and the fact that long-distance transport is needed, it is assumed that the price for GBFS will likely increase in the period up to 2030.

This research provides a first indication on the developments in FA and GBFS based on publicly available data and stakeholder interviews. There are many applications of GBFS and FA in different types of cement, which have different technical characteristics and applications. This research does not make a distinction between these applications. Also, substitutes for FA and GBFS are not considered. Sectors besides cement and concrete sector that use GBFS and FA are also excluded from the modelling part of this research. For a more in depth insight in the application and availability of FA and GBFS in the cement and concrete sector in the UK, it is recommended to perform further research into the applicability of different qualities of FA and GBFS in the different types of cement and concrete. Furthermore, we suggest to consider additional potential developments that influence the availability or demand of FA and GBFS, such as: higher shares of clinker substitutes, higher shares of Basic Oxygen Furnace slag turned into GBFS, the effects of efficiency improvements in the iron and steel sector and substitutes for GBFS and FA.

1 Introduction

1.1 Context of this project

The UK Government in close cooperation with the energy-intensive industrial sectors has developed Decarbonisation Roadmaps. To support the implementation of the Roadmaps, action plans are being developed. One of the key actions to reduce the CO¬2-emisisons of the cement industry is to substitute clinker with materials that have comparable (cementitious) properties. Clinker is the main constituent of cement (Type CEM I) and the calcination reaction that occurs during clinker production releases a substantial amount of CO2. The average CO2 intensity in 2014 of the production of a clinker in the UK was 826 kg CO2 per tonne of clinker (Cement Sustainability Institute, 2017).

Granulated Blast Furnace Slag (GBFS) from primary steel making processes and Fly Ash (FA) from coal-fired power plants are currently used as additional cementitious materials. These are materials that can be added to clinker to produce cement or added to cement to produce concrete. Over the last few years about 1.5 to 2 Mt of GBFS (Cement Sustainability Institute, 2017) and 2 Mt of FA (UKQAA, 2015) has been used annually in cement production as an addition to clinker or as an additional filler in (aerated) concrete production. The main drivers for their use are (1) the contribution to the properties of cement and concrete and (2) the reduction of CO2-emissions through the avoidance of clinker production. However, the future availability of both materials in the UK is uncertain, because of different reasons.

In November 2016, the UK Government announced its intention to close all unabated coal-fired power plants by 2025[1]. Comparable actions have been announced, or are being discussed, in other European countries, including Germany and The Netherlands. This will lead to a decreased availability of FA in the UK and Europe in the coming years.

The future availability of GBFS from the UK steel industry is currently uncertain, which is caused by among others the consolidation in the European steel sector, a shift to secondary steel making, overcapacity and imports from China. There have also been recent closures of steel plants in the UK, for example SSI Redcar in 2015.

1.2 Research question

These developments are expected to reduce the availability of FA and GBFS for the UK cement industry. The question is to which degree this will directly impact the ability of the cement sector to reduce its CO2 emissions as laid out in the sectors' decarbonisation roadmap. Therefore, the aim of this project is to undertake a market analysis of the future availability of FA and GBFS and the estimated impact of more limited availability on the price of these materials. This study will answer the following main question:

[1] www.gov.uk/government/consultations/coal-generation-in-great-britain-the-pathway-to-a-low-carbon-future

What is the commercial availability of FA and GBFS in the UK to 2030?

This question is subdivided into the following four questions:

- What relevant research has already been conducted in the UK or EU?
- What is the estimated impact of closure of UK coal-fired power stations and future of the UK's iron & steel industry on the availability of FA and GBFS, based on BEIS modelling, to 2030?
- What is the estimated price impact of more limited availability of FA and GBFS in the UK to 2030?
- What are the available alternative supply routes, such as imports, for FA and GBFS for the UK cement industry?

1.3 Stakeholder involvement

This study was based on a literature review and on interviews with the following stakeholders:

Organisation	Name	Coverage
H&H Celcon	Ed Surman	FA
Mineral Products Association	Diana Casey Pal Chana Richard Leese	FA & GBFS
The Concrete Centre	Guy Thompson	Concrete production
UK Cementitious Slag Makers Association (UKCSMA)	Mike Connell	GBFS
UK Quality Ash Association (UKQAA)	Robert Carroll	FA

1.4 Scope and limitations of this research

This research provides a first indication on this topic based on publicly available data and stakeholder interviews. During the research it became apparent that in some cases there was an inconsistency between some data sources. Further data analysis would be necessary to identify the reason for these differences, however this did not fit into the scope of this research.

There are many applications of GBFS and FA in different types of cement, which have different technical characteristics and applications. This research does not make a distinction between these applications. Also, substitutes for FA and GBFS are not considered. Sectors besides cement and concrete sector that use GBFS and FA are also excluded from the modelling part of this research.

There are also two major data gaps in this research. Publicly available information on price developments of FA and GBFS are not available. Furthermore, many of the stakeholders we contacted were unable to provide this information citing concerns over commercial confidentiality and competition law. There is also limited publicly available data on GBFS production. All assumptions on this and other data gaps are discussed in chapter 3 and 4.

1.5 Outline of the report

The second chapter provides an overview of the use and characteristics of different types of GBFS and FA, and also discusses the drivers and barriers in using these materials. The third chapter presents our analysis of the projected future availability of both materials to 2030 under four different scenarios. In the fourth chapter, we discuss the possible impacts on the price in these scenarios. Finally, chapter five summarises our overall conclusions, including the answers to the main and sub research questions. This chapter also provides our recommendations for further research.

2 FA and GBFS

This chapter describes the application of FA and GBFS in the UK cement industry. For both materials the types, drivers and barriers are discussed.

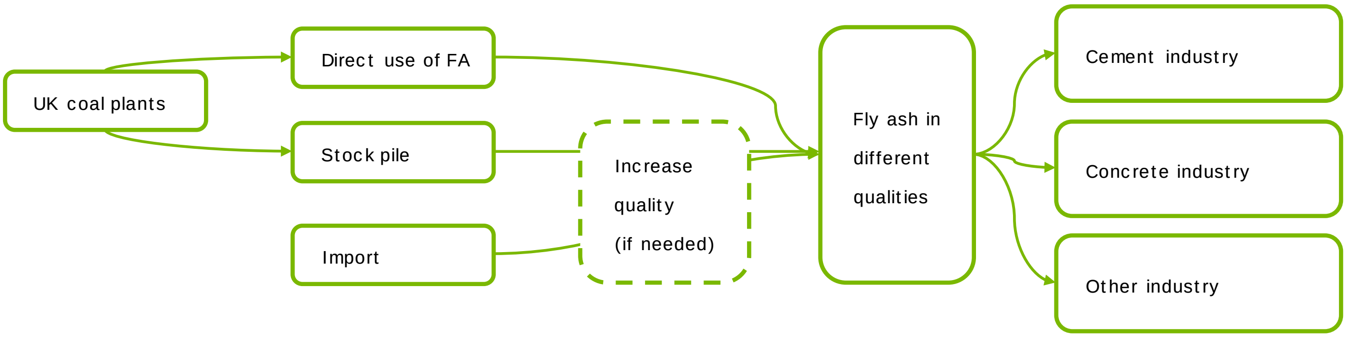
2.1 FA

FAs are one of the residues generated by coal combustion for electricity production and are captured by electrostatic precipitators, or bag filters, before the flue gases are emitted. FAs can either be siliceous or calcareous, depending on the coal type, and consist primarily of glassy spheres with some crystalline matter and unburnt carbon (Heidrich et al., 2013; Moreno et al., 2005).

FA types and their use

FA can originate from different sources and are used in various applications. The value chain of FA in the UK is indicated in Figure 1.

Figure 1: Value chain of FA



There are three different sources of FA: direct use from the coal plant, use of stockpiled FA and imported FA. The table below gives an overview of the different FA sources and their specific characteristics.

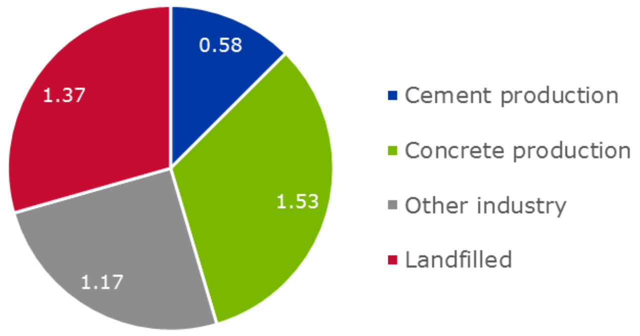
Table 1: Different sources of FA for the UK

Type	Characteristics
Fresh / imported FA	Freshly produced in a dry state. With some processing upgradable to standardised quality material (EN450[2]). This material can be readily used in cement and concrete production.
Stockpiled FA	Overproduction of FA is stockpiled, mainly in landfills across the UK. It can also be used for landscaping or as soil for woodland or agriculture. It is mostly stored in a moist state. During the stockpiling the reactivity reduces due to agglomeration.

[2] BS EN 450-1:2012 FA for concrete. Definition, specifications and conformity criteria

There has been significant amounts of FA produced in the recent years, much more than has been utilised. This has resulted in stockpiling of (moisturised) FA. As most processes require EN450 quality dry material, these stockpiles cannot be recovered very easily but need processing. There is currently an aerated concrete producer working partially on stockpiled FA in the UK[3], but this is not done at a large scale in the cement and concrete sector. Stakeholders mentioned that FA adds strength and durability to concrete, as the concrete is more dense and therefore less prone to decline due to contact with sulphur.

Figure 2: Applications of FA (UKQAA, 2015)



As seen in Figure 2, there are four main applications of FA.

1. **Cement sector - as clinker addition (kiln feed or interground)**: FA is directly added to the kiln as part of the clinker formation.

2. **Concrete sector - as cement addition**: FA can be used in pre-cast and in ready-mix concrete (also known as a Type II addition). The characteristics, quality and application methodologies of the end product can differ based on the quality of the FA, the ratio of FA used and the production process. Therefore, there are different standards for the end product, for example the European Standard EN450. With the selection of dry FA and (electrostatic) processing technologies the FA can be upgraded to meet the standard of EN450. For using FA in the UK concrete sector, the British Standard 8500 is also applicable. This gives specifications for concrete including the percentage of FA allowed in different classifications of concrete. Next to using FA as a cement addition (which is done with EN450 material), it can also be used as inert filler material (also known as a Type I addition).

3. **Other sectors**: Coal FA is also reused at a smaller scale in soil amelioration; the ceramics industry; catalysis; recovery of cenospheres, unburnt carbon and magnetic spheres; and in zeolite synthesis (Yao et al., 2015). These applications are out of scope for this research.

4. **Landfilled**: The FA not utilised in either the cement, concrete or other sectors is landfilled. The FA is moistened to ensure it stays in place. Sometimes a part of the landfilled ash is used as soil for woodland or agriculture or as filling for land reclamation. In these cases, the FA is not easily recoverable for upgrading to material usable in cement or concrete production.

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[3] H&H Celcon

The different types of application of FA in the UK are indicated in Figure 2. In the UK, some FA is added at the cement works, but the majority is added at the concrete works during concrete mixing. This contrasts to continental Europe, where FA is typically added in cement blending.

Drivers and barriers for the use of FA in the cement and concrete sector

There are several drivers and barriers for the use of FA in the cement sector. The most important ones are listed in Table 2.

Table 2: Drivers and barriers for application of FA in the cement sector

FA in the cement and concrete sector.

Drivers	• *Reduction of CO_2 emissions:* FA can reduce the CO_2 emissions if it reduces the amount of clinker used in cement and concrete. • *Reduction in the use of virgin material*: With using FA in cement and concrete the use of virgin raw materials (such as limestone and clay used to produce clinker) are reduced. • *Reduction of waste:* Carbonation of FA reduces the amount of FA usable stockpiles. • *Reduction of costs:* As substitute for clinker and as replacement of cement FA reduces the costs of cement since FA is on average less expensive than clinker and cement. According to the stakeholders interviewed, the use of FA can reduce the amount of clinker per tonne of cement from 850 kg to 600 kg. • *Increased Quality:* FA in concrete contributes to the properties of the hardness of concrete through hydraulic and pozzolanic activity. This is the main driver today.
Barriers	• *Uncertain availability on short term and long term:* There is typically over capacity of FA in the winter and under capacity in the summer; therefore sourcing a consistent supply can be difficult. Future availability is uncertain due to anticipated retirement of unabated coal plants in the UK by 2025 and in Europe. Due to low availability in summer 2016, problems with availability have already caused curtailment in some fresh FA dependent concrete producers. • *Reduced reactivity:* FA is subject to agglomeration[4] if stored outside, which affects its fineness and furthermore reduces its reactivity. This reactivity is essential for the cement process and therefore materials like lime are added to compensate the reduction in reactivity. • *Need for dry material:* The problem with using FA from stockpiles is that to be compatible with cement plant dry free flow material is needed. So the available wet FA needs to be dried.

Sources: Carroll (2015), ECRA (2017), Gomes et al (2016), Renforth et al (201111), Scotash (2016), UKQAA (2016), stakeholder interviews.

2.2 GBFS

GBFS is a by-product of the iron and steel making industry, more precisely the reduction of iron ore in a blast furnace. These steel slags are widely used as aggregates for road construction (Wei et al., 2014); railroad grade ballast (Banks et al., 2006) earthworks; armour

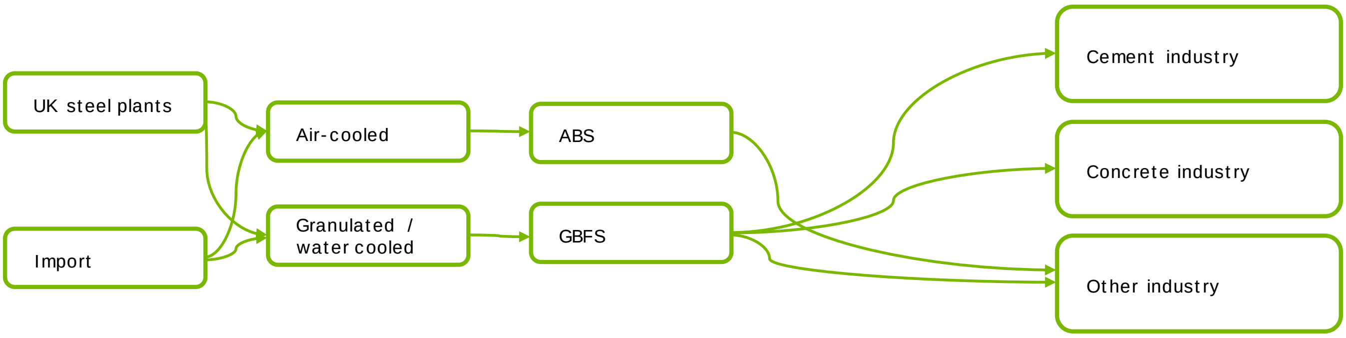
[4] When stockpiled the FA tends to agglomerate into bigger pieces. This reduces the surface area and thereby the reactivity of the material.

stones for hydraulic structures (e.g. stabilisation of shores); phosphate fertiliser (Motz and Geiseler, 2001); and as an additive to cement clinker production (Tsakiridis et al., 2008).

Slag types and their use

There are different types of steel slags, but GBFS is the only type that can be used as clinker substitute. GBFS is formed during the production of hot metal by thermo-chemical reduction of iron ore in a blast furnace. The amount of slag produced varies per plant depending on the composition of raw materials and the production process of iron and steel. For example, slag is not formed when electric arcs furnaces are used. According to the stakeholders interviewed there are also regional differences, based on the efficiency of the iron making process. Around 300 kg slag per tonne iron is formed in the UK, while in Japan this is 200 kg tonne slag per tonne iron. When the slag is tapped from the furnace, it can be treated in several ways (see Figure 4):

Figure 4: Value chain of slag



GBFS can be added to cement production, or to partially replace cement in concrete production. In the UK the utilisation of GBFS is mostly in concrete production but some is added at the cement plant. Application in concrete can range from 30% to 70% (lower range is typically pre-cast concrete and the higher range typically ready-mix concrete). This contrasts to continental Europe, where more GBFS is applied in the cement production instead of the concrete production. Setting times of concrete generally increase due to GBFS addition, which also impacts the application of the concrete (to processes where a longer setting time is not problematic). The stakeholders we consulted also mentioned that due to the longer setting time, the possibility of cracks decreased, increasing durability of the concrete. The industry has standards for application of GBFS in certain types of concrete, which results in concrete with predefined characteristics. High quality GBFS as applied in the cement and concrete sectors have hardly any competitive application in other products, processes or industries.

- **Air-cooled GBFS**: The slag is placed directly into pits or ground bays where it air-cools slowly. By this process the slag will form a crystalline structured mass called air-cooled GBFS (ABS). This material can be used as a construction aggregate.

- **Granulated GBFS**: When the slag is directed into a granulator and is rapidly cooled with large amounts of water it will form a glassy/amorphous granular called granulated GBFS, which can be used as an aggregate for e.g. road construction and can also be mixed with cement clinker and calcium sulphate to use as binder for cement, concrete, mortar and grout.

Table 3: Drivers and barriers for the use in the cement and concrete sector

GBFS in the cement and concrete sector

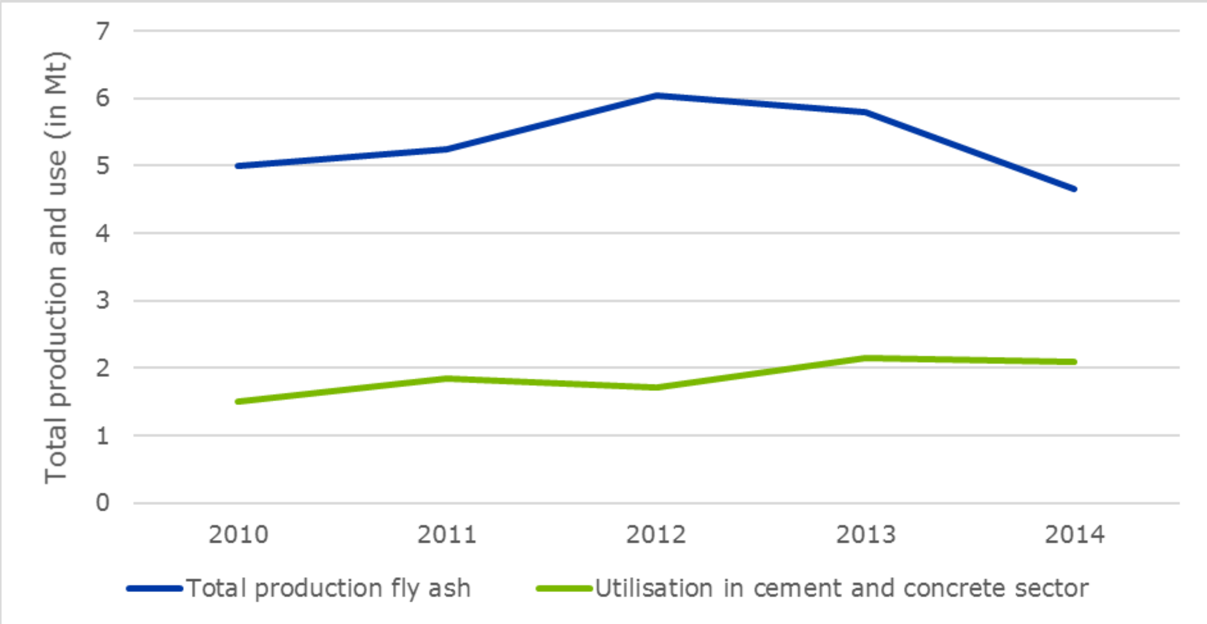
Drivers	• *Reduction of CO_2 emissions:* GBFS can reduce the CO_2 emissions if it reduces the amount of clinker used in cement and concrete. • *Reduction of landfill:* Through the successful utilisation of GBFS products, the need for landfilling is avoided. • *Reduction of costs:* Using GBFS is cheaper than using virgin products like clinker (clinker burning is expensive). • *Increased Quality:* Cements containing GBFS usually exhibit a lower early strength if ground to the same fineness and a lower heat of hydration. These cements often show higher long-term strength and particularly improved chemical resistance.
Barriers	• *Uncertain availability on short term and long term:* Availability depends among other things on the level of pig iron production and competitive situation concerning GBFS use. • *Standards and regulations:* Cement with GBFS has a different standard than cement without GBFS. • *Technical performance of concrete produced with cements containing GBFS is different:* GBFS can have a higher strength and durability, but the setting time is typically longer which makes them not suitable for all applications, which is regulated by standards. According to these standards, cement containing GBFS cannot replace Portland on a one-to-one basis.

Sources: ECRA (2017), EUROSLAG (expert interviews), Gomes et al (2016), MPA (2017), Renforth et al (2011), Scotash (2016), Piatak et al (2015), Wang et al (2016), stakeholder interviews.

3 Availability of FA and GBFS

3.1 Historic availability of FA

Figure 5: Historic availability of FA in the UK (UKQAA, 2015)



The historical production of FA in coal power plants and the utilisation of this production in the cement and concrete sector in the UK is shown in Figure 5. These figure includes the utilisation in the cement manufacture, Type II additions to concrete (as cementitious material) and utilisations in concrete and aerated concrete blocks. Type I additions (as inert filler material) are not included, as they are a substitution for other inert filler material and not for clinker or cement. In addition, Type I application of fly ash in concrete is not common, only constituting between 0.1% and 2% of total fly ash utilisation in the period 2010-2014.

The figure clearly shows that the production of FA exceeded the utilisation in the cement sector by a factor of 2.5 to 3.5 during the period 2010-2014. This can partly be contributed to utilisation in other industries (mainly land reclamation), but a large portion is landfilled (up to 3 Mt cumulative in the shown period). This process of overproduction has continued for 20 to 30 years, resulting in a large stockpile of FA. These stockpiles are estimated to be in the order of 50 Mt[5]. Currently, small volumes of FA are imported. In 2015 and 2016 the amount of coal consumed by power plants in the UK decreased sharply, from 38 Mt in 2014 to 12 Mt in 2016. This directly impacts the FA production, as will be shown in the demand-supply model in chapter 4. This also means that the amount of FA landfilled in 2016 is expected to be considerably less than in 2014. No data are available yet to back this assumption.

[5] www.ukqaa.org.uk/wp-content/uploads/2016/01/UKQAA-Ash-Availability-Report-Jan-2016.pdf

3.2 Future availability of FA

In November 2016, the UK Government announced its intention to close all unabated coal-fired power plants by 2025[6]. Comparable actions have been announced, or are being discussed, in other European countries, including Germany and The Netherlands. This will lead to a decreased availability of FA in the UK and Europe.

Coal power in the UK is also facing problems due to low electricity prices and the introduction of more renewable energy sources with lower marginal costs. This can be seen in the sharp decrease in coal consumption in power plants in the period 2014-2016, as discussed above. It is not likely that this trend will be reversed, as more renewable resources will be incorporated in the electricity grid.

The combination of closing of unabated coal-fired power plants and the more difficult circumstances of coal power plants on the electricity market will greatly reduce the availability of fresh FA in the near future and possibly even stop if all coal power plants are closed.

3.3 New sources of FA

There are two ways to compensate the decrease in fresh FA:

- According to the UKQAA a reported 50 Mt of FA is stockpiled. FA recovery is possible due to technological development. This is already done in France and Germany. In the UK, the UKQAA in partnership with the Concrete Technology Unit and the University of Dundee is currently investigating whether stockpiled FA could be recovered and used in concrete and cement. This research includes the development of a process route to transform stockpiled ash into FA which meets the specifications of EN450 (Dundee, 2014). At the same time […] is already using lower quality FA from UK stockpiles, which is sufficient for their aircrete product[7].
- EN450 quality FA can also be imported since it is standardised material
- Change engineering specifications so that cement/concrete with fly ash is only used to meet technical performance requirements.

There are, however, limitations to using FA from stockpiles and import.

Limitations for import:

- Price is likely to go up due to the transport and processing costs. Significant quantities of FA is available in China, but coal plants are typically located far from the sea, so transporting the FA is more difficult.
- Quality of FA is influenced by the production process and the storage of FA.
- Dependency on other countries like China and India.

[6] www.gov.uk/government/consultations/coal-generation-in-great-britain-the-pathway-to-a-low-carbon-future (visited on 22 March 2017)

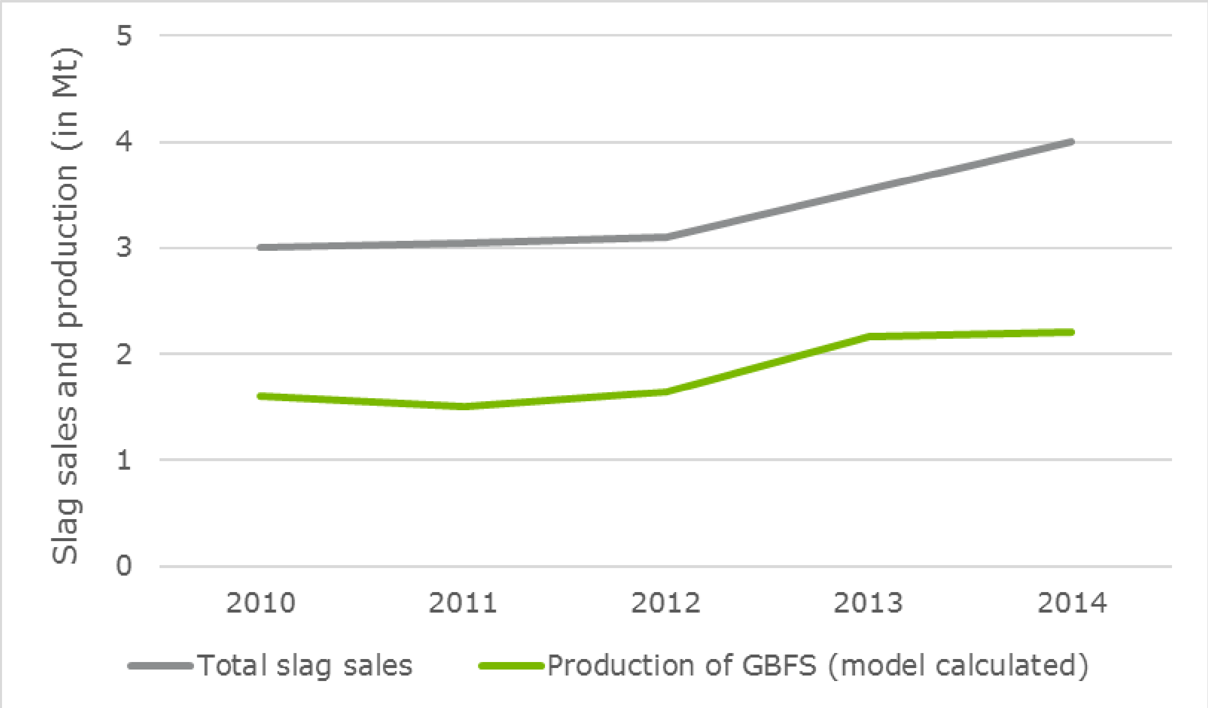
[7] www.hhcelcon.co.uk/ Our understanding is that other aircrete producers in the UK currently are reliant on using fresh FA.

Limitations for stockpiles:

- Quality of stockpiles differ because of the decreased reactivity of stockpiled FA which needs to be compensated with adding other binding materials (e.g. lime) which will increase costs.
- There are availability constraints since some stockpiled material has already been built over or has been returned to other uses (e.g. woodland, nature reserves or agriculture). Companies need permission to access these sources.
- Recovery needs energy use for the product to dry the FA (stockpiles are wet).

3.4 Historic availability of GBFS

Figure 6: Historic availability of GBFS in the UK (MPA, 2016; Cement Sustainability Institute, 2017)



There are less specific statistics on GBFS production and consumption available compared to FA. Although the total slag sales in the past years were available, this includes slags other than GBFS, such as Air-cooled blast furnace slag (ABS) and electric arc furnace carbon steel slag (EAF). These other types of slag are used in sectors other than the cement and concrete sector. Based on modelling, which is further discussed in chapter 4, the total GBFS production in the period 2010-2014 was estimated. Nearly all produced GBFS is used in the cement and concrete sector. A small volume is temporarily stockpiled, or otherwise used by other sectors (see section 2.2). As with the coal power plants, the iron and steel sector has seen sharp declines in the past 2 years in the UK, from 12 Mt crude steel production in 2014 to 8 Mt production in 2016. This directly impacts the availability of slag, as most steel is produced with iron and GBFS is an iron production waste stream.

3.5 Future availability of GBFS

The future availability of GBFS from the UK steel industry depends on the UK iron and steel production. In the last two years this has decreased quite sharply. Two main steel producing facilities in the UK remain (Port Talbot and Scunthorpe). Our understanding is that the blast furnaces at these facilities are currently running at half of total capacity. The industry development to 2030 is unclear; facilities may close or potentially undergo replacement with more modern Electric Arc Furnaces, which do not produce GBFS. This makes the production of GBFS in the future currently uncertain. If the blast furnaces are operating at full capacity, the GBFS production could double, if some of the blast furnaces are closed and others keep producing at half capacity, the national GBFS production could further decline.

This trend is also influenced by a shift to secondary steel making and international competition, mainly from China, which currently produces about half of the worlds steel. These factors will directly influence the iron and steel production in the UK and therefore the national GBFS production.

3.6 New sources of GBFS

The most promising way to compensate for the expected decrease of GBFS, is through import. Slag is already imported from Europe to the UK in relatively small quantities (mainly from France, Germany and The Netherlands)[8] to Purfleet on the Thames and Glasgow (KG5 Dock). Furthermore, in February 2017 the Redcar grinding plant has reopened and is receiving slag from China. In time this plant will receive up to 500 Mt of slag. It is evident that long range import of slag is therefore economically feasible. We also understand that slag is also imported in small quantities from Europe by companies for self-supply, even when it is not needed, to ensure that supply lines are kept open.

It is expected that to 2030 imported GBFS will still be available since China has significant surplus of GBFS. Other places in the world also have availability. There are also potentially advantages in the quality of imported GBFS. For example, Chinese GBFS has a higher reactivity than European GBFS, due to higher temperatures and pressure during the production process. However, a disadvantage is that Chinese GBFS has a relatively high aluminium content and has to be mixed with lower aluminium content UK GBFS to ensure that the end-use applications meet applicable standards.

A reliance on imports also introduces a security of supply risk. For example, China may in future look to utilise GBFS for its domestic cement industry, or could use its market position to increase price. At this moment to prevent dependency of China also import routes with Europe mainland are kept open.

Stored GBFS deteriorates in the longer term, it will form lumps and become less reactive.

[8] Import

4 Modelling the availability of FA and GBFS

Four scenarios were developed to model the impact of anticipated developments in the power sector and the iron and steel sector on the availability of FA and GBFS to 2030.

In this chapter, our approach to modelling the availability of FA and GBFS is presented. The aim is to evaluate when the UK production of FA and GBFS can no longer supply the domestic demand for these materials, and how other routes can meet this demand. As a starting point, we assessed the anticipated supply and demand (cement) sector developments. Next, we assessed alternative options to supply the demand, namely stockpiles and imports. These supply options introduce a security of supply risk due to unknowns about recoverability and use of stockpile materials and also the dependency on other countries for FA and GBFS supply. It also contains a degree of carbon leakage due to (for example) increased transport.

This will lead to two scenarios for FA and two scenarios for GBFS, leading to a total of four scenarios (as indicated in Figure 7).

Figure 7: Four scenarios for FA and GBFS

4.1 Model overview

The model estimates the future supply and demand of FA and GBFS based on historical data and assumed sector growth rates. The model characteristics are:

- **FA and GBFS consumption**: Consumption of FA and GBFS is based on historical consumption in the cement and concrete industry, where the cement industry is used as a proxy for total consumption in both industries (due to lack of data for concrete production). The growth rate of the cement industry in the UK is based on the middle scenario of the cement roadmap (0% per year). The expected growth rate of the world cement industry is based on the IEA Energy Technology Perspective report of 2015.[9]

- **FA and GBFS production**: Production of FA correlates with coal consumption in power plants. GBFS production correlates with steel production, which is used as a proxy for iron production which produces GBFS as a by-product. This is based on the assumption that nearly all iron will be used in the steel sector, and almost all steel is produced using iron. The growth rate of the UK steel sector is based on the yearly growth in the iron and steel roadmap (3% per year), while the growth in the world steel sector is based on the IEA Energy Technology Perspective report of 2015.

- **Correction for high utilisation of FA and GBFS in the UK**: Our understanding is that the use of FA and GBFS in the cement and concrete industry is likely to be relatively high in the UK compared to the rest of the world. Using the average amount of FA and GBFS in cement and concrete would be an overestimation of the use of these minerals in cement and concrete production in the world (because of the lower utilisation of these minerals). To address this, a correction factor has been introduced based on the amount of recycled materials in aggregates in the UK compared to the average of recycled materials in aggregates in the EU. This correction factor has been applied to estimate the use of FA and GBFS in cement and concrete production in the world, based on the use in the UK. The impact of this factor on the global demand is very high, as it directly correlates between cement and concrete production and the FA and GBFS consumption. Therefore the model is very sensitive to this correction factor.

- **Stockpiles of FA and GBFS**: The total stockpile of FA has been assumed to be 50 Mt, although only a small portion is likely to be recoverable and meet the EN450 standard which is needed for cement and some concrete production. Although there are some GBFS stockpiles in the UK, these stockpiles are not very large (expected to be around 0.6 Mt, mainly at the Redcar processing plant) and cannot compensate for a shortage in production for a significant period of time.

4.2 Scenario 1: Fresh FA availability and consumption of UK produced FA

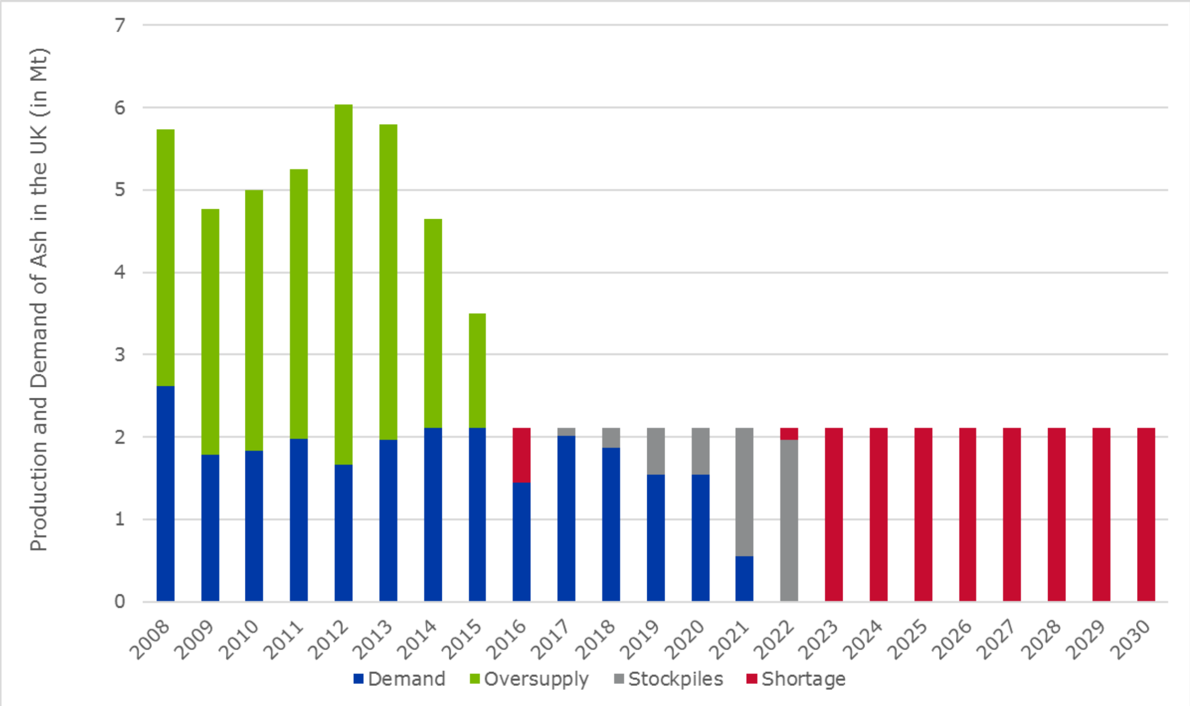
Methodology

- **FA production in the UK**: Based on historical data of FA production (2010-2014) and coal consumed in UK power plants (2008-2014). Future production is based on expected coal consumption until 2030 using the ‘Central scenario’ in BEIS’s future coal generation impact assessment (BEIS, 2016). This foresees a phase out of all unabated coal power plant capacity by 2022. The model assumes that at that time no abated coal power plants are still running.

- **FA consumption in the UK**: Based on historical FA consumption figures in cement and concrete industry and cement production figures and expected future cement production in the BEIS roadmaps (as proxy for cement and concrete production).

[9] The Roadmap cement takes an increase of cementitious substitution into account towards 2050. As the impact of these figures on the FA and GBFS application in the concrete sector are unclear, this is not taken into account in the model. The application of cementitious substitution in the roadmap is 8% in 2015 and is expected to grow to about 8.6% in 2030.

- **Stockpile availability**: Currently there is not any indication of the share of ash stockpiles which can be utilised for cement and concrete production. It is known that a large share cannot be utilised due to existing use (e.g. landscaping) and deterioration of the material (e.g. lower reactivity). In this scenario it is therefore set at a conservative 10%.



Conclusions

Based on the model outcomes, we see that in 2016 there was already a shortage of FA due to a sharp decline in coal consumption in power plants. This conclusion is supported by the indication that some FA dependent industries had to curtail production during the summer of 2016.

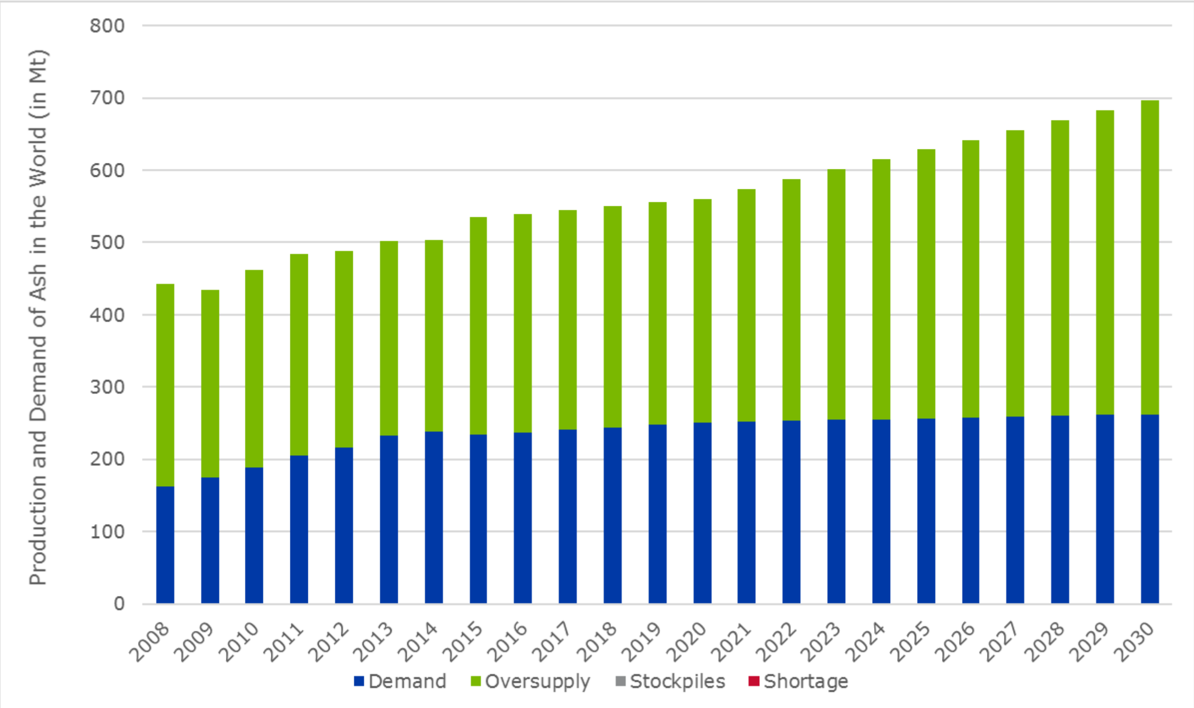
If the stockpiles can be easily recovered (which is currently being researched) in the coming years and a total of 10% could be recovered, the stockpiles can be used to supply the expected reduction in fresh FA up to 2022. If the stockpiles have to cover national demand up to 2030, then a total of 44% of the stockpiled material would have to be recoverable and usable in the cement and concrete industry. This, however, is not seen as likely based on the stakeholder interviews.

Overall, the FA production is already insufficient for the consumption in the cement and concrete industry, and this does not take into account the demand of other applications such as land reclamation. As the current planning and international developments foresee a (partial) closure of current coal power plant, it is likely that this shortage will increase in the short term, which can also be seen in the model outcomes.

4.3 Scenario 2: Fresh FA availability and consumption in the world

Methodology

- **FA production in the World**: World coal consumption in power plants is based on historical data between 2007-2014. FA production is based on this coal consumption and the average FA production per Mt coal in UK power plants. Future coal consumption is based on IEA World Energy Outlook 2016.
- **FA consumption in the World**: This is based on historical FA consumption figures in cement and concrete industry in the UK. As it is expected that FA application is relatively high in the UK compared to the rest of the world, this is corrected by a factor of 4, based on general data on recycled materials in aggregates use in the UK versus the rest of Europe (as proxy for the world). Future demand is based on expected future cement production from the IEA Energy Technology Perspective report of 2015 (as a proxy for cement and concrete industry).
- **Stockpile availability**: While it is likely that internationally significant stockpiles exist, there are not taken into account in the modelling. It is assumed that if there is necessity of obtaining FA from stockpiles worldwide, this will hinder the import towards the UK (as countries will try to use their stockpiles for their national demand first).



Conclusions

Based on the model outcomes, it is evident that historically there has been a very high oversupply of FA, and as global coal consumption in power plants is expected to grow faster than cement and concrete production to 2030, this oversupply is expected to grow. This oversupply could also be used for other applications, such as soil stabilisation and land reclamation.

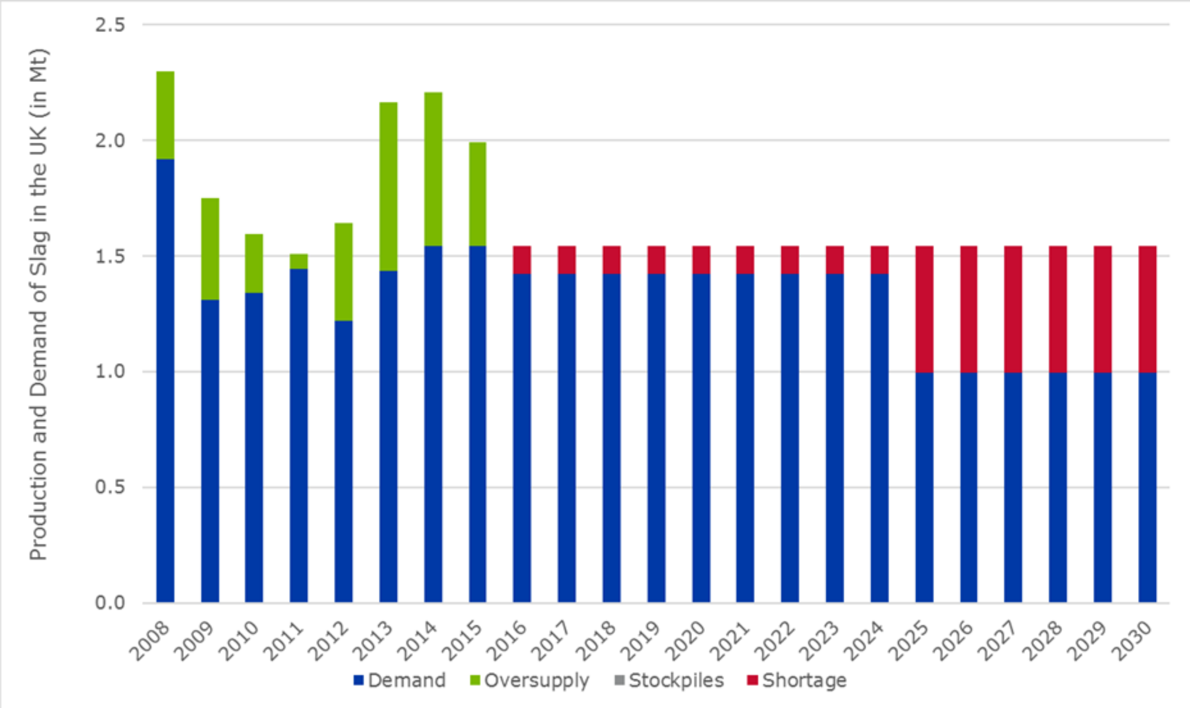
A small portion of this global oversupply could be used to address the shortage in the UK. Although the import routes are not yet developed (there is very little import of FA in the UK), based on the model outcomes this is not restricted by shortage in the world. Import of FA could thus serve as an important alternative supply option to compensate for lower future production in the UK.

International stockpiles are not taken into account, but based on the model outcomes it is likely that large stockpiles exist worldwide. To what extent these stockpiles are recoverable for cement and concrete production is unknown (as it is with the UK).

4.4 Scenario 3: Granulated GBFS availability and consumption within the UK

Methodology

- **GBFS production in the UK**: The production of GBFS in the UK is based on historical data of Basic Oxygen Furnaces (BOF) steel production (as proxy for the iron production, which is the process that produces GBFS). This steel production is translated to GBFS production through 300 kg slag production per tonne of iron, 90% iron in steel, a small portion of scrap-based steel making (90%) and the efficiency of slag to GBFS production (90%). The future expected steel production in the UK is based on the growth rate assumed in the BEIS roadmap (0% annual growth). The UK’s blast furnaces are at the end of their lifespan in the coming years. They can be either rebuilt, closed or undergo investment, for example to deploy Electric Arc Furnace technology (which does not produce GBFS). To indicate the potential impact of plant closure, the model assumes a 30% reduction in the UK steel production in 2025. This is not necessarily expected, but is intended to provide an insight into the possible shortages arising from such a closure (or deployment of EAF).
- **GBFS consumption in the UK**: The historical data for GBFS consumption in the cement and concrete sector is based on the Getting the Numbers Right (GNR) database of the Cement Sustainability Initiative. It is possible that this database does not include all GBFS in cement and concrete, as it only takes into account GBFS usage in cement and as cement substitute, but not for example as filler material in concrete. It is assumed this is a rather small amount, but this is a sensitivity within the model. Future consumption is based on the expected growth of the cement industry from the BEIS roadmap (as a proxy for the cement and concrete industry).
- **Stockpile availability**: There are small stockpiles available throughout the year, but these are not used for stockpiling of large quantities of GBFS. Therefore the stockpiles are neglected within the model.



Conclusions

The model shows a substantial oversupply in the period 2012 to 2015. This is not seen in practice by the stakeholders we consulted, as there are no major alternative uses or stockpiling in the last years. This could be due to the fact that the data used for the consumption calculation (GNR data) are incomplete. Data availability in the slag sector is limited and within the short timeline of this study it was not possible to verify this data. The production data were verified with the stakeholders and are seen to be representative. The effect on the model is that it could be that consumption is significantly higher, resulting in larger shortages in the coming years.

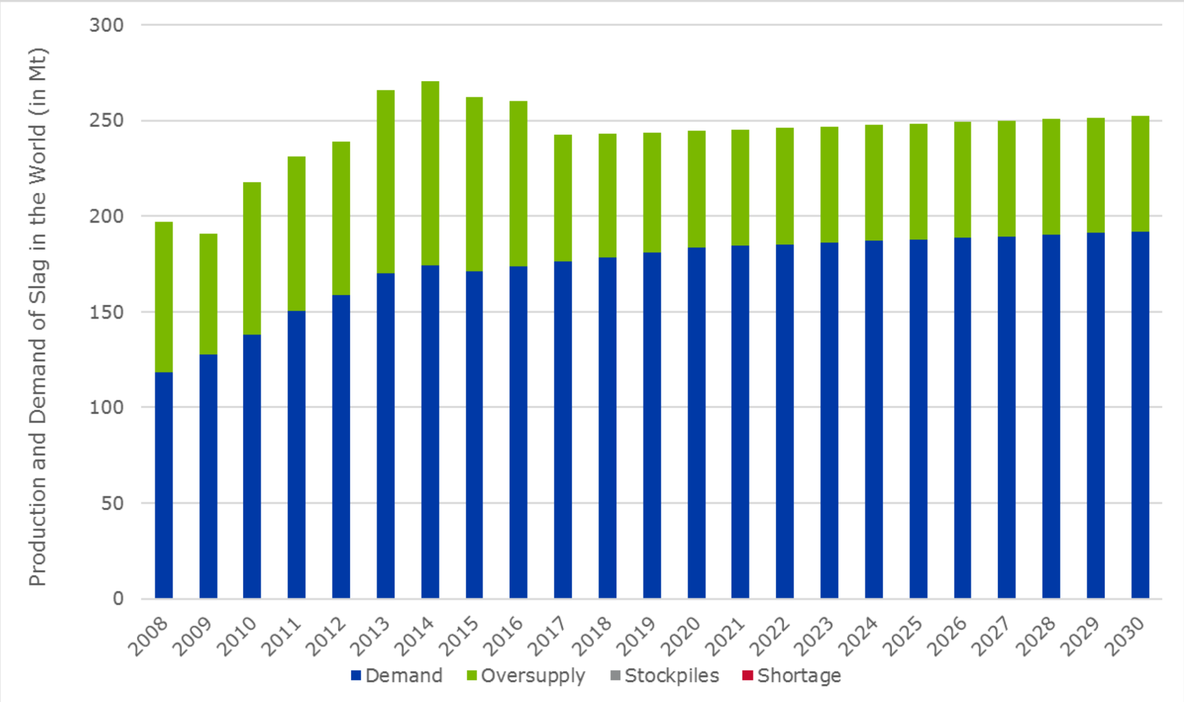
Based on the model outcomes, it is expected that there is a small shortage of GBFS at a national level. This is currently being addressed by imports from China which commenced in February 2017. The shortage increases significantly in 2025 due to the assumption of closing blast furnaces, and is therefore a direct consequence of this input (and not necessarily expected). Closing down of furnaces will directly result in higher shortages in the future. However, currently the blast furnaces are running at half of their full capacity. As such, should the market conditions in the steel sector improve in the future, this shortage can be easily compensated by more GBFS production (as currently the steel production capacity is already in place, but not utilised).

The model outcomes suggest it is likely that shortages in GBFS will be seen in the short term, but this is very dependent on the future developments in blast furnace utilisation which is still largely unknown at this time.

4.5 Scenario 4: Granulated GBFS availability and consumption in the world

Methodology

- **GBFS production in the world**: The production of GBFS in the world is based on the same principle as the production of GBFS in the UK, namely BOF steelmaking as a proxy for the GBFS production. The total BOF is corrected for slag production, iron consumption within the process and efficiency of GBFS, in the same way as in the UK.
- **GBFS consumption in the world**: In line with the GBFS production, the GBFS consumption is also calculated in the same way as in the UK. However, due to an expected lower consumption per tonne of cement and concrete, a correction factor is introduced (as discussed in the world FA scenario). This correction factor is based on the recycled material use in aggregates in the UK compared to the average of the recycled material use in aggregates in the EU. Based on this data, a correction factor of 4 is used, which indicates that the world consumes per tonne cement and concrete 4 times less GBFS compared to the UK. This has a high impact on the model results. The cement production is used as proxy for the cement and concrete industry and the growth of cement industry is based on the IEA Energy Technology Perspective 2015.
- **Stockpile availability**: Based on experiences in the UK, stockpiles of GBFS are neglected within this model.



Conclusions

The model shows a substantial oversupply in the past and future years. This would indicate other usage sectors or stockpiles of GBFS. The expert interviews indicated the existence of oversupply of GBFS especially in China, but it is unclear what is currently done with this oversupply (other usage or stockpiling). It is possible that these stockpiles currently exist, but this requires further investigation.

However, the model outcome suggest a year by year oversupply of GBFS, so it may not be necessary to utilise these stockpiles, but just utilise fresh production. The overproduction every year is enough to address shortages in the UK market, so import would be a viable solution (solely based on overproduction in other countries) to shortages on the UK market. There have been recently some imports from China, so this also seems to be economically viable. However, the oversupply is very dependent on the correction factor used (as discussed above) and could easily shift around if China start utilising the GBFS in the amounts per tonne cement and concrete which the UK is currently doing.

5 Qualitative analysis of the price impact

This chapter discusses the price impact of the developments in FA and GBFS. Publicly available information on price developments of FA and GBFS are not available, and furthermore many of the stakeholders we contacted were unable to provide this information citing concerns over commercial confidentiality and competition law. Online the current prices in some regions (mainly China) can be found, but these are not readily comparable since they cover FA and GBFS in different qualities and quantities from different locations outside the UK.

According to the consulted stakeholders, supply of both FA and GBFS is typically agreed on a bilateral basis on short-term contracts. One of the interviewees indicated that they aim to secure long term supply contracts with power supply stations for FA (min. 3 years), but that the contracts include an exit clause to accommodate for limited availability (i.e. should the power station not run). FA is sold directly or through third parties (ash merchants).

Our understanding is that there are three main factors that can influence the price of FA and GBFS:

- Change in demand
- Change in availability
- Transport costs

There are also specific factors that can influence the price of FA specifically:

- Going from dry ash to stockpiled (wet) ash
- Use of less reactive stockpiled FA

According to one of the interviewed stakeholders, the costs for FA have increased by 85-100% over the past five years (2012-2016). Current prices for FA range from 5 GBP (low-quality FA) to 45 GBP (EN 450 quality FA) per tonne (excluding transport). The price range depends on the quality of FA and the volume that is purchased.

5.1 Change in demand and availability

As discussed in chapter 4, there is no domestic availability expected in 2030, as it is assumed that no coal-fired power plants will be in operation in the UK. For GBFS the availability will largely depend on the developments in the steel sector and the utilisation and renewal of blast furnaces in particular. The modelling suggests that currently the demand is circa 10% higher than the UK availability. This shortage will increase if blast furnaces are closed or renewed to Electric Arc Furnaces (which do not produce GBFS). According to simple market economics, this growing gap between demand and availability will result in a price increase. However, this will also lead to exploring other options to reduce the supply shortage, including the use of imports or stockpiled material.

5.2 Cost of transport

Imports can be an interesting alternative for both domestic FA and GBFS. However, this will add transport costs, which can potentially (partly) be compensated by buying FA and GBFS in markets that have FA and GBFS available at lower costs.

During the interviews with stakeholders it was mentioned that the cost of transport for GBFS are relatively low, while for FA it was mentioned that the costs are significant. This makes sense as FA is more voluminous than GBFS (FA has a density of 860 kg/m^3, and GBFS of 2,400 kg/m^3). Transporting one tonne of FA requires 2.5-3 times as large a volume than GBFS. Hence, the higher transport costs.

GBFS is already imported from China to meet in the demand for the Redcar slag grinding plant. Although no price details are known, this indicates that it is apparently cost-effective to transport GBFS over long distances.

5.3 Specific factors for FA

Using FA from stockpiles has two consequences that will influence the price. Firstly, FA in stockpiles is wet and requires drying before it can be used in the cement and concrete sector. The drying process needs energy. An option is to use waste heat from the cement industry (if available) or other industries with waste heat. Secondly, the reactivity of FA in stockpiles decreases over the years. This reduced reactivity has an implication for the use of FA in cement and concrete. Currently, this is compensated with the addition of lime, which is more expensive than FA.

Both factors can increase the process costs and therefore will likely increase the price of FA (drying process) and the end-product (compensation for reactivity).

5.4 Expected price developments

Based on the change in demand, change in availability, and costs of transport that influence prices it is assumed that the price for FA and GBFS will be likely to increase on the short and long term. For FA also the factors for extra energy use and compensation for reactivity can increase the price.

6 Conclusions & Recommendations

FA and GBFS are commonly used in different stages of the production processes of cement and concrete. They provide multiple purposes in the process of cement and concrete making, either as clinker substitute in cement, cement substitute in concrete or as filler material in concrete. The markets in the UK are mature (developed), as significant amounts of GBFS and FA production has been sold to cement and concrete manufacturers over several years. The use of both FA and GBFS is standardised within the UK (and the EU), which is also an indication of the common application of these substitutes. The market is already looking into alternatives in case that availability in the UK is decreasing.

6.1 Findings on FA

In the past couple of years, there has been significant overproduction of FA in the UK. Although there are some other applications than utilisation in the cement and concrete industry, a significant share has been landfilled. This has resulted in large stockpiles of FA within the UK, which have been built up over the last 20 to 30 years and are about 10 times the yearly production of 2014. Not all FA can be utilised, as older FA tends to agglomerate and lose reactivity. Also it has been used for soil stabilisation or for land reclamation, which makes extraction difficult. In these cases the FA is stored moist, while for most applications it needs to be dry and of standardised quality (EN450).

FA is said to increase strength and durability of the concrete, which makes it harder to replace with other materials. If used as a clinker or cement substitute, it also reduces the CO2 emissions associated with the production of clinker. Furthermore, as it is cheaper than using clinker or cement it also reduces costs. In 2016 the availability of FA was constrained due to a sharp decline in coal consumption in power plants. It has been mentioned that some manufacturers had to curtail their production due to a lack of fresh FA availability. Only a small portion of standardised EN450 FA is currently imported to the UK. However, due to the overproduction in the UK in the recent years, importing FA is yet not common practice.

Based on the outcomes of our modelling, it is expected that domestic FA availability will further decline in the coming years due to closure (or low utilisation) of coal fired power plants. This indicates that the shortage seen in 2016 will continue and increase towards 2022, when no more fresh FA will be produced if all coal power plants are closed down in that year (based on BEIS' Central Scenario'). There are two main methods of compensating for this shortage: either by recovering stockpiled ash or by importing from other countries. There is currently some recovery of stockpiled FA in Germany and France. Within the UK, the University of Dundee is working together with the UKQAA to look into the possibilities of recovering quality FA from UK stockpiles. If the outcomes of this research would be successful, a share of stockpiled FA could be utilised in the coming years to compensate for the lower FA production. However, the stakeholder consulted indicated that it is unlikely that a large share of these stockpiles will be recoverable for cement and concrete production due to the problems with agglomeration and reduced reactivity of stockpiled ash.

The outcomes of the modelling suggest that it is possible to import the necessary amounts of FA from other countries. However, there are potential barriers that may limit the scope for imports. Although China is a major producer of FA, its coal fired power plants are located far from the coast, which makes transportation more difficult and expensive. (Fly ash has a very low density.) Furthermore, continental Europe will likely face the same availability issues in the near future if coal plants are phased out as planned and will therefore compete with the UK for FA. As in the long term importing FA is likely to be the only supply source that will be able to provide a steady stream of FA, it is important to develop FA import routes as a priority.

The price of FA is likely to be influenced by the change in demand, change in availability, and costs of transport for imported FA and extra energy use and compensation for reactivity for stockpiled FA. These factors caused according to one of the interviewed experts that the costs for FA have increased by 85-100% over the last five years (2012-2016). According to the interviewed expert the current prices of FA are between 5 GBP (low-quality FA) to 45 GBP (EN450 quality FA) per tonne. The price range is dependent on the quality of FA and also the volume purchased. Based on the above-mentioned factors that influence prices it is assumed that the price for FA is expected to increase in the period to 2030.

6.2 Findings on GBFS

In the past years GBFS has been used as clinker and cement substitute in concrete production. In the UK this is mainly done at cement production, contrary to continental Europe. The production of GBFS is based on iron production in Basic Oxygen Furnaces. The slag from this process can either be actively cooled, which produces GBFS or cooled using air flows, which produces air-cooled BFS, which is not utilisable in the cement and concrete sector. Precise data on the production and consumption of GBFS in the cement and concrete sectors were not readily available, but it is known that over the past years the production was in line with consumption. However, the steel industry has declined significantly in the last two years, reducing the amount of slag available. GBFS is said to increase the durability of concrete due to a increased setting time (which reduces the possibilities of cracks in the concrete), but this reduced setting time reduces also applicability when setting time is important.

It is known that there are some stockpiles of GBFS at the Redcar plant, as the slag produced there before closure of the blast furnaces was not fully processed. However, the stockpiles within the UK are limited to about 0.6 Mt, not enough to sustain through multiple years of shortage in production. Recently the Redcar GBFS grinding facility has reopened which is currently importing GBFS from China. This GBFS is too high in aluminium content to meet the UK standards for GBFS. Therefore it is necessary to mix the Chinese GBFS with UK stockpiled GBFS to reduce the aluminium content of the final GBFS. Our understanding is that the first shipment has arrived recently, but the imports are expected to be of substantial amounts (one or several hundred thousand tonnes). GBFS is said to be of higher quality (better reactivity) and cheaper than UK GBFS, but does also bring uncertainties regarding source security.

The modelling outcomes indicate that an oversupply of GBFS was available in the period 2012-2015, however this was not evident to the stakeholders we spoke to. As such, it is likely that the data obtained on consumption omits some applications of GBFS, but this is not known for sure. However, it is known that the GBFS production has declined due to lower steel production in the last years, which constitutes a vulnerability in availability of GBFS. Existing stockpiles could be sufficient to compensate for small shortages, but it is expected that this will not be enough in the coming years. It is also possible that the UK's remaining blast furnaces may be closed, or replaced with Electric Arc Furnaces which do not produce GBFS. In this case a larger shortage will be seen at the UK level. At a global scale, there appears to be an oversupply of GBFS, which is also backed-up by the stakeholders. In particular, there are said to be high amounts of GBFS available in China. One import route for Chinese GBFS to the

Redcar grinding plant is currently being developed, but to address possible shortages in the future it will be important to further develop these opportunities.

Based on the change in demand, change in availability, and costs of transport that influence prices it is assumed that the price for GBFS will be likely to increase in the period to 2030.

6.3 Recommendations for further research

This research provides a first indication on this topic based on public available data and stakeholder interviews. During the research it became apparent that in some cases there was an inconsistency between some data sources. Further data analysis would be necessary to identify the reason for these differences, however this did not fit into the scope of this research.

In addition, greater insight in to the quality and applicability of different qualities of FA and GBFS in the different types of cement and concrete is recommended. It is also important to take into account other alternatives to fly ash and GBFS in future research, such as ground limestone. This alternative is already standard practice in some other European countries (e.g. Ireland).

Furthermore, we suggest to include additional developments in the modelling. For example, the model could include changes in demand using specific scenarios presented in the Cement Roadmap and a potentially larger use of clinker substitute. Other updates could include changes in availability due to abated coal power plants (in contrast to unabated coal plants), additional GBFS production in the steel industry (e.g. decrease of air cooled slag); decrease of GBFS due to a more efficient steel and iron process where less slag is produced; and more import from Europe and other world regions, including China as main producer of iron and steel. In addition, the separate modelling of development in Europe versus the rest of the world would provide insight into the possibility to import from shorter range with more stable trade partners.

References

BEIS (2015a). Industrial decarbonisation and energy efficiency roadmaps – Cement

BEIS (2015b). Industrial decarbonisation and energy efficiency roadmaps – Iron & Steel

BEIS (2016). Impact Assessment: The Future of Coal Generation in Great Britain.

British Standard (2010). Concrete Complementary British Standard to BS EN 206-1. Extracted from: http://legacy.ybsitecenter.com/multi-images/uk/legacy/var/ag/13819/105399-Concrete_Complementary_British_Standard.pdf [27-03-2017]

Carroll, R.A. (2015). Coal Combustion Products in the United Kingdom and the Potential of Stockpile Ash. World of Coal Ash (WOCA) Conference in Nashville, TN. May 5-7 2015.

Cement Sustainability Institute (2017). Getting the Numbers Right (GNR) database: cement production, mineral use in cement production, mineral use as cement substitute. Extracted from: www.wbcsdcement.org/index.php/key-issues/climate-protection/gnr-database [19-03-2017].

Deutsche Bank Market Research (2016). The building blocks for growth. Extracted from: www.dbresearch.com/ [16-03-2017].

Ecofys (2014). International comparison of fossil power efficiency and CO2 intensity - Update 2014. Extracted from: www.ecofys.com/files/files/ecofys-2014-international-comparison-fossil-power-efficiency.pdf [23-03-2017].

ECRA (2017). Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead, Revision 2017. Extracted from: www.wbcsdcement.org/pdf/technology/Technology%20papers.pdf [19-03-2017].

EEF (2016a). World crude steel production 1997 – 2015. Extracted from: www.eef.org.uk/uksteel/About-the-industry/Steel-facts/Output-EU.htm [21-03-2017].

EEF (2016b). Output UK - Annual crude steel production and numbers employed, 1995 – 2015. Extracted from: www.eef.org.uk/uksteel/About-the-industry/Steel-facts/Output-UK.htm [21-03-2017].

Gomes, H., W. Mayes, M. Rogerson, D. Stewart, I. Burke (2016). Alkaline residues and the environment: a review of impacts,management practices and opportunities. *Journal of Cleaner Production*, 112 pp. 3571 – 3582.

IEA (2015). Energy Technology Perspective.

IEA (2016). World Energy Outlook 2016.

IEA (2017). World Energy Balances: Energy Balance Flows, extracted from: www.iea.org/Sankey/ [22-03-2017].

MPA (2016). The Mineral Products Industry at a Glance, extracted from: www.mineralproducts.org/documents/Mineral_Products_Industry_At_A_Glance_2016.pdf [23-03-2017].

MPA (2017). Economic and Market Briefing. MPA Briefing, 28-02-2017.

Piatak, N.M., M.B. Parsons, R.R. Seal (2015). Characteristics and environmental aspects of slag: a review. *Applied Geochemistry*, 57, pp. 236-266.

Renfort, P., C. Washbourne, J. Taylder, D.A.C. Manning (2011). Silicate Production and Availability for Mineral Carbonation. *Environmental Science and Technology*, 45, pp. 2035-2041.

Scotash (2017). EN 450 Fly Ash. Extracted from: www.scotash.com/content/en-450-fly-ash

UEPG (2016). Estimates of Aggregates Production Data 2015, extracted from: www.uepg.eu/statistics/estimates-of-production-data/data-2015 [24-03-2017].

USGS (2009). Iron and Steel Slag Statistics. U.S. Department of the

Interior and U.S. Geological Survey: 2009. Extracted from: www.flyash.info/2013/135-Feuerborn-2013.pdf .

UK Government (2016). Historical coal data: coal production, availability and consumption 1853 to 2015, extracted from: www.gov.uk/government/statistical-data-sets/historical-coal-data-coal-production-availability-and-consumption-1853-to-2011 [20-03-2017].

UKQAA (2015). Ash Utilisation Statistics 2010-2015. Extracted from: www.ukqaa.org.uk/information/statistics/ [20-03-2017].

UKQAA (2016), Ash Availability Report - Jan 2016. Extracted from www.ukqaa.org.uk/information/statistics/ [20-03-2017].

University of Dundee (2014). University to lead ash research project. Extracted from: www.dundee.ac.uk/news/2014/university-to-lead-ash-research-project.php [27-03-2017].

Wang, H., J.J. Wu, Z. Zhu, Q. Liao, L. Zhao (2016). Energy-environment-economy evaluations of commercial scale systems for blast furnace slag treatment: Dry slag granulation vs. water quenching,

Applied Energy, 171, p.p. 314-324.

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