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TOWARDS THE DECARBONISATION OF THE SOUTH AFRICAN CEMENT INDUSTRY: OPPORTUNITIES AND CHALLENGES

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CONTENTS

GLOSSARY

Alkali activator – alkaline chemical, usually in solution, which reacts with a powdery aluminosilicate such as fly ash to produce a cement capable of making concrete.

Aluminosilicate – material with a high level of silica (SiO_2) and aluminium oxide (Al_2O_3).

Calcined Clay – clay that has been heated in a kiln to drive out volatile materials. Used as a supplementary cementitious material which can act as a partial replacement for clinker.

Calcination – process of heating to separate a chemical compound into simpler compounds.

Caustic Soda – sodium hydroxide – an effective but highly caustic alkali activator, and the precursor to sodium silicate.

Cement – chemical agent which hardens into rock – like substance, binding aggregates (sand and gravel) to make concrete. Also mixed with water, lime and sand to make mortar.

Clinker – the main ingredient of cement. It is a mixture of various calcium silicates. It is produced in a rotary kiln by heating a combination of limestone and clay. The vast majority of cement related emissions are from clinker production.

Concrete – a building material made from a mixture of crushed stone or gravel, sand, cement and water which can be spread or poured into moulds to form a stone like mass on hardening.

Fly ash – main waste product of coal-fired power stations – a fine grey powder that collects in the exhaust flues. Some fly ash is pozzolanic and useful as a clinker substitute or raw material for geopolymer cement.

Geopolymer cement – a type of cement made from aluminosilicate material (such as fly ash or metakaolin) reacted with a strong alkali source. The term geopolymer cement is synonymous with alkali-activated cement (in this report) and is an example of a novel cement.

Ground granulated blast furnace slag (GGBS) – glassy material chemically similar to Portland cement and useful as a clinker substitute or a raw material for geo polymer cement. Made by quenching molten iron slag from a blast furnace in water.

Metakaolin – a calcined form of the clay mineral kaolinite

Pozzolan – any aluminosilicate material which when mixed with water reacts with calcium hydroxide to form cementitious compounds.

Serpentine – a dark green mineral consisting of hydrated magnesium silicate. Raw material for both mineral carbonation and carbon negative cements.

Sodium silicate – the most useful alkali activator in geopolymer cements.

Supplementary cementitious materials (SCMs) – products that can be used to replace a proportion of the clinker of Portland cement such as fly ash, ground granulated blast furnace slag and metakaolin. SCM’s react with clinker, playing a role in the strength development of concrete.

Source: Zero Carbon Australia (2017) and author

ABBREVIATIONS

ACMP	Association of Cementitious Material Producers
BYF	Belite-Ye'elimite-Ferrite
CACs	Calcium Aluminate Cements
$CaCO_3$	Calcium Carbonate
CaO	Calcium oxide (lime)
CC	Competition Commission
CCS	Carbon Capture and Storage
CO_2	Carbon dioxide
CSS	Cement Stabilised Soil
CSCs	Calcium Silicate Cements
DEA	Department of Environmental Affairs
GDP	Gross Domestic Product
GgCO2e	Gigagrams of Carbon Dioxide Equivalent
GPCs	Geopolymer Cements
HRM	Horizontal Roller Mill
IEA	International Energy Agency
ITAC	International Trade Administration Commission of South Africa
kWh	Kilowatt hour
LC^3	Limestone Calcinated Clay Cement
MJ	Megajoule
MNCs	Multinational Corporations
MOMs	Magnesium Oxide Derived Cements
MPA	Mitigation Potential Analysis
Mt	Metric ton
NOx	Nitrogen Oxides
NPC	Natal Portland Cement
OPC	Original Portland Cement
PPC	Pretoria Portland Cement
R&D	Research and Development
SABS	South African Bureau of Standards
SANS	South African National Standards
SARS	South African Revenue Service
SO_2	Sulphur Dioxide
VRM	Vertical Roller Mill

1. INTRODUCTION

Concrete is the most manufactured product on the planet. It is the second most consumed product after water (Lenne and Preston 2018). The core ingredient of concrete is cement, of which a massive 4.1 billion tons was produced globally in 2015 (IEA 2018). This figure is expected to grow to 18 billion tons by 2050 (Naqui and Jang 2019; WWF 2007) due to increased demand from developing countries as gross domestic product (GDP) expands, urbanisation increases and populations grow.

Unfortunately, the manufacturing of Original Portland Cement (OPC), which accounts for 98% of global cement production, is highly energy intensive (47 British thermal units of energy per ton of cement) and involves a chemical process of converting limestone into clinker which releases massive quantities of CO_2. Each ton of cement manufactured produces close to a ton of CO_2. At these high levels, it is unsurprising that cement manufacture currently accounts for 8% of all global greenhouse gas emissions, which is more than all the world's cars put together (Zero Carbon Australia 2017). If cement demand increases as expected, and the industry does not embark on a low-carbon pathway, it is possible that by 2050 cement production alone could account for almost one quarter of all global greenhouse gas emissions.

There is general consensus that the roadmap to a low-carbon cement industry is based on various mixes of: decreasing electricity usage in the production process; increasing thermal efficiency and the use of alternate fuels in clinker making; increasing the use of substitute cementitious materials (SCMs) to decrease clinker ratios and make blended cements; creating new novel cements such as geopolymers; and decreasing the demand and usage of cement in construction works. Carbon capture and storage (CCS) is also seen to play a major role in decarbonising the sector by 2050.

The cement industry globally is highly concentrated, and in all countries is characterised by a few large players with substantial market power. Cartelisation has historically been a global problem in the industry and, despite national government measures across the world, the degree of competition in most markets remains a concern. The power and influence of the industry tends to be high and this has allowed the industry to largely maintain the operating status quo.

Undertakings by the industry, such as improving electricity efficiency, thermal efficiency and using SCMs, have resulted in CO_2 emissions per ton of cement decreasing globally from an average 0.94 in 1990 to 0.64 in 2016. Progress on novelty cements, decreasing the demand and usage of concrete in construction and even some of the work on blended cements have been less successful due to a combination of factors. These include economic considerations such as the massive capital outlay to establish a cement plant and the 30-year period in which to earn a return on investment; the intrinsic conservatism of the engineering and construction industry which is responsible for the safety of users of their buildings and infrastructure and hence reliance on tried and tested materials and construction techniques; the ease of use of OPC compared to more complicated and knowledge intensive use of alternative blended and novelty cements; and problems related to standards, testing and track records for new products. Indeed one of the reasons why OPC-based concrete is the most manufactured product in the world is its ease of use (by skilled and unskilled labour); its ability to be used in a vast array of situations from small home DIY projects to huge dams and skyscrapers; its compatibility with current construction and site management techniques and processes; and perhaps most importantly its 200-year track record of durability and performance.

In 2016, South African cement plants produced on average 671kg[1] of CO_2 per ton of cement. This is above the global average of 642 $kgCO_2/t$ cement but better than the Middle East (712kg), Russia

[1] This average figure is examined in detail later in the document where it is shown that different types of South African cement have different CO_2 emission values – ranging from 980kg to 430kg, depending on the amount of clinker used.

(707kg) and North America (745 kg) (GNR Indicator n.d.). South Africa's emissions are, however, higher than those of its other BRICS trading partners with India producing on average just 582 kgCO_2/t cement and Brazil 604 kgCO2/t cement. In absolute terms, South Africa lies very much in the middle of the country pack and is neither a weak nor a strong performer. More interesting is the trend of emissions overtime. In 1999, South African plants on average produced 783kg CO_2/t cement. This fell to 706kg in 2006 and reached an industry low of 665kg in 2015. Since 2015, emissions per ton of cement produced has increased marginally from 665kg to 671kg in 2016. This is part of a global trend where an uptick in emissions is noted in most reporting regions (GNR Indicator n.d.). A second observable trend in South Africa and other countries is that the rate of emissions decrease has slowed in the past five years. This seems to indicate that most low hanging fruit has been picked and that more difficult and expensive mitigation options remain untapped. As will be shown, South African cement firms have made significant strides in improving electricity and thermal energy efficiency thereby reducing their carbon footprint. Firms have also made some progress in decreasing the clinker to cement ratio, although this trend appears to have stuttered in the current adverse market conditions. Market penetration of blended cements and novel cements remains underdeveloped in South Africa and globally and hold the greatest practical to decarbonise the industry in the short to medium term.

Section 1 begins with a description of the complete cement value chain and a brief introduction to the manufacturing process of cement and the cement industry in South Africa. Analysis of the industry is severely limited following a 2009 decision by the Competition Commission (CC) prohibiting the collection, dissemination and publication of all data related to cement except aggregated sales volumes on a quarterly basis (and trade data collected by the South African Revenue Service - SARS). As such, the industry is largely opaque to economic investigation. The analysis undertaken is based on the last published data (2006) and updated to the extent possible using expert opinion on trends in the intervening period.

Section 2 describes the universe of possible solutions along the cement value chain to make the industry more climate compatible. A complete range of mitigation and adaptation options are considered, including methods to reduce electricity consumption and increase electricity efficiency; options to replace fossil fuels with alternative fuels; increasing thermal efficiency along the production process; decreasing clinker content and increasing the use of extenders such as industrial waste products to produce lower carbon cements; developing the next generation of non-OPC novelty cements, such as geopolymers and magnesium based cements; and finally looking at the construction industry and considering how the demand for concrete and cement can be reduced. CCS is also considered briefly as, according to the IEA (2018) and the WWF (2007), it will be required to contribute up to 48% of cumulative global CO_2 emissions reductions to meet the 2°C scenario vision for 2050.

Section 3 applies the findings of the research to describe the possible development pathways available to domestic cement firms and establishes a view of different potential levels of ambition within the industry. As will be shown, many of the "easier" greening activities have already been completed by the industry due to cost pressures and attempts to maintain operating margins. Further levels of ambition (if they exist or can be fostered) would require substantial lead times and would require an enabling environment to support the industry potentially transitioning to a more climate compatible development pathway. As with many industries, the cement industry is reluctant to change and the national and global lobbying power of the large cement Multinational Corporations (MNCs) act to minimise climate change dynamics from fundamentally disrupting the industry.

2. CEMENT VALUE CHAIN IN SOUTH AFRICA

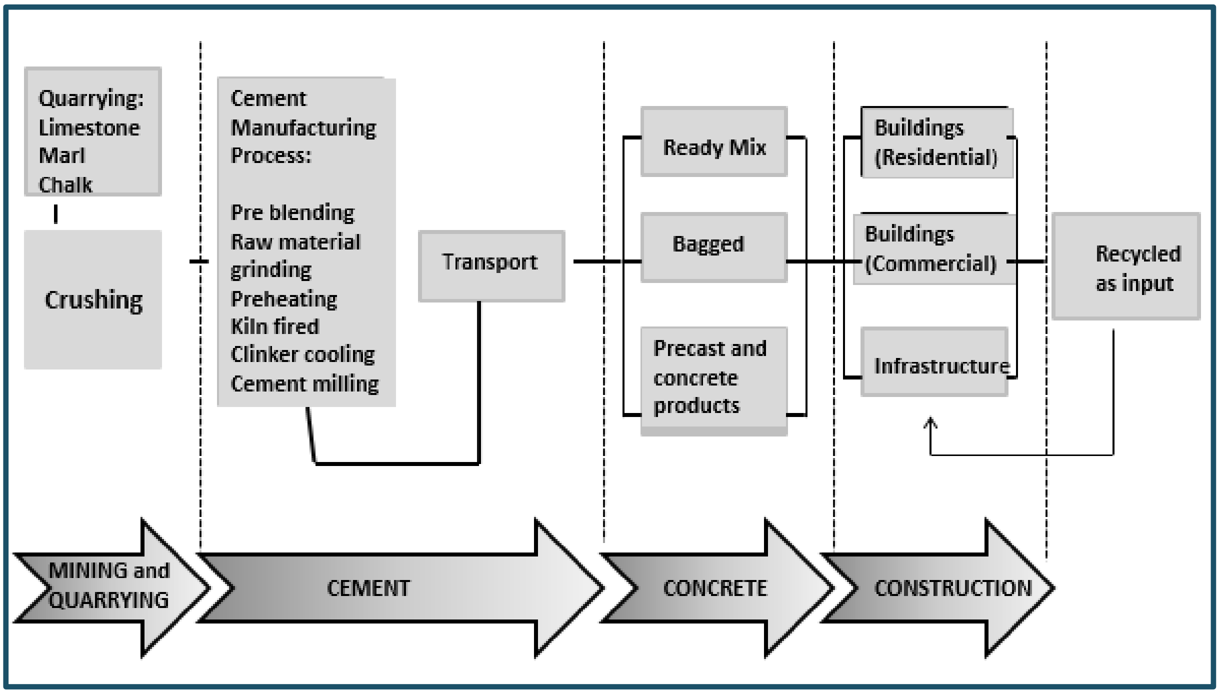
2.1. Cement value chain

The cement value chain traverses multiple sectors, beginning with the mining and quarrying of raw materials. The main ingredient of OPC is limestone, which is quarried to provide the key ingredient of clinker, calcium carbonate ($CaCO_3$). Cement production facilities are usually located close to quarries to reduce the expensive transportation of high volumes of rock. Very small amounts of iron ore, bauxite, shale, clay and sands may be needed to provide the extra mineral ingredients that make up the raw mix which enters the cement kiln. These additional mined and quarried inputs provide necessary iron oxides, alumina and silica in accordance with the specification of particular types of cement. Quarried raw material undergoes an initial and secondary crushing process on-site to produce 10cm pieces.

On entering the cement manufacturing plant, crushed limestone and other necessary mineral inputs are mixed and milled together to produce a raw meal. This raw meal is then preheated and precalcined before entering the cement kiln where clinker is produced. From the kiln, hot clinker is rapidly cooled. Gypsum is then added to the cooled clinker and the mixture is ground into a fine powder. Additional blending may then occur.

The final product is homogenised and stored in cement silos and then packed into bags ready for shipping or transported in bulk by road or rail.

Figure 1: Cement value chain



Source: Author's own design

Cement is the crucial ingredient (10%-12%) of concrete and binds sand and aggregate (65%-85%) and water (14%-21%) together. Concrete users access cement through three channels. The most common channel (in South Africa) is purchasing cement in bags from resellers in the retail and wholesale market. Contractors then mix their purchased cement with aggregate and sand and form concrete for use on-site. An alternative to bagged cement is the use of ready mix cement. In this channel contractors specify a concrete mix design to a ready mix company, which mixes cement, aggregate, water, sand and other design ingredients off site and delivers a ready to use liquid concrete to the client's site in concrete mixing trucks. Due to the setting time of ready mixed concrete, this channel only works if the distance between the construction site and the ready mix plant is relatively short. Finally, cement can be delivered in dry bulk to producers of final concrete products such as roof tiles, cement building blocks, fibre cement roof sheets, precast slabs and walls, pipes and roof beams. This cement is then mixed on-site by the fabricator to a specification suited for the final use of the product. The concrete is then placed into moulds and dried and cured ready for distribution into the market.

Cement and concrete are used in the construction industry to erect buildings and infrastructure. The design phase of the construction process (which engages the client with architects, structural engineers and contractors) determines the specification, characteristic and amount of cement and concrete that will be utilised in a particular construction project. Most residential buildings are designed to last 70 years, office buildings 100 years, and commercial buildings 50 years. Although commercial buildings are designed to last 50 years on average, they are replaced every 25 years due to thorough renovations to meet new functional requirements. (Lenne and Preston 2018, Celadyn 2014).[2] Big infrastructure projects, such as dams and roads, are designed to last more than 100 years with on-going maintenance factored into the original design and life cycle specifications. At the end of the life cycle of a building, concrete can be recycled as aggregate for use in the production of new concrete as a substitute for virgin gravel and stone.[3] Concrete cannot be recycled as an input into cement manufacture. Concrete which is not recycled usually finds its way into landfill sites.

2.2. The cement industry in South Africa

The first OPC was produced in South Africa in 1892 by the Pretoria Portland Cement Company (PPC). The company operated as a monopoly until 1934 when Afrisam, Lafarge and Natal Portland Cement (NPC) entered the market. These four companies were the only suppliers of cement in South Africa until 2006 when Sephaku (backed by Dangote from Nigeria) entered the market. This was followed by Chinese cement manufacturer Mamba Cement in 2016.

The big four of PPC, NPC, Lafarge and AfriSam created a legal cartel in 1940 for what were deemed public interest considerations by the government of the day. This cartel and its highly collusive behaviour endured until 1996. Under the democratically elected government of 1994, the cement cartel was dismantled in 1996 with authorities believing that companies would set their own prices and begin competing for market share. Instead, the four companies colluded to maintain the market shares they had under the cartel; establish pricing parameters to support the maintenance of market shares; and agree on marketing and distribution and geographic parameters. Each company agreed to make sales by region, packaging type, transportation, customer type, pricing, quantities and market share data available to an association of auditors which would aggregate the information and then disseminate it to the four companies. This information allowed the four to maintain market shares and devise joint strategies to maximise profits.

This illegal cartel operated from 1996 to 2006 when the Competition Commission (CC) began investigating the industry. After research confirmed non-competitive behaviour in 2009, PPC applied to the CC for leniency and immunity, which was granted on condition that the company stopped releasing data to the industry association of auditors, thereby halting the exchange of information between cement firms. The CC assumed that without this information cartel members would not be

[2] The age profile of South African structures could not be found.

[3] As will be shown in the document, one way to mitigate cement-related emissions is to use less cement, which will be possible if buildings are designed in the future to be increasingly more recyclable. This will add to the circular economy in construction.

able to monitor compliance among other firms, resulting in increased competition in the market. In 2011, Afrisam settled with the CC followed swiftly by Lafarge in 2012.

In principle, there is no longer collusive behaviour in the local cement industry but CCRED (2015), Vosloo and Mathews (2018) and Theron and Van Niekerk (2018) all suggest that collusive behaviour is a recurrent behaviour in the cement industry worldwide and, given the history of the industry in South Africa, cartel-like behaviour is likely to reappear. Several people interviewed in the research process believe that high levels of tacit collusion continue to characterise the industry in South Africa today.

Due to the agreement by the cement companies to halt releasing data, there is no cement industry data publically available save quarterly sales data and data collected by SARS on imports and exports. As such, no-one outside the industry has a dynamic view of the sector today, either at a descriptive level or in terms of trends over time. This hampers policy and decision-making for supporting the industry in issues such as the International Trade Administration Commission of South Africa (ITAC) raising tariffs to protect the local market against cheap and inferior quality imports or impacts of the carbon tax.

As of 2016, there were six cement producers in the South African market, which were estimated to be worth R48 billion in 2014 and employed about 7 000 workers (Arp, Bole-Rentel and Jakuja 2018). PPC enjoys the largest market share at 22%, with NPC at 15%, Sephaku at 12%, Afrisam and Lafarge at 9% each and Mamba at 5%. The remaining 29% of the market is serviced by imports (about 5%) and third-party blenders[4] (Perrie 2014; Arp, Bole-Rentel and Jakuja 2018; PPC 2018). Ninety-one percent of the local market is OPC. In 2006, the retail market accounted for 52% of domestic sales. Ready Mix accounted for 15% of the market and 16% of cement production was channelled to concrete product manufacturers. Direct civil engineering company purchases accounted for 9% of sales, third-party blenders 6%, and 2% for others[5] (Perrie 2014).

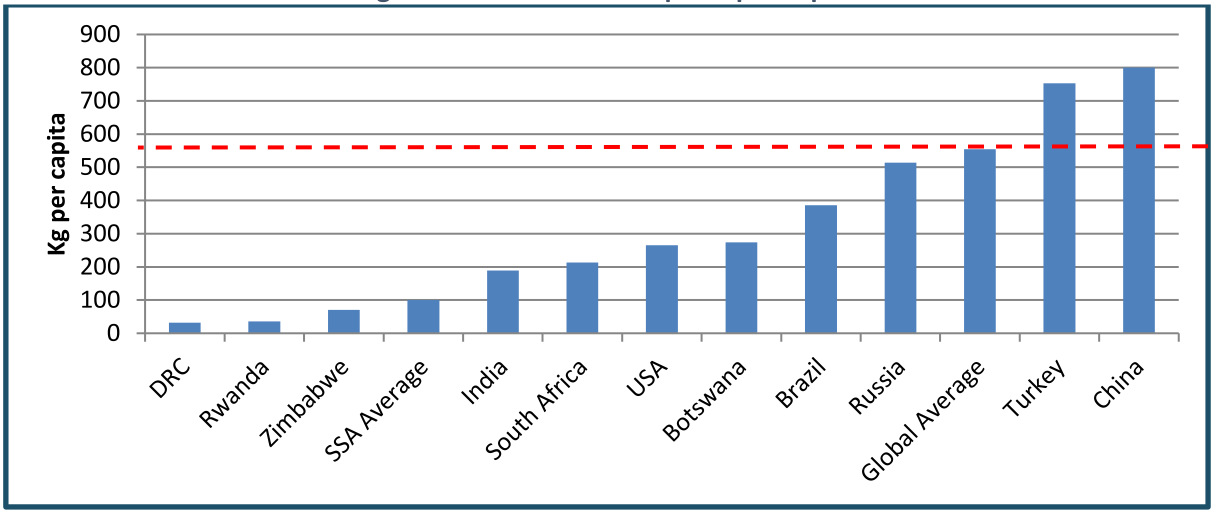
More recent estimates suggest that the share of the retail market has increased to 70% (Brown and Hasson 2016). South Africa's market share of bagged cement differs from that found in Europe and most parts of Asia where the ready mix segment dominates the market. In the United States, Australia and South Africa the ready mix market is smaller and the bagged market dominates due to the extensive distances, which make ready mix site delivery unfeasible.

Developed countries accounted for less than 25% of the global demand for cement in 2005 and demand growth is relatively consistent at 1% to 2% per annum (WWF 2007). The majority of demand growth is driven by developing countries, a trend which is forecasted to continue until at least 2050. Estimates for the growth of demand in cement to 2050 range from the International Energy Agency's (IEA) 12% to 23% to the WWF's 25% to 50%. Figure 2 shows per capita cement consumption in developing countries falls well below the global average. This is due to limited levels of investment in the built environment and infrastructure in developing countries compared to developed nations.

[4] Third-party blenders are small unbranded companies which buy clinker from large firms, blend the clinker with SCMs and sell directly into the market or through some retailers. Their product is essentially "unbranded" cement.

[5] South African cement exports are minor due to the expense of transportation and the fact that most South African cement firms also operate plants in the rest of Sub Saharan Africa, then decreasing the demand for inter-regional exports.

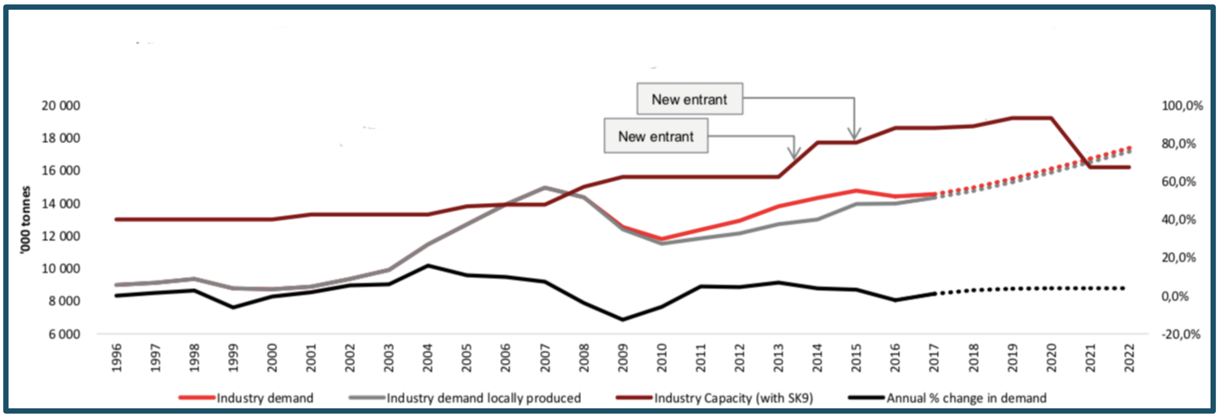
Figure 2: Cement consumption per capita



Source: Author

Population increases, growing urbanisation and burgeoning middle classes in developing countries will continue to drive demand for housing and associated infrastructure, thereby supporting an upward trend in the demand for cement and concrete. In South Africa, demand remained relatively stable post the 1994 election, peaking in 2006 and 2007 driven by infrastructure preparations for the World Cup, substantial investment in low cost residential housing, and the building of the Gautrain.[6] The global financial crisis of 2008 strongly impacted the construction industry negatively and this, coupled with decreasing rates of private and public sector investment over the next decade, has resulted in depressed demand for cement even as new entrants Sephaku and Mamba entered the market.

Figure 3: Industry demand for cement 1996-2022



Source: Author's modification of PPC (2018)

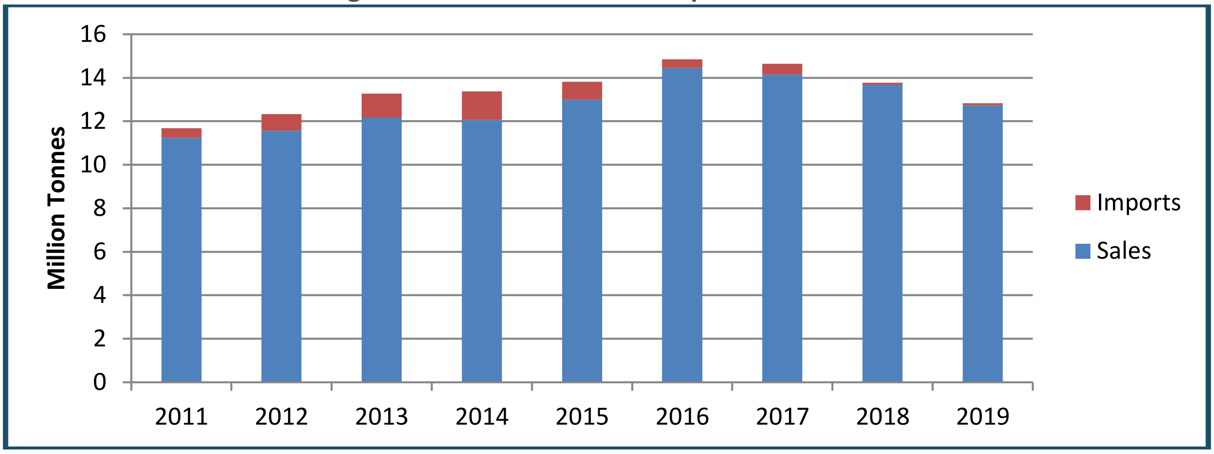
As a result of low levels of demand and increased productive investment, the capacity utilisation of the country's cement industry stands at a low 70% (PPC 2018; ACMP 2018), while industry stakeholders claim an 85% to 95% utilisation ratio is required to ensure profitability. Local cement producers claim they are facing "a perfect storm" of unfavourable conditions. Demand conditions are weak due to low levels of economic growth, as seen by a decrease in the number of building plans passed and lack of implementation of government infrastructure build programmes.[7] The entrance of Sephaku and Mamba have increased industry supply capacity at a time of low demand. Cheap imports since 2013 from Vietnam, Pakistan, India and China have been entering the local market and are up

[6] With residential housing accounting for 50% of demand for cement, interest rates are important in influencing demand.

[7] On average, between 2008 and 2020, 55% of demand has been residential buildings, 32% non-residential buildings and 13% infrastructure works (SARB n.d.2020)

to 45% cheaper[8] than domestic products (PPC 2019). In these conditions, the bargaining power of retailers (which account for 70% of sales) has increased, leading to falling prices and historically low industry profitability. Added to this, increases in the cost of electricity, labour and the newly introduced carbon tax all make current market conditions very difficult according to industry insiders.

Figure 4: Cement sales and imports 2011-2019



Source: Author, based on the Concrete Institute (2020)

With sales averaging 13 million tonnes a year over the past nine years, and an industry installed capacity of 22 million tonnes, capacity utilisation has on average been 60%.[9] Sales and import data show that although imports began to increase in 2011 at a high percentage rate this was off a low base and, in tonnage market penetration, was in fact modest. In 2015, ITAC provided tariff protection and imports have declined accordingly. Sales volumes increased modestly from 2011 to 2017 with annual growth rates declining by 2.2% from 2016 to 2017, 3.3% from 2017 to 2018 and a strong 7% contraction from 2018 to 2019.

Industry experts, however, believe that the announcement in the President's 2019 State of the Nation Address of R500 billion of new public sector investment and R43 billion of new private sector investment will go some way to increasing domestic demand if this is implemented. In addition, ITAC have agreed to impose tariffs on cheap cement imports to decrease market penetration. Rising freight costs and falling imports, due to a lack of shipping availability on the back of decreased coal exports to India, should also decrease imports – collectively resulting in an upswing of domestic capacity utilisation.[10] Local industry stakeholders have identified no new plant coming on stream and given that it takes up to nine years to bring new capacity to market, for the near future the supply side of the industry is fixed with the potential for demand conditions to improve.

Despite analysts predicting a more positive outlook, given current poor trading conditions in South Africa, the big four are focusing on their productive capacity in the rest of Sub Saharan Africa where growth prospects are viewed as being superior to those in South Africa. PPC for example is investing in new plant in non-South African markets, with an expected 6% annual growth rate due to current low cement per capita consumption and positive demand dynamics. The annual reports of all South African producers suggest a current view that future growth will be derived outside of South Africa.

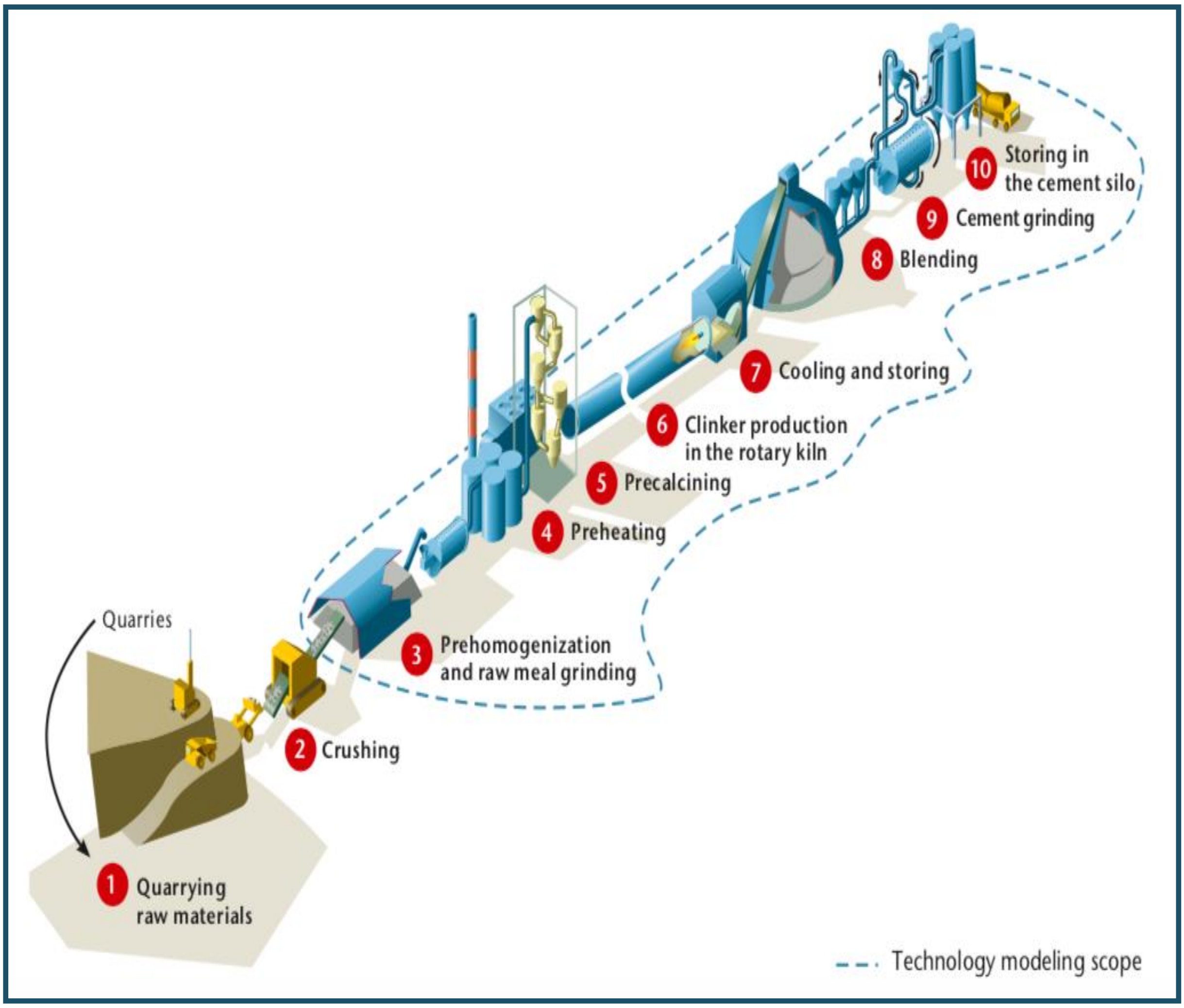
[8] High price differentials are due to dumping and cheap transport options using empty ships returning from South African coal exports (especially to India).
[9] This is leading to plant rationalisation in the domestic market.
[10] Analysis done pre-COVID 19.

3. MANUFACTURING CEMENT AND CLIMATE CHANGE

The production process

Cement manufacture is a three-stage process: raw material preparation, clinker production, and grinding with other components to produce cement. Naturally occurring sources of calcium carbonate (the key ingredient of cement), such as limestone, marl or chalk, are quarried and crushed into small pieces. Small amounts of other materials such as iron ore, bauxite, clay or sands which may provide extra amounts of iron oxide, silica and alumina are added to the calcium carbonate source to ensure the right chemical composition of the mix to meet the process and product performance standards of the cement to be produced.

Figure 5: Cement manufacturing process



Source: IEA (2018)

All the necessary raw materials are mixed to achieve the required chemical composition in a process called pre-homogenisation. This crushed material is then milled to produce a fine powder called raw meal. From the preparation of the raw meal the next step is preheating. A preheater is a series of vertical cyclones through which the raw meal is passed. The 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 reaches the kiln. Manufacturing plants may have up to six stages of cyclones depending on the moisture content of the raw materials. During the process of preheating the temperature of the raw meal is raised to 900°C.

The next stage is precalcining. Calcination is the decomposition of limestone into lime. This takes place in a combustion chamber at the bottom of the preheater above the kiln and partly in the kiln. Here the chemical decomposition of limestone ($CaCO_3$) into lime (CaO) releases large amounts of CO_2 which typically accounts for 70% of the total CO_2 emissions from cement manufacture. The precalcined meal then enters the kiln in the part of the process where clinker is actually formed. Fuel is fired directly into the kiln to reach temperatures of 1450° C. As the kiln rotates (about five times a minute) the material slides and falls through progressively hotter zones towards the flame which burns at 2000°C. The intense heat causes chemical and physical reactions that partially melt the raw meal into clinker. The reactions in the kiln complete the calcination of the limestone that began in the precalciner. During this process, more CO_2 is driven off the limestone resulting in more emissions. The CO_2 emission in the precalciner and the kiln together constitute the "process CO_2 emissions" in the production of cement.

The next step in the process is cooling. Hot clinker from the kiln is rapidly cooled from 1000° C to 100°C using a grate cooler (the most common cooler system). In the grate cooler, incoming combustion air is blown into the clinker. The air blowers use electricity and heated blown air circulation to improve thermal efficiency.

Once clinker is cooled, it looks like molten grey rocks and is moved into storage before being further processed. Clinker is removed from storage and blended with other mineral elements. All types of cement contain between 4% and 5% gypsum, which improves the setting time of concrete. In addition SCMs such as slag, fly ash, limestone or other materials can be inter-ground or blended to replace part of the clinker. This produces a blended cement.

Once the cooled clinker and gypsum are mixed, they are finely ground into a grey powder known as Original Portland Cement. If SCMs and additional mineral elements are added, such as fly ash or slag, then a blended cement is created. Ball mills have traditionally been used for grinding although in more modern plants roller presses and vertical mills are often used due to their greater energy efficiency. After grinding, the cement is stored in silos before being put in bags or transported in bulk.

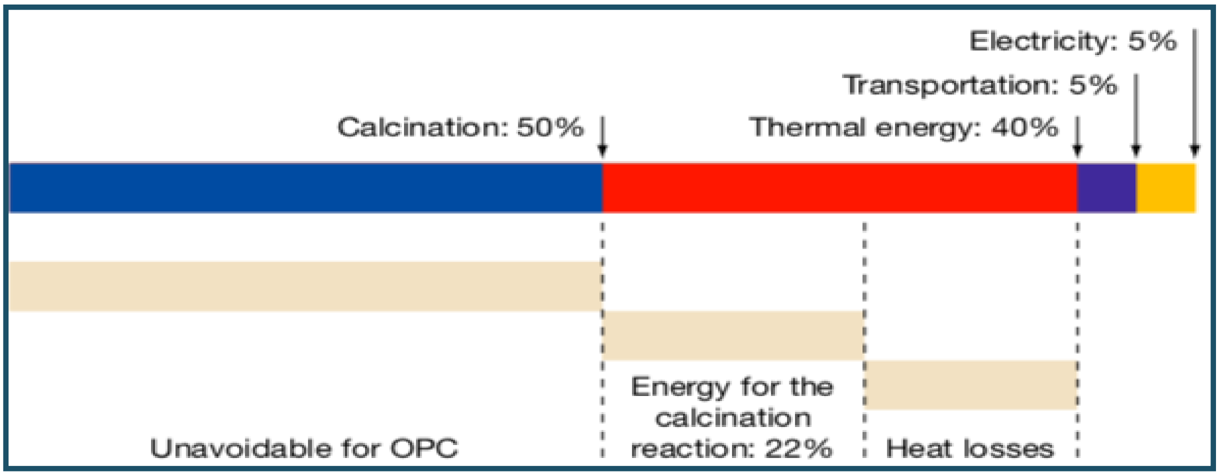
Climate change dynamics

In 2000, it was estimated by the WWF that a ton of cement released on average 0.87tons of CO_2. This value ranges between a low of 0.77 tons for high performers such as Japan to a high of 0.99 tons for poor performers such as China. CO_2 emissions depend on the region and the type of manufacturing process and infrastructure.[11]

Figure 4 shows where emissions of CO_2 arise. 50% of CO_2 emissions are released during the calcining process and are thus unavoidable in the production of OPC clinker. This distinguishes the cement industry from other industries where fuel combustion accounts for the majority of greenhouse gas (GHG) emissions.

[11] More up to date figures are available from Getting the Numbers Right (GNR) but they do not coincide with the figures used in the IEA and WWF Reports. According to the GNR website, in 2016 World average carbon emissions per ton of cement were 642kg. Strong performers were India (580kg), Brazil (614kg) and Germany (573kg). The US was a poor performer at 762kg. Figures for China, Japan and South Korea are aggregated so GNR does not report on China individually.

Figure 6: CO_2 emissions during the production of cement

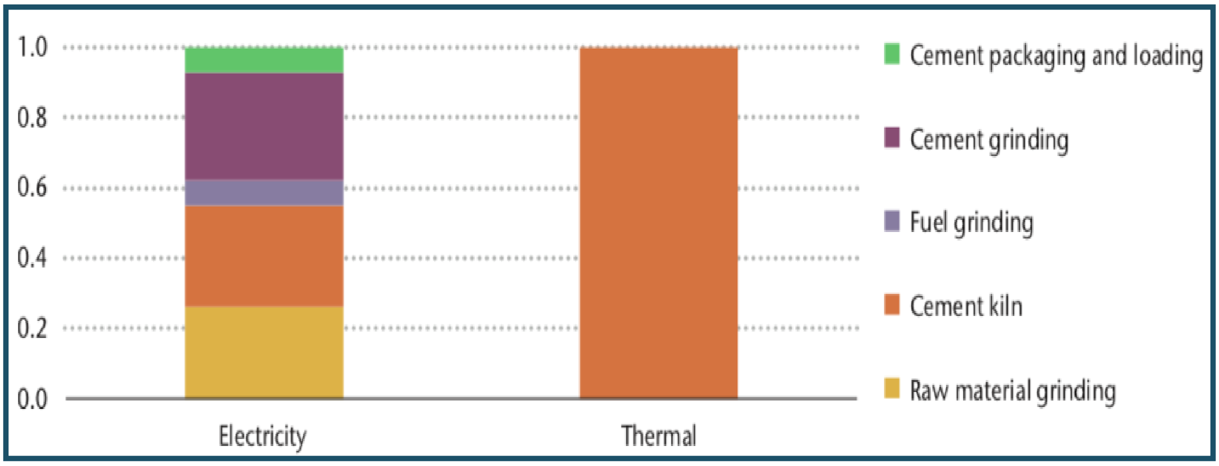


Source: IEA (2018)

About 40% of GHG emissions in cement production arise from burning fuel to generate the thermal energy necessary for the calcining process. In 2018, the IEA calculated that, of the 40% of emissions relating to burning fuel, 22% was energy used directly for calcining and 18% was the result of heat loss. Emissions related to the use of electricity for cooling and grinding account on average for 5% of total emissions, and cement distribution and storage accounts for 5% of emissions. As such the industry is intrinsically a high producer of CO_2 emissions as the fundamental chemical reaction of reducing limestone $CaCO_3$ to lime CaO creates process emissions.

Figure 7 disaggregates the energy demand distribution of each step of the manufacturing process. Energy usage differs across the globe from a low 3100MJ per ton of clinker achieved in Japan, to 4710MJ per ton in China; and the most energy intensive processes found in the US at 5500MJ per ton of clinker. As explained, electricity is used along the entire process chain with thermal energy used to fire the kiln and complete the calcining of limestone into clinker. The IEA (2018) calculate that 31% to 44% of electricity is used in the final grinding phase of cement production; 26% in raw material grinding to create the raw mix; 28% to 29% in clinker production (especially cooling) and 3% to 7% in the grinding of fuels for the kiln.

Figure 7: Energy usage by activity in production process



Source: IEA (2018)

Thermal energy for use in the cement kiln is traditionally coal or coke although recently mixes with alternative fuels have been introduced. On average, in 2014, the electricity intensity of cement was 91kWh per ton of cement (IEA 2018) with a thermal energy intensity of clinker being 3500MJ per ton of clinker (Arp, Bole-Rentel and Jakuja 2018).

4. OPTIONS TO SET THE SOUTH AFRICA'S CEMENT VALUE CHAIN ON A CLIMATE-COMPATIBLE PATHWAY

4.1. The universe of options

The WWF 2007 Blueprint for a Climate Friendly Cement Industry report argues that, if demand from emerging and developing countries increases as anticipated and if no mitigation efforts are adopted, CO_2 emissions from the industry will be 260% higher in 2050 than they were in 1990. To limit global warming in the 21st century to just 2°C CO_2 emissions, rates need to be at less than 50% of their 1990 levels by 2050. Given this, a pathway to a climate compatible cement industry is urgently needed. Currently the process of manufacturing one tonne of cement releases between 0.67 and 0.99 tons of CO_2 depending on the efficiency of the process, fuels used and type of cement produced. Given the volume of cement produced globally each year, even a slight decrease in the global average emissions per tonne has a large overall emissions reduction potential. Every 10% reduction in cement CO_2 intensity by 2050 could save around 0.4GtCO_2 and make a substantial contribution towards slowing climate change (WWF 2007). The IEA Technology Roadmap to a Low-Carbon Transition in the Cement Industry document presents a vision to decrease the cement industry's global direct emissions by 24% from current levels by 2050, which amounts to reductions of 2.2GtCO_2 per year.

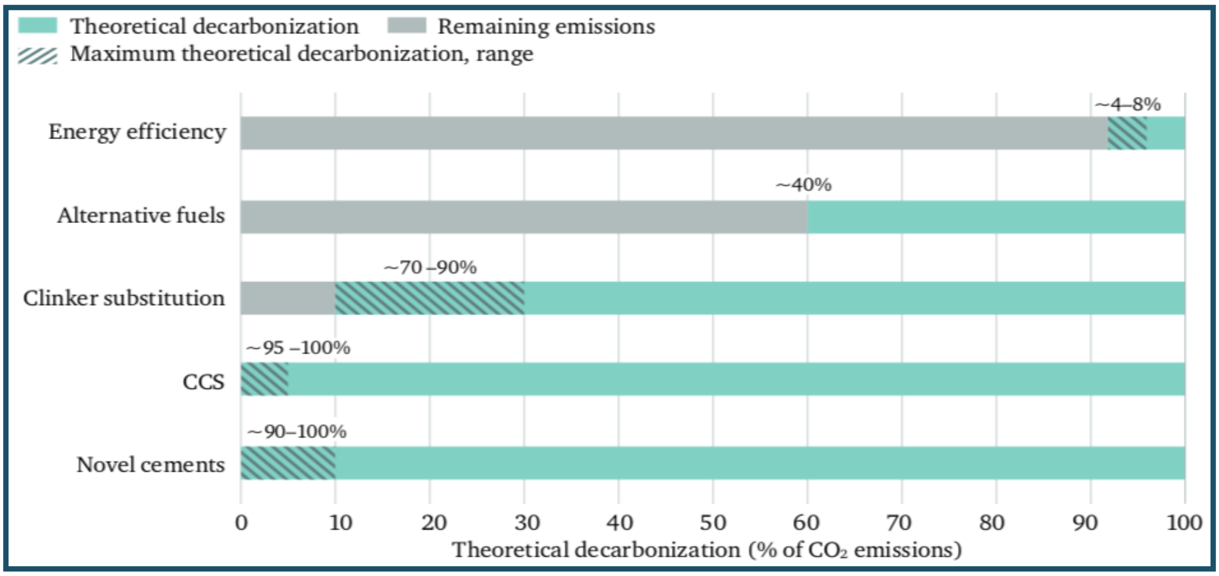
Across all the literature there is consensus on the potential mitigation and adaption options available to the cement industry to reduce its GHG emissions.

There are seven areas to consider:

1. Increasing the electrical efficiency of plant processes especially grinding and cooling.
2. Increasing thermal efficiency in the manufacturing process.
3. Increasing the use of alternative fuels as a source of thermal energy
4. Decreasing the ratio of clinker to cement by introducing SCMs and creating blended cements.
5. Increasing the production of non-OPC cements, known as new binders or novel cements.
6. Disruptions in the built environment which lead to decreased demand for cement.
7. Carbon capture and storage.

The IEA Technology Roadmap (2018) only considers the first four carbon emission reduction levers and CCS. It does not include novel cements and argues that no independent publically available and robust life cycle assessments for alternative binders or a comparative quantification of production costs currently exist. It argues that novelty cements do offer emissions reduction opportunities but that inclusion at this time is premature. It does, however, forecast that 48% of CO_2 emissions reduction in its scenario will be related to CCS. Changes in the built environment are also excluded as they fall outside the scope of the IEA paper. The majority of other studies (WWF 2007; Zero Carbon Australia 2017, Leanne and Preston 2018, The Concrete Institute 2014) all cover increasing electrical efficiency, thermal efficiency and the use of alternative fuels, but concentrate on decreasing the ratio of clinker to cement by creating blended cements, developing new binders or novel cements, and disruptions to the built environment as sources of future decarbonisation.

Figure 8: Sources of CO_2 emissions reduction[12]



Source: Leanne and Preston (2018)

4.2. Increasing electrical efficiency

As 90% of the energy usage in cement manufacturing is accounted for by thermal energy using fossil fuels, many experts minimise the attention paid to the 10% of energy use accounted for by electricity. In South Africa, this is not the case because although electricity accounts for only 10% of energy use it contributes more than 30% of energy costs. (Eskom 2011, Vosloo and Mathews 2017). The WWF report argues that optimising and reducing electricity in modern cement making is hard to source but needs to be explored. Given that 30% to 40% of electricity is used in finishing and final grinding; 26% to 32 % in raw material grinding; and 28% to 30% in clinker cooling it is unsurprising that the majority of electricity efficiency gains are focused on grinding, which accounts for two thirds of electricity consumption. In general, it takes approximately 85kWH to 90kWh of electricity to produce a ton of cement. A saving of 5kWh per ton of cement would thus indicate a 6% saving in overall electricity intensity.

There are four major types of grinding mills. Sixty percent of finish grinding worldwide is still performed by ball mills. These are cylindrical steel shells with steel liners. Rotating drums contain grinding media that crash and tumble onto raw material to grind down the particle size. Most ball mills use a closed circuit grinding method that returns material that is too coarse back into the mill inlet while material fine enough to meet product requirements is sent on to storage. A separator determines which particles are returned and which are sufficiently fine to meet specifications. Ball mills, as will be seen, are not the most efficient means of reducing the size to materials but their reputation for consistency and their simplicity of operation have made them historic favourites. If a ball mill is used, electricity efficiency gains of 3kWH to 5kWh per ton of cement can be enjoyed by improving the grinding media, increasing the ball charge distribution, and increasing the wear resistance of the mill lining (IFC 2017).

Although ball rollers are ubiquitous in the cement industry globally, they are now considered outdated technology especially in terms of electricity consumption. Vertical Roller Mills (VRM) are viewed as a

[12] Note the green bars indicate the theoretical reduction in carbon emissions as a percentage of all current emissions. The grey bars indicate the remaining emissions. So, for example, for novel cements there will be a theoretical 100% reduction in carbon emissions with no remaining carbon emissions.

major technological advancement and are now considered the industry standard. VRMs employ a mix of compression and shearing using two to four grinding rollers carried on hinged arms riding on a horizontal grinding table. The material is ground on the rotating table by rollers that are pressed down using spring or hydraulic pressure. The material is forced off the table using centrifugal force where it is swept into an internal classifier which returns particles that are too large. An IFC report on energy efficiency in the cement industry (IFC, 2017) claims that shifting from a ball mill to a VRM can save 9kWh per ton of cement produced. The IEA (2018) claims that VRMs provide a 70% reduction in electricity usage over ball mills.

In the late 1990s, a third type of grinding technology was introduced into the market – the Horizontal Roller Mill (HRM). The HRM is a tube shell that rotates at hypercritical speed. Inside the shell, a hydraulic roller exerts pressure on the grinding bed. Scrapers then remove this material from the side of the tube, which then falls onto a diverting system that pushes the material against the shell face for regrinding and adjusts the motion of the material inside the mill. Material is ground several times before being classified by a dynamic separator. HRMs are claimed to save an additional 10% of electricity usage compared to VRMs. The technology is very new and has only been included in new build plants to date as retrofitting HRMs is viewed as too expensive.

Finally, high-pressure roller press systems feed material between two large rollers using pressure to force coarse material to break up into smaller particles. A separator classifies materials and material which is insufficiently fine is fed back through the rollers again. The main electricity saving advantage of this system is less the energy saved during grinding but the new static separator and use of a bucket elevator instead of the less efficient pneumatic conveying system used in VRM and HRM technology (Eskom 2011). The IFC claims that high-pressure roller systems can be used to pre-grind materials before they enter into a traditional ball mill which will allow an electricity saving of 7kWh to 10kWh per ton of cement. If a high-pressure roller system is used for final grinding the electricity saving can reach 24kWh per ton of cement manufactured. The IEA claims that high-pressure roller presses will provide 50% electricity savings compared to VRMs.

Cutting across all technologies, the literature suggests that substantial electricity savings can be enjoyed by optimising existing systems through process control and management. An Eskom brochure produced for the cement sector suggests that top autopilot control systems in the South African market are claiming to deliver a 12% reduction in electricity consumption. There are also cross-cutting suggestions that introducing variable speed drives for mills can reduce electricity consumption by 1.5kWh to 2kWh per ton of cement. These two efficiency suggestions apply to all types of milling technology and, importantly, can be introduced without substantial capital investment, plant reconfiguration or substantial retrofitting. As such, both are viewed by the IFC as highly cost effective interventions.

Interventions to fundamentally change the type of grinding technology at a cement plant come at a substantial cost, running from between R750 million and R2 billion depending on the technology and required reconfiguration of the plant. The IEA report (which was co-written by cement industry players) argues that such major retrofits and upgrades are seldom commercially viable. Indeed the document goes so far as to argue that other emissions reduction strategies, such as CCS, the implementation of systems to lower NOx and SO_2, and the increased air flow in a kiln required to allow alternative fuel combustion will all increase electricity consumption and more than offset any electricity use saving achieved through improved grinding efficiency. As such the industry reflects in the report that only a small kWh per ton of cement saving is possible.

Following product grinding, cooling clinker as it emerges from the kiln is the second highest user of electricity in the manufacturing process. Clinker must be cooled rapidly to avoid glassing. The design of clinker coolers has evolved significantly over time. Traditional coolers include rotary, planetary and older design grate coolers. More modern upgraded technology features a static inlet section followed by a deep bed section. Air is passed through the clinker bed to cool the material and preheat the secondary air for combustion in the kiln (or tertiary air for combustion in preheaters and precalciners). Clinker cooler optimisation is all about heat recovery. Heat recovery can be improved by the reduction of excess air volumes, control of the depth of the clinker bed and upgrades in the design of grates on which the clinker rides.

As with grinding, research shows two ways to reduce electricity use efficiency during cooling and heat recovery. First, changing from an old style planetary or rotary cooler to a grate cooler is likely to save 0.16GJ per ton of clinker and increase heat recovery from 2% to 5% (IFC 2017). Second, improving process control and management is calculated to return an energy saving of 0.05GJ to 0.08GJ per ton of clinker. As such, even though progress has been made in cooling technology and heat recovery only small additional opportunities exist to decrease electricity consumption in the cooling phase of the manufacturing process.

Aside from lowering electricity consumption in grinding and cooling processes, the literature also considers potential electricity savings related to gas handling systems in the manufacturing process, material conveying systems, and motor and motor systems (Eskom 2011, IFC 2017).

Cement production processes require the transport of large volumes of air, combustion and drying gasses at various stages of the process. For example, hot kiln gases are recycled and moved through preheaters to increase the temperature of the raw mix before it enters the kiln, oxygen is moved into the kiln to allow for combustion and hot air is removed in cooling clinker as it leaves the kiln. In all these processes fans are used to move air and gases. According to Eskom, fans are subject to more misuse and faulty applications than virtually any other type of equipment. Eskom argues that energy consumption by fans can be improved by: reducing dust build up, abrasion and poor inlet design; improving filter technology; specifying the correct type of fan in a particular use; specifying appropriate and efficient drive systems; and very importantly allowing for variable speed drives. It suggest that fans are notoriously over specified and that if fan speed is reduced to 60% then the power drawn by the motor will decrease by 22%. Variable instead of fixed speed fans are thus a cheap and easy way to reduce electricity consumption.

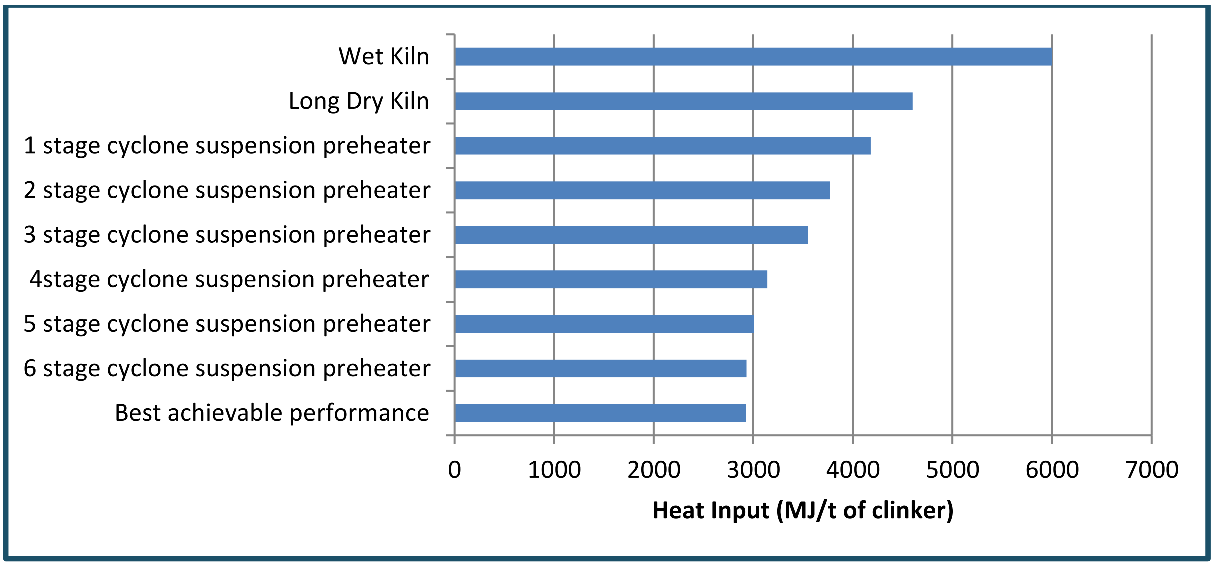
In terms of material conveying systems, the most common method of conveyance is an air lift. In an air lift, fine powdered material is transported in a piped stream of fast blowing air from one part of the plant to another. An alternative to this is bucket elevator technology which uses mechanical power to move materials. Eskom claims that bucket elevators draw on average 0.41kWh per ton of material compared to 1.1kWh by air lifts. Switching would thus provide a 63% electricity saving.

Although electricity consumption is not a large portion of the energy usage in the production of cement, given the high Scope 2 emission of electricity in South Africa and the high (and rising) cost of electricity, any savings based on the above would already have been considered by the industry, according to interviews. Capital costs of changing grinding technology are seen as prohibitive given current and near-term market dynamics. Globally, however, the IEA, despite its scepticism of the final net effect of reducing electricity consumption by upgrading grinding and cooling technology, suggests in its roadmap that the 91kWh/ton of cement electricity intensity of the industry in 2014 can decline to 87kWh by 2030, 83kWh by 2040, and 79kWh per ton of cement by 2050. This 13% reduction in electrical consumption is derived predominantly from improvements in grinding technology.

Increasing thermal energy efficiency

In 2014 the thermal energy intensity of clinker (not cement) was 3.5GJ per ton. In the IEA Technology Roadmap this should be reduced to 3.1GJ per ton by 2050 to support a 2°C scenario. Cement kilns are the key infrastructure in a cement plant and act essentially as a huge furnace where clinker is made. Preheated and sometimes precalcined raw material is fed into an angled rotating tube. As the material tumbles through the tube it moves through section of increasing heat as it moves closer to the flame which sits at the bottom of the kiln. The kiln is supplied by a raw mix of fuels to form an intense flame which reaches temperatures of 1850 to 2000°C. The efficiency of a kiln is mainly determined by the type of kiln technology but equally importantly the design of the clinker making process. Unfortunately, the typical lifespan of a kiln is 50 years (WWF 2007) and given the substantial capital replacement cost most kilns in use today do not represent world best practice. As seen below different kiln technologies have fundamentally different energy consumption requirements.

Figure 9: Thermal energy consumption by rotary kiln type[13]



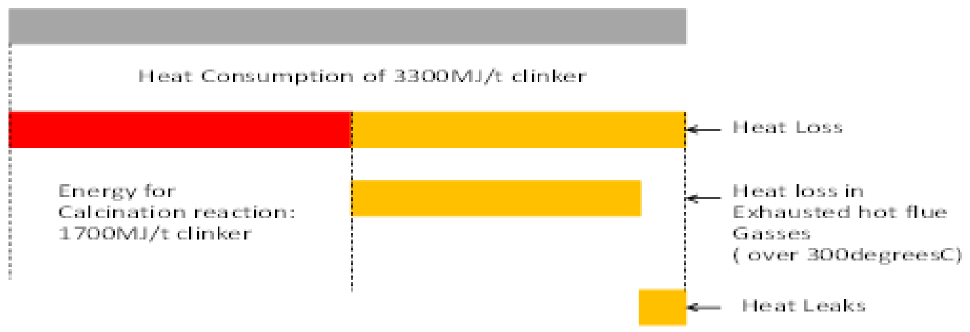
Source: IEA (2018), WWF (2007), IFC (2017)

The majority of globally operating kilns today are long dry kilns. Larger kilns are more efficient than smaller kilns but a key performance indicator in a kiln is the quality of refractory materials used to provide thermal insulation.

The IEA claims that refractory insulation materials are usually domestically produced and in developing countries the quality of such materials is far inferior to best performance materials used in developed countries. This in part explains why energy intensity of cement manufacturing in Western Europe averages 4400MJ/t clinker versus for example 5500MJ/t in Vietnam. However, the most important component of thermal energy efficiency relates to heat loses and how these are managed.

[13] As will be shown, most South African cement plants operate Long Dry Kilns. Large mega plants by industry leaders have 6-stage cyclone preheaters. Smaller and older plants have from 1- to 4-stage cyclones and pre-heaters.

Figure 10: Heat Consumption in cement plants



Source: WWF (2007)

If a kiln uses on average 3300MJ of thermal energy to produce a ton of clinker, only 52% of the thermal energy is used in creating the chemical reaction of calcinations. The remaining 48% of energy is lost either in the form of unrecoverable heat loss (mainly due to insulation and process design) but predominantly in hot flue gasses which exit the kiln at temperatures in excess of 300°C. Improving technology and processes to increase heat recovery is thus crucial to improving thermal efficiency. State of the art heat recovery is currently undertaken by preheaters which act as a form of heat exchangers where the raw mix for cement is heated by the captured exhaust gasses leaving the kiln. As a result of preheating, the thermal energy required in the kiln to reach required temperatures of 1650°C are substantially reduced. Modern gas suspension heaters consist of 1 to 6 stages (most commonly 4) and can precalcine 20% of the feed. The WWF notes that although technically additional stages can be added, beyond 6 stages, the consumption from fans used in the process of moving heated gasses would be unviable compared to the little gain that can be achieved. As shown above, a long dry high volume kiln with a 6-stage cyclone suspension preheater consumes energy equal to the best available performance in the industry given current technology. The IEA Roadmap predicts that the retrofitting of preheaters in all plants will provide a 0.6GtCO_2 reduction by 2030 (IEA 2018)

Besides investing in state of the art heat recovery systems, the IFC suggests that significant thermal savings can also be derived from improved operating and maintenance best practice. The key efficiency improvements it suggests are firstly reducing kiln exit gas losses by operating optimal oxygen levels in the kiln and optimising the burner flame shape and temperature. By using a multi-channel burner instead of a mono-channel burner a fuel saving of 50MJ to 80MJ per ton of clinker can be expected using a conventional long kiln. This is a low-cost retrofit but may not be cost effective given the cost of coal in some countries. Second, it recommends plant managers reduce the amount of dust in exhaust gasses by minimising gas turbulence. Dust carries energy away from the kiln where it is captured by dust collectors. The dust is recycled into the raw mix before it enters the cyclones or kiln. Decreasing the incidence of dust decreases additional demand for thermal energy required to bring a given volume of raw mix up to temperature. Third, the IFC suggests that it is possible using control processes to lower the clinker discharge temperature from the kiln. This allows more heat within the pyro-processing system to be maintained. Finally, it suggests that in many cases seals can be upgraded to minimise cold air leakage into the system and losses of heat out of the system.

As shown, state-of-the-art technology and best practice, currently, return a 2.95GJ/t of clinker energy requirement. The IEA Roadmap calculates that the theoretical minimum requirement of 1.85GJ/t to 2.8GJ/t clinker is defined by chemical and mineralogical reactions. As such, if a kiln is fitted with a 6-

stage preheater and precalciner, it is operating at near to the theoretical minimum of energy required in the production of clinker.

Both the above thermal energy and electrical efficiency sections show that most cement plants using best practice and state of the art technology are very close to being energy efficient with only marginal gains being available from additional improvements. As such, these two areas receive less attention in the literature than the next three possible decarbonisation interventions: the use of alternative fuels, the creation of blended cements, and the design of novel cements.

The use of alternative fuels

At a global level, it is estimated that 70% of thermal fuel used in the cement industry comes from coal, 24% from natural gas and oil and only 5% from alternative fuels (biomass and waste). These global estimates (WWF 2007), however, hide substantial regional variations. For example, in Germany and the Czech Republic 60% of fuels used in the cement industry are derived alternate fuels, while in America the percentage is 26%. China, India, Africa, the Middle East and Eurasia all have very low (if any) usage of alternative fuels, thus decreasing the global average to just 5%. The IEA Roadmap suggests that it should be possible to decrease the share of fossil fuel from 95% to 70% by 2050 by increasing the use of alternate fuels. This could result in a 24% decrease in the CO_2 emissions of the industry as the current thermal energy demand which produces 0.088tCO_2 per GJ could be reduced to just 0.058tCO_2 per GJ (IEA 2018). These types of substitution rates are mirrored in the WWF report, which suggests a 6% to 16% displacement of fossil fuels by 2030 and a resultant decrease of cement sector emissions of 0.16Gt CO_2 emissions a year can be achieved. The WWF report does, however, stress that since large cement plants are a suitable application for low-quality coal and coke fuels, and given the comparatively low cost of these inputs, there will be limited economic viability expected in the coming decades for a switch to less CO_2 intensive fuels.

Suitable alternative fuel used in the cement industry can be derived either from fossil-based alternatives or alternatives of biological origin, i.e. biomass. Most fossil-based alternate fuels are derived from industrial processes without the intent of being used as fuel. They can either be domestic or industrial wastes. The most common industrial wastes which can be used are tyres,[14] waste oils and solvents. Residues from the oil, pulp and paper industries, chemical wastes, plastics, coal slurries, distillation residues, oil shales, and packaging wastes can also be used and often have a high calorific value. Hazardous materials can be used as an alternate fuel in the cement industry as the high temperatures found in the kiln are sufficient to dissociate most toxic molecules.

Table 1: Alternative fuels compared to coal

Fossil Fuel Type	Energy Content GJ/t	Emissions Intensity CO_2/GJ
Coal	29	92
Waste oil	38	74
Waste tires	36	85
Mixed Industrial Waste	19	83
Solvents	22	74
Plastics	30	75

Source: WWF (2007)

Bar shaft kilns and wet kilns, most modern cement plant kilns (long dry kilns) are suitable for burning waste materials in the kiln as an alternative to burning coal or coke. There are, however, limits to what

[14] Tyres are being used as alternative fuel at two plants in South Africa. Details described later in the document.

can be used as a minimum average calorific value of 20GJ/t to 22GJ/t of fuel is required to fire a kiln. As such, waste oils with a calorific content of 38GJ/t, waste tyres with 36GJ/t and plastics with 30GJ/t are all suitable for kiln firing and provide higher energy content than coal at 29GJ/t. Mixed industrial wastes at 19GJ/t and solvents at 22GJ/t are less suitable for use in the kiln but can be burned as fuel in the precalciner which operates at a lower temperature. Kilns are also highly flexible and can use a mix of fuels without requiring substantial retrofitting.

The use of fossil-based alternative fuels is not without its technical challenges. Many of these waste streams have a high moisture content, and high concentrations of chlorine and other harmful metals such as cadmium, thallium and mercury. The higher moisture content requires additional thermal energy to dry the waste out, while chlorine and trace amounts of dangerous metals require additional procedures to ensure the removal of kiln dust is properly handled. In some (but not all) instances, the metal content of the dust can be added to the raw mix used to produce clinker with no decrease in the quality of the clinker. The need to minimise the presence of harmful substances and the need to optimise the fuel mix and ensure uniform and consistent composition requires pre-processing of alternate fuels. This pre-processing cost is in some circumstances offset by revenue generated by the cement plant for disposing of waste materials for a fee.

The common challenges to using alternative fuels in any industry apply equally to the cement industry. Issues such as maintaining a ready, predictable and consistent stream of waste, waste management legislation, and social levels of acceptance of co-processing all apply as do the complex and expensive regulatory actions necessary for such processing to occur. In addition, competition for supply between the cement industry and the waste-to-energy incineration industry is an issue especially in developed nations.

Biologically derived alternate fuels (biomass) can also be used in cement production. The most common sources of biomass globally are by-products from the agricultural and food industries including: rice husk ash, waste wood, straw, pulp and paper residues, and food wastes. Water treatment sludge and solid wastes can also be used. Biomass cannot be burned directly in commercial kilns. Direct combustion of biomass can, however, be used for preheating and precalcining before the raw mix enters the kiln. This is due to lower calorific values such as straw with 15GJ/t, coconut husks and sewer sludge both at 14GJ/t, or wood at 20GJ/t (WWF 2007). Biogas can be used in the calcining process in a long dry kiln.

Key challenges in using biomass as a source of thermal energy are its moisture content and its need to be ground into a uniform size. As with using fossil based alternative fuels, the issues of using biomass in the cement industry are the same as those in other industries.

Reducing the clinker to cement ratio (blended cements)

There is consensus that blended cements offer one of the most viable, attainable and effective means by which to reduce carbon emissions by the cement industry in the short to medium term. The IEA Roadmap suggest that 37% of the carbon reduction in its scenario to 2050 would be derived from the uptake of blended cements, while Leanne and Preston (2018) believe that blended cements could theoretically account for a 70% decline in carbon emissions for the industry.

The concept of blended cements is relatively straightforward. The share of clinker in cement on a mass basis is defined as the clinker to cement ratio. As CO_2 emissions originate in the production process to form clinker, if cement is manufactured with a lower clinker ratio, this will decrease the emissions per ton of cement.

Zero Carbon Australia (2017) calculates that, for every 10% substitution of clinker, CO_2 emissions decrease by 6%. This means that if the industry is able to decrease clinker content by 50%, cement industry emissions would fall by 30%. The IEA estimate that 3.7GJ and 0.83 tons of CO_2 could be saved per ton of clinker replaced. Traditional OPC has a ratio of 95% clinker and 5% gypsum. The IEA Roadmap believes that an average clinker ratio of 60% could be achieved globally by 2050. According to South Africa's greenhouse gas mitigation potential analysis (MPA),[15] decreasing clinker content in cement would account for 50% of total mitigation potential for the sector in the short run. If, on average, clinker content can be reduced to 66% in South Africa this would mitigate 0.75MtCO_2 emissions per annum with a marginal abatement cost of R122/tCO_2 emissions in 2020. Almost all countries currently produce some blended cements with varying levels of clinker substitution. Arp, Bole-Rentel and Jakuja (2018) claim that clinker substitution cements have already produced a global saving of 500Mt of CO_2 emissions.

There are two kinds of substitutes for clinker. The first are known as fillers. These fillers are not chemically reactive and thus do not contribute to the performance of the cement and specifically do not play a role in the strengthening of concrete. The most common filler is raw ground limestone. Third-party blenders often buy clinker from cement manufacturers and then extend this clinker to form cement by adding large quantities of limestone. This often results in cheap cement with inferior performance properties that fall short of national standards. In 2019, PPC undertook a market surveillance exercise to determine conformity of cement products in the local market. Using an independent laboratory, it found that 11% of extended cements failed weight tests. More worryingly, 73% of extended cements sold in South Africa failed strength tests as per national regulations (Engineering News 2019) even though they carried the South African Bureau of Standards (SABS) stamp. As contractors and builders are unable to determine the strength of cement products, the illegal use of fillers to produce cheap inferior cement poses a risk for the built environment.

The second substitute for clinker is known as supplementary/substitute cementitious materials. SCMs are different to fillers as they react with the clinker and play an active role in the strengthening and overall performance of the concrete it is used to produce. When talking about blended cements, stakeholders refer to SCM blends, not blends with non-reactive fillers. South African standards allow for: siliceous fly ash, calcareous fly ash, blast furnace slag, silica fume, natural pozzolana/clay and natural calcined pozzolanas/clay to be utilised as SCMs. The three most commonly used SCMs globally and in South Africa are: Ground Granulated Blast Furnace Slag[16] (GGBS); fly ash and calcinated clay/ natural pozzolana. GGBS is an industrial waste product produced by the pig iron and steel industry; fly ash is an industrial waste product produced by the burning of coal and calcined clay is widely available across all regions of the world. Utilising GGBS and fly ash blended cements not only reduce overall CO_2 emissions by decreasing the need to produce clinker but they improve resource use efficiency and reduce additional environmental impacts from disposing of these products in landfills and dams. The percentage of SCMs allowed in a cement mix depends on national standards as shown in Figure 11 and this leads to a complex range of differentiated cement products that have different characteristics and different applications.

[15] The MPA is dealt with in more detail in the South African analysis in Section 5.

[16] Dr Cyril Attwell notes that in South Africa Ground Granulated Corex slag is also used (Interview in 2020).

Figure 11: Cement specifications – South African National Standards 50197 (SANS)

Main types	Notation of products (types of common cement)		Composition, percentage by mass[a] Clinker K	Blast-furnace slag S	Silica fume D[b]	Pozzolana Natural P	Pozzolana Natural calcined Q	Fly ash Siliceous V	Fly ash Calcareous W	Burnt shale T	Limestone L	Limestone LL	Minor additional constituents
CEM I	Portland cement	CEM I	95 - 100	-	-	-	-	-	-	-	-	-	0 - 5
CEM II	Portland-slag cement	CEM II A-S	80 - 94	6 - 20	-	-	-	-	-	-	-	-	0 - 5
		CEM II B-S	65 - 79	21 - 35	-	-	-	-	-	-	-	-	0 - 5
	Portland-silica fume cement	CEM II A-D	90 - 94	-	6 - 10	-	-	-	-	-	-	-	0 - 5
	Portland-pozzolana cement	CEM II A-P	80 - 94	-	-	6 - 20	-	-	-	-	-	-	0 - 5
		CEM II B-P	65 - 79	-	-	21 - 35	-	-	-	-	-	-	0 - 5
		CEM II A-Q	80 - 94	-	-	-	6 - 20	-	-	-	-	-	0 - 5
		CEM II B-Q	65 - 79	-	-	-	21 - 35	-	-	-	-	-	0 - 5
	Portland-fly ash cement	CEM II A-V	80 - 94	-	-	-	-	6 - 20	-	-	-	-	0 - 5
		CEM II B-V	65 - 79	-	-	-	-	21 - 35	-	-	-	-	0 - 5
		CEM II A-W	80 - 94	-	-	-	-	-	6 - 20	-	-	-	0 - 5
		CEM II B-W	65 - 79	-	-	-	-	-	21 - 35	-	-	-	0 - 5
	Portland-burnt shale cement	CEM II A-T	80 - 94	-	-	-	-	-	-	6 - 20	-	-	0 - 5
		CEM II B-T	65 - 79	-	-	-	-	-	-	21 - 35	-	-	0 - 5
	Portland-limestone cement	CEM II A-L	80 - 94	-	-	-	-	-	-	-	6 - 20	-	0 - 5
		CEM II B-L	65 - 79	-	-	-	-	-	-	-	21 - 35	-	0 - 5
		CEM II A-LL	80 - 94	-	-	-	-	-	-	-	-	6 - 20	0 - 5
		CEM II B-LL	65 - 79	-	-	-	-	-	-	-	-	21 - 35	0 - 5
	Portland-composite cement[c]	CEM II A-M	80 - 94	←				6 - 20				→	0 - 5
		CEM II B-M	65 - 79	←				21 - 35				→	0 - 5
CEM III	Blastfurnace cement	CEM III A	35 - 64	36 - 65	-	-	-	-	-	-	-	-	0 - 5
		CEM III B	20 - 34	66 - 80	-	-	-	-	-	-	-	-	0 - 5
		CEM III C	5 - 19	81 - 95	-	-	-	-	-	-	-	-	0 - 5
CEM IV	Pozzolanic cement[d]	CEM IV A	65 - 89	-	←		11 - 35		→	-	-	-	0 - 5
		CEM IV B	45 - 64	-	←		36 - 55		→	-	-	-	0 - 5
CEM V	Composite cement[d]	CEM V A	40 - 64	18 - 30	-	←	18 - 30	→	-	-	-	-	0 - 5
		CEM V B	20 - 39	31 - 50	-	←	31 - 50	→	-	-	-	-	0 - 5

Notes

(a) The values in the table refer to the sum of the main and minor additional constituents.

(b) The proportion of silica fume is limited to 10%.

(c) In portland-composite cements CEM II A-M and CEM II B-M, in pozzolanic cements CEM IV A and CEM IV B, and in composite cements CEM V A and CEM V B, the main constituents other than clinker shall be declared by designation of the cement.

Source: The Concrete Institute (2020)

Portland cement, which has a clinker content of >95%, is described by the class CEM I. CEM II cements can be grouped depending on their clinker content into categories A (80%-94%) and B (65%-79%). CEM II cements thus have more SCM usage and are higher blended cements than CEM I cements. Equally, CEM III types of cement can be categorised into two sub-groups A (35%-64% clinker) and B (20%-24% clinker) and have higher substitution ratios and are more blended than CEM I or CEM II cements. The table also illustrates the type of SCM or extender used in the blended cement. For example, S identifies the percentage use of blast furnace slag while L shows the range of limestone substitution which can occur in different types of cement. The cement nomenclature is thus highly descriptive and the SANS regulations identify the universe of possible cements, substitution rates and substitution materials. For instance, CEM II A-V indicates a specific kind of cement which has between 65% and 79% clinker and has been extended with fly ash. Building companies provide consumers with information about the strength, drying time, and the timing of strength development for each type of cement. Different cements are thus required for different uses and application environments.

In 2008, when data was last collected on product sales, CEM I accounted for 29% of sales, CEM II A 26% of sales, CEM II B 26% of sales, 12% CEM III plus CEM V and 7% to third-party blenders. CEM I and CEM II remain the most commonly purchased forms of cement for general contracting.

Fly ash is the main waste product of coal-fired power plants and exists as a fine grey powder that collects in exhaust flues. It contains high levels of silicon and aluminium. For a long time power stations saw fly ash as an inconvenient waste to be dumped in ash dams. Today, it is increasingly in demand as an SCM. Fly ash from different power stations varies significantly in its chemical composition and particle size and hence needs to be processed and classified before it can be used as an SCM. It is crucial that the carbon content of the ash remain below 5% as any higher and the resultant concrete will lack final strength.

South Africa produces an enormous 40 million tons of ash per annum, with Eskom producing 31.5 million tons of fly ash and 3.5 million tons of bottom ash and Sasol producing five million tons of gasification ash. Currently, fly ash from Eskom's Kriel, Matla, Kendal, Matimba, Lethabo and Majuba plants is reprocessed but this accounts for only 5% of ash produced annually. The remaining 95% is dumped in ash dams or in landfill where it runs the risk of toxic seepage into adjacent soils and waters (Shekouvtsova 2015). This ash utilisation level is very low compared to 80% usage in Germany, 65% usage in France and 55% in the UK[17]. Low utilisation rates in South Africa are usually ascribed to the fact that the placement of coal-fired power plants and cement plants are far apart geographically and transport is expensive and difficult given that fly ash is very fine and very bulky (Maqhawe Technical & Financial Services 2006). Internationally there is concern that sources of fly ash are drying up as coal fired power stations are replaced with more environmentally friendly power generating options. As such, experts tend not to focus on fly ash as an important SCM globally. In South Africa, however, access to good quality fly ash should remain unproblematic until at least 2050, thus fly ash blended cements can and should become more commonly used.

Ninety-five percent OPC clinker cement usually costs between R1 100 and R1 500 a ton. Fly ash is available at about R400 to R500 a ton making it a cost effective option compared to OPC. The current standards allow for up to 35% fly ash substitute to be added to clinker. This limitation is because of the technical performance of fly ash blended cement. Essentially fly ash blends suffer from slower setting times and low short-term strength as measured at seven and 14 days. This makes such blends less appealing to contractors when deadlines and short turnaround times are often required. Even if contractors are prepared to wait for longer setting and strength times, the delays will increase the overall cost of the project, negating any cost saving in using a cheaper product. Long-term strength of fly ash blended cement is, however, improved post 28 days, it is less prone to cracking, and requires less water to mix into concrete. Attwell (2020) draws attention to the fact that fly ash can technically substitute far higher percentages of clinker than currently allowed in the regulations. In the City Deep Container Port, slabs were thrown with a 68% fly ash cement mix, and in Chicago, a Hindu Temple was constructed using 65% fly ash cement (Zero Carbon Australia 2017). Experts agree that standards based on specific maximum percentages of SCMs limit the use of SCMs.

Ground granulated blast furnace slag is a by-product of refining iron ore in a blast furnace. GGBS is a glassy coarse material which is chemically similar to Portland Cement clinker. GGBS contains silicon

[17] These utilisation rates are higher as there are fewer coal-fired power stations and hence a smaller (and decreasing) volume of ash available for reprocessing.

and aluminium and about 40% calcium oxide. To be useful as an SCM, GGBS must be chilled rapidly as it leaves the furnace and then finely ground. As such, a fair amount of co-processing is required. In South Africa, ArcelorMittal have a co-processing facility at Van der Bijl Park where GGBS is produced. Unfortunately, this slag is not freely available in the market as ArcelorMittal have an offtake agreement with AfriSam. Unlike fly ash, GGBS promotes faster setting rates, but it also suffers from low strength gain at seven and 14 days. Its long-term strength post 28 days, however, outperforms 95% clinker OPC (Zero Carbon Australia 2017). In addition, GGBS cement blends are less prone to sulphate attack and corrosion.

GGBS is approximately double the price of fly ash at R800 to R900 a ton, but still cheaper than 95% OPC clinker cement. This cost differential is mainly due to the high cost of grinding the slag once it cools. Because of the chemical composition of GGBS, WWF (2007) claims that slag-based cements can perform as well as clinker OPC cements at a 70% level but national standards do not permit this. In two experimental projects, London Paddington Station's new roof slab contained 72.5% GGBS clinker substitute (Arp, Bole-Rentel and Jakuja 2018) while in South Africa the Loeriesfontein Wind Farm used a 95% GGBS clinker substitution resulting in a cost saving of 2% and a carbon emissions saving of 30% (Attwell interview 2020).

In South Africa, GGBS substitution percentage can be as high as 95%. Internationally there are concerns about the availability of GGBS in the long term as blast furnaces are replaced with environmentally friendlier Electric Arc Furnaces, which produce steel slag as a by-product. Research is underway to use steel slag instead of GGBS but to date no products using steel slag are available on the market and no experimental projects have been completed. In addition, research is underway to see if it is possible to utilise the millions of tons of blast furnace slag which has been discarded over the past 50 years. The suitability of stockpiled slag is unknown but may provide a massive resource for SCMs in the future.

Given that globally there are concerns about the long-term availability to fly ash and GGBS, the majority of global blended cements are based on calcined clays[18], also known as natural pozzolanas. This SCM has received the greatest attention globally as it exists in virtually unlimited, easily accessible quantities in virtually every region in the world (WWF 2007). Using calcined clays requires the same process as manufacturing clinker but calcination occurs at only 600°C thus substantially decreasing the thermal energy required in production. Scrivener (2014) suggests that calcined clays can only be used as a 30% substitute for clinker while Zero Carbon Australia (2017) believe that up to 50% replacement is possible. In South African standards, substitution up to a maximum of 35% is permissible.

Uncertainty regarding the percentage use of calcined clays has led to double substitutions and the development of limestone calcinated clay cement (LC^3). LC^3 contains 30% calcined clay, 15% limestone, 5% gypsum and 50% clinker. Using the Zero Carbon Australia factors that a 10% clinker reduction achieves a 6% carbon emissions reduction, producing LC^3 instead of 95% OPC clinker would reduce carbon emissions by 30%. An additional advantage of LC^3 is that the 15% limestone used in the blend can be low quality limestone that is of insufficient quality to be used in OPC clinker production. By using this poor quality limestone quarrying resources are better utilised and a limestone quarry's lifespan can be extended. Berriel (2016) found that LC^3 outperformed 95% OPC, while Scrivener (2014) found that LC^3 cements had poorer one-day setting and strength performance versus OPC but

[18] Calcined clay is clay that has been heated in a kiln to drive out volatile materials. It is used as a supplementary cementitious material and can act as a partial replacement for clinker.

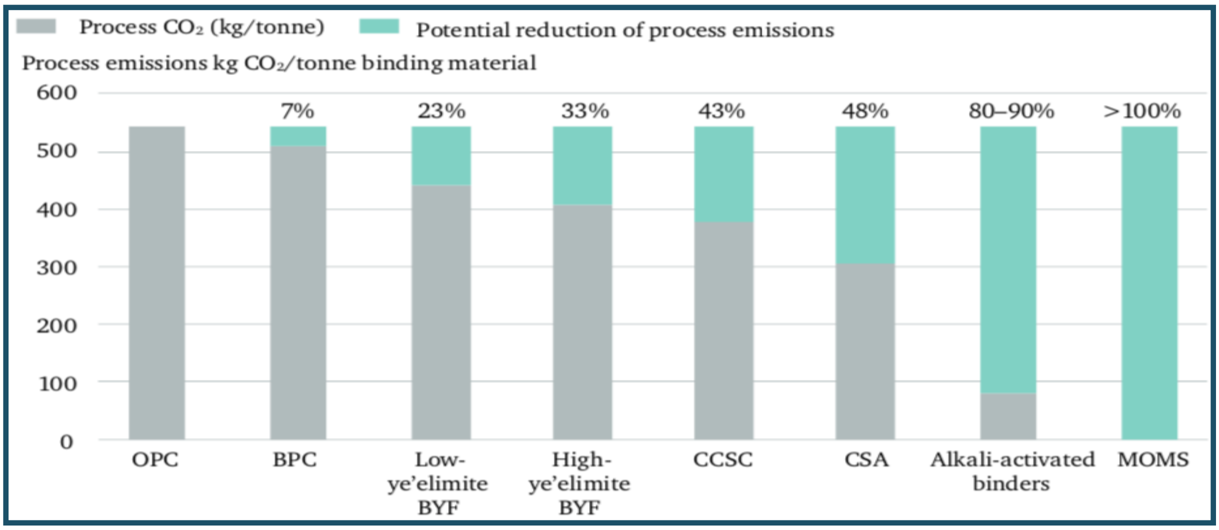
similar strength and mechanical properties after seven days. Long-term durability of LC^3 remains an issue and research is ongoing.

The creation of blended cements (using fly ash, GGBS and calcined clays) offers great potential for the industry to lower its carbon footprint going forward. Current rates of global clinker substitution average 65%[19] but the IEA believes that this global average can be decreased to 60% by 2050. As shown in Figure 8, Leanne and Preston believe that 70% to 90% of the theoretical decarbonisation of the cement industry can be achieved through clinker substitution. Three key constraints and limitations exist. First, durability remains an unknown factor given that many blended cements have only been in field use for a limited number of years and their performance over the lifespan of a piece of infrastructure is not yet known. Second, education among contractors and engineers is a limit on adopting blended cements, and finally, composition-based standards instead of performance-based standards limit the rates of substitution which can be undertaken. Supporters of a lower carbon footprint for the industry are calling for performance-based standards rather than formulaic standards as currently exist.

Novel cements

Novel cements are substances made from alternatives to Portland clinker that mimic the properties of traditional OPC but can be produced using less energy and releasing fewer emissions during their production. Novel cements use hydraulic minerals to bind aggregates. Commonly researched novel cements include: high and low belite-ye'elimite-ferrite (BYF) clinkers, calcium sulfoaluminate cements calcium aluminate cements (CACs), carbonatable calcium silicate cements, alkali activated binders also known as geopolymer cements (GPCs) and magnesium oxide derived cements (MOMs). Figure 12 shows the process CO_2 emissions for these different types of novel cements and hence their relative potential to reduce process emissions.

Figure: 12 Process CO_2 emissions for different novel cement types



Source: Lenne and Preston (2018)

According to the South African Mitigation Potential Analysis (MPA) (DEA, 2014), GPCs are identified as one of the two novel technologies (together with CCS) that offer the largest emissions reduction potential in the sector in the long term. The MPA assumes that GPCs production techniques will account for 2.5% of total cement production by 2040 and will have the highest long-term emissions

[19] Clinker substitution rates differ substantially across countries: Japan 90%, Malaysia 89%, China 75%, the European Union 78%, Brazil 65% and Morocco 73%.

reduction potential of all cementitious materials in 2050 (Arp, Bole-Rentel and Jakuja 2018). The Greenhouse study suggests that a 50% uptake of GPC is possible by 2030 and 100% by 2050 (Lewis et al 2017). The IEA Roadmap (2018) however, discounts novel cements in its 2050 targets as it argues that there are no currently commercially viable options available, while Leanne and Preston (2018) suggest that novel cements are no silver bullet for the industry but one of a range of potential solutions that offer different prospects under different circumstances.

A brief overview of some of the advantages and disadvantages of some of these novel cements provides a sense of the challenges facing their commercialisation, and also lays a foundation for understanding that the future of cements may be non-commodity based products but specific cements designed for specific applications.

CACs have been produced since the 1960s and were originally invented to resist sulphur attack. Unfortunately, the product is open to a process known as conversion, which leads it to becoming more porous overtime. As a result, several buildings made with CACs collapsed in the 1970s. Second, CACs are about five times more expensive to produce than OPC (Arp, Bole-Rentel and Jakuja 2018) and require access to bauxite which is not readily available in South Africa and very expensive. The Arp, Bole-Rentel and Jakuja (2018) report thus suggests that although CACs decrease carbon emissions during the production process, they would only be viable in specific applications and circumstances when its advantageous properties warrant its higher cost.

According to Shi, Jimenez and Palomo (2011), calcium silicate cements (CSCs) and BYFs based on ye'elemite can be produced at a temperature of between 1200°C and 1300°C and release less CO_2 emissions during the pyro phase, resulting in a 50% CO_2 emissions reduction when compared to OPC. CSCs and BYFs have the advantage of exhibiting expansive properties which are useful in the production of products such as self-stressed concrete pipes. Unfortunately, its inputs are very expensive and there is a lot of diversity in CSC mixtures making it difficult to generalise or commoditise the product. Substantial consumer support would be required, which would materially increase the cost of the product. High levels of consumer support and high input costs thus minimise the chances of CSCs becoming widely adopted in the marketplace.

MOMs are entirely experimental at present and only exist in laboratories, yet they must be considered as the offer the technical possibility for cement to become climate neutral. MOMs are based on magnesium oxide which can be sourced from magnesium silicate rocks such as olivine or serpentine. These magnesium silicates contain no carbon dioxide and can thus be processed to form magnesium oxide without GHG emissions. This magnesium oxide can then be made to react with carbon dioxide and water to create a hardened cement consisting of stable magnesium hydroxyl carbonate hydrates. These hydrates can capture carbon dioxide and can thus make a substantial contribution to reducing atmospheric carbon dioxide levels. Novacem, an Australian innovation company (which has subsequently gone out of business), did produce a MOM which they proved had a negative carbon footprint of 0.6 tonnes of carbon dioxide per ton of MOM. There is, however, general consensus that innovation and technology of MOMs is sufficiently nascent that it cannot pragmatically be considered as a mitigation option in any reasonable 2050 climate change scenario.[20]

The novel cement with the greatest near-term potential to decarbonise the industry is GPCs. GPC is an alkali aluminosilicate binder which forms a gel or geopolymer when aluminosilicate is activated (turned on) by an alkali substance. When mixed with aggregates and sand, the gel holds these substances together to form a concrete. Aluminosilicate for GPCs can be sourced from GGBS, fly ash, calcined clays and other industrial waste streams. The alkali substance used for activation needs to be produced in one of two ways. First, the activator can be manufactured by fusing sodium carbonate

[20] MOMs do not appear in the MPA.

and silica in a 1000°C furnace. It is estimated that this production method produces 540kg of CO_2 emissions per ton of product (Zero Carbon Australia 2017). An alternate production method is the electrolysis of salt water to produce caustic soda which must then be fused with silica sand in a furnace at approximately 1000°C. This second process is highly energy intensive and is only viable as a mitigation strategy if renewable energy is used. McClellan et al (2011) found that GPCs cost between 7% lower and 39% higher than OPC, while Tempest et al (2015) suggest that GPCs are three times more expensive than OPC.[21]

Over and above issues of cost, much debate exists on the performance of GPCs, the practical usability and workability of GPCs and indeed how environmentally-friendly they really are. WWF (2018) provides a good summary of the current debates. Proponents of GPCs claim that they are an extremely viable low-carbon substitute for OPC with no quality trade-offs. Indeed they argue that GPCs have advantages over OPC including: high compression strength, low shrinkage, high acid resistance, low thermal conductivity, high temperature stability, and decreased repair and maintenance costs over its lifetime. This together with the potential to achieve 75% to 90% CO_2 emissions reductions over traditional OPC make supporters of GPCs confident that this novel cement has a central role to play in the long term decarbonisation of the industry.

At the same time, however, a number of studies suggest that the emissions reduction potential of GPCs is lower than commonly suggested. McLellan et al's life cycle analysis (2011) found that GPCs only reduced carbon emissions by between 44% and 64%. Turner and Collins (2013) found that GPCs only reduced GHG emissions by 9% compared to OPC when all the energy and emissions of sourcing raw materials, and especially creating the alkali activators, were taken into account. As such, the eco credentials of geopolymer cements remains to be accurately assessed.

Leanne and Preston (2018) look in detail at the barriers to the possible diffusion of novel cements from both a supply and a demand perspective. On the supply side, the most important concern for cement producers is that shifting to GPC production would strand their current assets as GPC require a completely different production process. If the demand for GPCs was rapidly scaled-up, this would decrease the demand for clinker and decrease the value of clinker production assets. A second supply side concern is the availability of raw materials. To be able to displace large percentages of OPC, GPC producers would need to be able to source required inputs which would in all likelihood be controlled by producers outside the cement industry. This would fundamentally change the commercial relations in the cement value chain, as currently cement producers control their own clinker input chain through the ownership of limestone quarries.

Demand side barriers appear even higher. The first point which Leanne and Preston (2018) make is that currently consumers are not asking for lower carbon cements, as novel products are seen as too risky, more costly and more difficult to use. The biggest demand barrier to GPCs is that they change the characteristics of concrete. GPCs tend to have lower early strength development and longer setting times than OPC. This does not support current on-site practices where concrete is cast in the afternoon and then demoulded the next morning. In addition, strong alkalis pose a safety risk to workers as they can corrode human tissue. Using GPCs would require appropriate handling and safety procedures on-site as well as substantial education of the work force.

Second, the lack of understanding of the technical performance of GPCs over time is a major barrier to adoption and acceptance. Understanding this technical performance is limited by the reality that all current technical performance testing is based on OPC and these testing methods and measures

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[21] Cost differentials exist due to different production technologies employed, different scales of production, different input materials and different costs of energy used in manufacture.

have limited applicability to novel and GPC cements in particular. This means that not only does technical performance need to be established, but new testing methods and measures are required to achieve this understanding.

A third issue is that of long-term durability. OPC based cements have been in use for over 200 years, thus decades of durability knowledge has been accumulated. In introducing a novel cement, durability can be extrapolated only by exposing a small sample to extreme conditions for a short period in a laboratory setting. This extrapolation based durability test can only ever be indicative and most construction sector stakeholders believe that it is necessary to wait five or six decades to fully assess durability in field tests before novel cements can be confidently demanded in the market.

Finally, the issue of standards create a high regulatory barrier to any future adoption of GPCs at scale. Current cement specifications and regulations are prescriptive and take the form of compositional requirements to fulfil specific requirements for a specific application. Developing performance-based standards would be a fundamental change in how standards are set and this could take decades in an industry which is highly conservative.

Leanne and Preston (2018) argue that these supply and demand barriers are interlinked and reinforcing. They suggest that these barriers together with the global concentration of cement firms and the representation of dominant cement companies in the preparation of technology roadmaps for the industry have resulted in the current industry being able to create a "soft lock on the status quo". This lock is echoed in the South African operating environment in which industry players in a WWF workshop in 2018 argued that the potential of GPCs to deliver the emissions reductions suggested by the MPA was questionable, and that concentrating on cement blends which reduce the clinker content of cement can "play a larger role in mitigation in the cement industry than purely substituting OPC for GPCs".

There are some examples of GPC use in the field to date but these are limited and all have been flagship projects in niche markets driven by the public sector. GPC was used at the City Deep Container Terminal in Johannesburg and at the Brisbane Airport in Australia to resurface a taxiing apron. Both are sufficiently recent that durability and performance measurements are still nascent.

Disruptions to the built environment

The sixth option to reduce the carbon footprint of the cement industry value chain is possible disruptions in the built environment which result in a decrease in the demand for cement and concrete. As Zero Carbon Australia (2017) phrases it – the most effective method to decrease the emissions of cement is to decrease the use of cement. This section looks briefly at key ideas which could contribute to decarbonising the built environment. Unfortunately, none of the existing literature quantifies the scale of possible emissions reduction and savings.

To change how building is undertaken would require innovations at five points along the construction chain: design, materials, construction, operation and use, and end of first life. Leanne and Preston (2018) identify that most carbon emissions from the built environment are related to the operation and use of a building or piece of infrastructure during its lifespan – these emissions account for 83% of total emissions from the built environment. Only 15% of the built environment's emissions come from the actual supply of construction materials. Thus, while the decarbonisation of the use of buildings and infrastructure remains the most important and crucial aspect of decarbonising the broader built environment, opportunities exist along the construction chain which cumulatively would impact the demand for cement and concrete moving forward.

Starting with design, topology optimisation is a term used to describe design aimed at optimising material usage within a given shape. So, for example, a concrete beam may not have to carry the same load across its entire length, and the ends may need less strength than the middle of the beam thus less cement is necessary along some parts of the beam leading to the optimal minimum amount of cement usage consistent with function. Other advanced software can produce new and novel shapes of design which also minimise concrete and cement usage. For example, computers can generate shapes for bridge support foundations that use 23% less concrete to deliver the same strength as an architect designed and structural engineer checked foundation. The problem is many of these optimal design shapes cannot be produced using conventional construction techniques or the existing skills base in the construction industry[22] (Zero Carbon Australia 2017). Finally, design can also be managed to substitute high-strength concretes in place of normal concretes. High-strength concrete is specially designed to achieve greater compressive strength than ordinary concrete. These high-strength concretes can be as strong as 230 megapascal, which makes them stronger than steel. High-strength concretes require more cement per cubic meter than ordinary concrete; however, significantly less concrete is necessary to support a given load. As a result, using high-strength concrete can lead to an overall reduction in the amount of cement used in a given construction project. Zero Carbon Australia found three examples of high-strength concrete usage which resulted in a 20% decrease in the volume of cement demanded compared to specifications using ordinary strength cement. An added advantage of high-strength concrete is that it extends the lifespan of the building or piece of infrastructure, resulting in a net decrease in cement usage over time.

Substitution products for traditional concrete can also substantially decrease demand for concrete and thus cement. Experimental building techniques using timber, hempcrete, straw bales and rammed earth[23] are gaining popularity. So too is the use of hybrid engineered composite products such as beams made of timber and steel in place of concrete beams and even recycled plastic bottles stuffed with plastic film as substitutes for brick. The use of these alternatives is often limited by the conservative nature of clients, architects and structural engineers who may lack knowledge of alternative materials, may be put off by the lack of long-term testing of their performance and durability, or negative perceptions of high costs and a bias against low-carbon products as inferior. Currently, supply issues also substantially constrain the ability of substitute materials to displace concrete as the dominant input for new buildings and infrastructure in the built environment.

The third element of disruption in the built environment may arise from fundamental changes in construction techniques themselves. Ideas here revolve around the automation of construction sites and the use of robots to undertake certain construction tasks. Such automation would remove the bottleneck of current techniques to the adoption of computer-aided optimal design and utilising shapes which are hard to create using human driven current methods of building.

In terms of operations and use, a huge opportunity exists to reduce cement and concrete consumption simply by maintaining buildings for their full design life. Residential and office buildings are generally expected to last 100 years and commercial buildings 50 years, but on average are replaced after only 25 years.[24] As Leanne and Preston (2018) point out, it is paradoxical that, as technical ability has increased in terms of creating more durable structures, the length of buildings' operational lifespan

[22] The literature suggests for example that curved and wavy foundation patters may be optimal in certain situations but that current cement formwork systems and training do not support their use on-site.

[23] Building technique using recycled motor vehicle tyres filled with soil, which is compacted into each tyre, forming an alternative to block work for walls.

[24] Of all the categories of buildings commercial buildings have the shortest lifespan. This is often due to tenant turnaround and the building needing to be substantially retrofitted for an alternate use. For example, when a Laundromat becomes a restaurant and then later is turned into a retail space.

has steadily declined. Insufficient durability is seldom the reason buildings are demolished, rather it is due to financial, aesthetic or practical reasons. Part of the fix to this problem is to extend the lives of buildings by adopting flexible design parameters at conception and using precast elements that can be reused. Designing buildings with highly flexible floor plans and modular wall arrangements could allow for different configurations for different uses without having to replace the overall structure. The use of precast wall panels, for example, would allow walls to be removed and placed in a different structure with no additional demand for cement or concrete.

Finally, there is the issue of end of life and the possibility of introducing building demolition rubble back into the economy rather than throwing it away (in line with a circular "closed loop" approach). Recycling concrete at present is problematic from a commercial perspective. Demolition concrete can be crushed and made into aggregate which could be used in future concrete mixes, however, the energy required to process demolition concrete is higher than that to process virgin aggregate. In addition, concrete for recycling is very heavy and high volume, making the transport cost extremely high. Currently demolition concrete is used in low-quality applications – predominantly roads. Examples do exist where demolition concrete can be commercially and viably recycled for aggregate, but this is most often the case when the demolition site and a site in need of substantial amounts of backfill happen to be adjacent or geographically close to each another.

Carbon capture and storage

The last possible intervention to decarbonise the cement industry is the use of carbon capture and storage technology. As per the IEA Technology Roadmap (2018), this future technology would account for up to 56% of its projected cumulative CO_2 emissions reductions in pursuit of its 2° scenario vision by 2050. CCS is appealing to the industry as it involves capturing the CO_2 emissions from a conventional cement plant and then securing the carbon dioxide component underground. It thus deals with the emissions from the calcining of limestone rather than requiring the industry to reduce emissions by other means. Globally, the main obstacle of CCS is its huge cost. Zero Carbon Australia estimates that adding CCS to a new cement plant would double the capital cost of the plant and result in operating costs also nearly doubling. It also notes that, given the location of cement plants near to limestone quarries, it is unlikely that plants would be close to geographical formations suitable for locking away carbon dioxide. In South Africa, the geological structure is unsupportive of the characteristics necessary for carbon storage thus CSS as a mitigation option is highly moot.

Despite these limitations, CCS remains the mainstay of the potential solution to decarbonising the cement industry in both the IEA 2018 and WWF 2007 studies. In the MPA, CCS back-end chemical absorption is projected to be taken up by 50% of the sector by 2050. CCS oxyfueling is predicted to be taken up by 25% of the sector by 2050.

5. GHG EMISSIONS IN SOUTH AFRICA'S CEMENT VALUE CHAIN

According to the Association of Cementitious Material Producers (ACMP 2011), South Africa's cement industry contributed 1% of the country's total GHG emissions in 2010. According to the Department of Environmental Affairs (DEA 2014), annual GHG emissions from the industry rose 27% between 2000 and 2010 from 3.3MtCO_2 to 4.2MtCO_2 emissions. In the DEA's GHG National Inventory (2016), the cement industry accounts for 84% of all mineral industries emissions and these increased by 17.9% between 2000 and 2015. In 2000, the local industry produced 3871GgCO_2e and, by 2015, this had risen to 5205GgCO_2e, driven by the increase in residential building. However, importantly since 2008 there has been a year-on-year reduction in emissions per ton of cement driven by increased use of clinker substitution. According to the ACMP, clinker substitutes rose from 12% in 1990 to 23% in 2000 and a substantial 41% in 2009. The MPA calls for this to rise to 60% by 2030.

In 2010, The Concrete Institute commissioned a study of GHG emissions in the local industry. Calculations of Scope 1, 2 and 3 emissions of inputs into the concrete industry were considered as well as emissions related to different types of cement as per Figure 11. The expanded scope is useful as it provides emissions figures for fly ash and slag, two most common SCMs used in current cement blends in South Africa, and which would also be used if GPCs were commercially produced. An equivalent (publically available) study has not been completed in the intervening period, therefore, the 2010 study remains the benchmark figure by which to assess the industry. The key finding of the 2010 report is that, relative to international norms, the South African cement industry performs relatively favourably with an average level of Scope 1 emission of 670kgCO_2/t cement, which is towards the bottom end of the global scale which stretches from 665kgCO_2/t cement to 935 kgCO_2/t cement. According to the GNR Indicator, South African cement plants produced on average 671kg[25] of CO_2 per ton of cement in 2016. This is above the GNR-calculated global average of 642 kgCO_2/t cement but better than the Middle East (712kg), Russia (707kg) and North America (745kg) (GNR Indicator n.d.). South Africa's emissions are, however, higher than its other BRICS (Brazil, Russia, India, China South Africa) trading partners with India producing on average just 582kgCO_2/t cement and Brazil 604kgCO_2/t cement. In absolute terms, South Africa lies very much in the middle of the country pack and is neither a weak nor a strong performer.

Table 2: GHG emissions per type of cement in South Africa

Cement type	Composition %)				GHG emissions (in kgCO_2/ton)			
	OPC	Fly Ash	GGBS	Limestone	Total	Scope 1	Scope 2	Scope 3
CEM I	100%	0	0	0	985	818	145	21
CEM II A-L	85%	0	0	15	838	696	124	18
CEMII A-S	80	0	20	0	814	665	131	17
CEMII A-V	80	20	0	0	788	654	116	17
CEMII B-L	73	0	0	27	721	598	107	15
CEM II B -S	70	0	30	0	728	588	124	15
CEM II B -V	70	30	0	0	690	572	102	15
CEMIII A	50	0	50	0	557	435	110	10
CEM IV A	65	35	0	0	641	531	95	14
CEM IV B	58	42	0	0	572	474	84	12
CEM V A	57	18	25	0	594	479	102	12
CEM V B	38	31	31	0	414	327	79	8

Source: InEnergy (2010)

[25] This average figure is examined in more detail in the document when it is shown that different types of South African cement have different CO_2 emission values – ranging from 980kg to 430kg, depending on the amount of clinker used.

South Africa's trend of decreased emissions per ton of cement over time has predominantly been driven by increased levels of clinker substitution (blended cements), as explained above. For all types of cement (CEM I-CEM V), Scope 1 emissions constitute the majority of emissions due to the release of CO_2 in the production process of limestone-based clinker. For CEM I, which has no blended use of SCMs and is 100% OPC clinker, Scope 1 emissions account for 74% of GHG emissions. These are direct and process-related emissions which are unavoidable in the production of OPC clinker. Scope 2 emissions for CEM I account for 18% of emissions and are the indirect emissions attributable to CEM I through the use of electricity in the manufacturing process. The remaining Scope 3 emissions, which are other indirect emissions, largely represent transportation and distribution associated emissions. Total emissions decrease as the ratio of clinker decreases. For example, CEM I with 100% OPC produces 985kg of CO_2 per ton as opposed to CEM V which produces only 415 kg of CO_2 per ton. The variable responsible for the lower CEM V emissions value is the fact that CEM V B cement contains only 38% OPC clinker with SCMs making up the remainder of the mix.

The proportion of Scope 1 emissions to total emissions remains relatively constant across different types of cement due to the fact that emissions from GGBS and fly ash are comprised predominantly of Scope 2 emissions (which is to be expected given that they are industrial waste products). The report calculates that fly ash Scope 1 emissions are only 1% with Scope 2 emissions producing 90% CO_2 emissions. For GGBS, the ratio is different given that slag from the furnace requires high-speed cooling which is done with generators run on coal. This results in 41% Scope 1 emissions for GGBS and 59% Scope 2 emissions, which also accounts for the electricity used to mill the cooled slag into a ground powder for use as a SCM.

In 2018, the ACMP made a submission to the National Council of Provinces on the cement industry and the carbon tax. The association contends that the kilograms of CO_2 emitted per ton of cement manufactured in South Africa has been declining since 1999 from a high of 783 to a low of 665 in 2015 before worryingly increasing in 2016[26] (ACMP 2018). It argues that the sector is facing a perfect storm of difficult market conditions with low economic growth, lower domestic demand, increased cheap imports, electricity price increases, labour cost increases, environmental compliance costs and now a carbon tax. Unsurprisingly, ACMP argues that the industry will be unable to absorb the additional cost of the carbon tax and will pass such costs onto consumers. The report quantifies the anticipated price increase to be 2.5% of the current retail price. Industry players argue that this will widen the price gap between local and imported cements, which is already increasing due to electricity and fuel price increases. They argue that this will result in trade exposure challenges over and above those addressed in the carbon tax regime.

The ACMP presentation paints a second scenario in which carbon tax costs are not passed onto the consumer but are absorbed into an increased cost of doing business for the country's cement producers. It claims such a decision would lead to cost-cutting measures in other areas of the business and inevitably result in increased mechanisation, staff rationalisation and sector consolidation. This possible sector consolidation would mirror overseas trends where consolidation of firms and plants has led to mega plants and fewer market players.

In conclusion, the ACMP argues that the impact of increased carbon pricing would further decrease returns of an industry already in distress. It argues that such increases would decrease the ability of the industry to attract investors to fund continuous investment improvements and that local economic

[26] Explained in section on PPC below.

development would be compromised, particularly because cement plants are located in decentralised hubs where there tends to be low levels of economic activity.

Looking at individual firms track records, reporting standards vary considerably across South Africa's main cement producers.[27] Reporting for NPC and Lafarge is limited because both are part of global MNCs with no detailed reporting for their South African operations in consolidated head office reports. AfriSam, Sephaku and Mamba do not publish detailed sustainability reports, although key quantification of variables such as GHG emissions must be collected in terms of required legislation. The only detailed sustainability reporting identified is from PPC, which is accepted as the country's lead firm and market leader enjoys a 35% market share. The 2019 PPC Annual Report shows that generally sustainability measures and interventions are moving in a positive direction and, as expected, substantial emphasis in terms of capital budget spend has been placed on energy efficiency and the necessity of the firm to contain costs in a difficult operating environment.

Vosloo and Mathews (2017) looking at electricity usage in the local cement industry identify that typically 88% of plant energy is provided by coal and only 12% by electricity. However, due to the relative price differential electricity accounts for 39% of energy costs and coal just 61%. As such, Vosloo and Mathews believe that South African cement companies will follow a different path from their international equivalents focusing on electrical efficiency over thermal efficiency improvements. As electricity is predominantly used in cooling and grinding, this analysis would suggest that local companies would be retrofitting or recapitalising these processes in their plants.

The 2019 PPC report confirms this behaviour to some extent but also shows substantial investment in improved thermal efficiency and the use of alternative fuels (albeit at a small scale). PPC reports a R2 billion capital upgrade at the Dwaalboom and Hercules plants to install a new grate cooler and a vertical roller mill. Grate cooler systems were also introduced at Slurry, Jupiter and De Hoek. In addition, four plants were retrofitted with 6 stage preheaters, while De Hoek (which is a lower capacity plants) was fitted with a 4 phase preheater. Overall, R4.5 billion have been invested in a 10-year plan to modernise its plant and install energy saving technology upgrades. As a result, five of its plants have a 5-star efficiency rating and one a 4-star efficiency rating.[28] Overall, PPC report a saving in production costs of R40/ton of cement and a 6% decline in energy usage.

PPC also run a co-processing facility at De Hoek and Slurry to utilise waste tyres as an alternative fuel source for its kilns and calciners. The company has a target of 80% alternative fuel substitution for its calcinater and 48% for its kiln system.[29] In 2015, 229 tons of tyres were processed. In 2019, this had grown to 15 000 tons at De Hoek and 22 000 tons at Slurry. The company is committed to increasing the use of alternate fuels but problems with accessing waste tyres remain a constraining factor and are part of an on-going conversation between the Department of Environment, Forestry and Fisheries and PPC. Most importantly in the context of this report, PPC shows a decline in the CO_2 emissions per ton of clinker from 1054kg of CO_2 per ton in 2016 to 1020kg of CO_2 per ton in 2019. These reductions were achieved by closing down inefficient and old plant and boosting production in newer 5-star rated kilns. Paradoxically, however, it reports that the kilogrammes of CO_2 per ton of cement rose from 767kg to 788kg, a similar upward tick to that identified in the ACMP presentation. The explanation appears to lie in the fact that while clinker emissions have indeed fallen, the ratio of

[27] This research was undertaken under lockdown restrictions Level 5 and 4. As the cement industry was unable to operate at these levels, all approaches to industry players for interviews were denied as executives dealt with pressing short-term issues. As such this section is based on published materials and Annual Reports of the country's cement companies.
[28] It is unclear what rating system is being referred to in the Annual Report.
[29] The timeframe remains uncertain from the 2019 Annual Report.

clinker to cement has been increased reducing the amount of SCMs used by the company. Industry experts suggest that substitution rates in the market have been falling as cement firms seek to sell more clinker to achieve economies of scale and higher returns on investment. As data on types of cement sales are not publically available, trends in substitution rates cannot be accurately assessed. If clinker ratios are rising this would be a worrying trend.

Given the limitations of the available data and a lack of company interviews, it is possible to argue that in terms of the seven listed possible areas of intervention to reduce carbon emissions in the cement industry, the first four possible interventions (electricity efficiency, thermal efficiency, alternative fuels, and reduction of the clinker to cement ratio) are the most relevant and applicable to the operations of the country's cement manufacturers at present. All four are driven by cost containment strategies but all four directly contribute to reducing CO_2 emissions per ton of cement. Most of the gains in South Africa to date seem to arise from the increased sales of cements with lower clinker ratios, but this trend is no longer certain. Given the availability of fly ash and GGBS in South Africa, and the market's acceptance of existing blended cements, it is unsurprising that industry players feel that future emissions reduction will most easily be gained by improved and increased SCM-blended cements.

Based on the research conducted, there appears to be no appetite among the large cement majors to invest in research and development (R&D) related to novel cements and further development of blended cements over and above what is designated in the existing standards. Lafarge is the only company with an in-house R&D facility but this is overseas based. This does not mean that innovation in new blended cements and even novel cements and especially GPCs is not being undertaken in South Africa. Small innovative environmental firms, alternative construction materials firms, and especially concrete mix experts with a strong background in chemistry are creating exciting new blends and novel cements, but the commercialisation and adoption of these is constrained and are only used in pilot flagship projects rather than in the mass market. Cement industry activity related to decreasing the demand for cement through disruptions to the built environment and construction industry also appears to have achieved little support locally – a reality that is understandable given the existing spare capacity in the industry.

The MPA assumes that, in the medium term, emissions reduction will first be sourced from a 25% fuel switch from fossil fuel to zero carbon waste and biomass fuels. The report cites that such a shift is technically possible by 2030, but company experiences show that a reliable source and supply of waste at competitive process needs to be established before the sector would undertake such a shift at scale. Second, the mitigation report believes that clinker substitution rates can be increased to meet a 60% target by 2030. This is an estimate in line with international goals such as the WWF and IEA and is technically feasible in South Africa but may be less commercially attractive given the low capacity utilisation of industry infrastructure, especially in light of plant rationalisation over the past decade. Third, the report assumes that 2.5% of cement production can be supplied by geopolymer production techniques by 2040. This assumption is relatively conservative, but given the on-site usage and long-term performance concerns regarding such novel cements, the 2.5% goal may be overly optimistic – especially given the current economic environment. The MPA also believes that there will be a 50% sector uptake of CCS back-end chemical absorption by 2050 and a 25% take up of CSS oxyfueling by 2050. As no capital or additional annual operating costs for the two systems are quantified, it is impossible to determine the viability or probability of sector uptake but with suggested abatement costs of R630/t CO_2e (CSS back-end chemical absorption) and R540/t CO_2e (CSS oxyfueling), it is unlikely that the systems will be implemented by 2050.

6. POSSIBLE PATHWAYS FOR THE CEMENT CHAIN

Table 3 shows three stylised pathways which the South African cement industry could follow going forward.

Pathway 1 represents the status quo based on the 10-year identified decline in CO_2 emissions achieved by the industry but importantly excluding the 2015-2016 uptick in CO_2 emissions which are dismissed as a short-term action and not indicative of a change in direction of the industry. Pathway 1 shows a minimum level of ambition regarding making the industry more climate friendly.

Pathway 2 represents a pathway where clinker to cement ratios decline in line with the IEA Technology Roadmap to 2050, with an aim of achieving an average of 60% rate of substitution. Given that the ACMP reports substitution rates in South Africa of 41% in 2014, substitution activity would need to increase by an additional 50% to meet the IEA's (and MPA's) 60% threshold by 2050. A shift from Pathway 1 to Pathway 2 would probably occur over a 20 to 30 year period. Pathway 2 represents a substantial increase in the industry's level of ambition to decarbonise.

Pathway 3 represents a new industry where traditional OPC clinker is no longer produced, clinker based factories and plant have been stranded and new novel cements are the only binders available on the market. On this pathway the cement industry is no longer a carbon-intensive industry and depending on the type of novel cements in the marketplace (for example MOMs), it may indeed be a net carbon absorbing industry. Pathway 3 would be a long-term pathway achievable post 2050 at the earliest (although some market share will be achieved earlier). A shift to Pathway 3 would indicate a commitment to fundamentally move the dial in terms of decarbonising the industry and making it part of a future solution to global warming and climate change.

Focusing on the next 20 to 30 years and the transition from Pathway 1 to Pathway 2, it is useful to unpack the actions and activities which would support overcoming the barriers to increasing the substitution of SCMs for clinker in cement in South Africa. Experts agree that carbon pricing and the development of new product standards are the two vital elements for driving changes in the sector and stimulating demand for lower-carbon products. Neither, however, are likely to prove sufficient to expand low-carbon construction material product markets or to build a sustainable supply chain for them in the short term. Rather this would be a 20 to 30 year process with activities taken in the immediate short term having a substantial bearing on when future shifts will be viable.

Three key areas for action are identified in the global literature to support a shift from Pathway 1 to Pathway 2 and eventually Pathway 3.

Table 3: Pathways for the cement industry

	STAKEHOLDER ACTIVITY	COST	BENEFIT
Status Quo *	*Firms:* • Continue to close down inefficient kilns and upgrade capacity of more efficient kilns • Continue to upgrade plant to increase thermal and electricity efficiency • Continue to improve process control • Maintain substitution rates and use of GGBS and fly ash in blended cements • Increase use of alternative fuels *Government:* • Regulatory framework and incentives to resolve supply issues related to waste by-products for SCM and alternative fuel • Improve access and competitiveness of market for SCMs including fly ash and GGBS • Maintenance of carbon tax and monitoring to ensure clinker to cement ratios do not rise • Support voluntary promotion schemes such as the Green Building Council South Africa to encourage uptake of high blend cements	• Capital expenditure for retrofitting and upgrading capital equipment and process systems • Capital expenditure for co-processing increased volume of waste materials • Training workforce to manage co-processing and control fuel composition and quality	• Further reduction of CO_2 emissions as inefficient kilns closed down and capital upgrading occurs • Decrease in the volume of industrial waste products going to landfill and slag and ash dams • New jobs created in increased co-processing of alternative fuels
Status Quo with increase in substitution rate to 60%	*Firms:* • Best practice demonstration and dissemination to downstream users of cement • Increased service-orientated business model with scaled-up marketing of higher blended cements • Work with government and downstream players to improve testing procedures and measurements to support new standards *Government:* • Improve access, classification, standards and competitiveness of market for SCMs including fly ash and GGBS (amend Waste Act of 2008) • Incentivize industrial waste producers to process waste for use as input in cement industry • Change public procurement and tender specification to utilise higher blended cements • Invest in large-scale infrastructure demonstration projects using higher blended cements • Regulations on the embodied carbon content of buildings and structures • Agreement on application and performance-based standards for blended cements rather than constituent-based standards (complete new standards SANS 50197 and 50413)	• Lower capacity utilisation of clinker kilns as ratio of clinker to cement declines • Return on investment of existing capital base declines • Lower capacity cement plants will be closed down and output centralised in a few mega plants leading to mothballed factories and job losses in decentralised economic hubs • Increased costs related to education and customer service orientation • Increased investment in waste processing and quality management to ensure sufficient SCM input for cement industry	• Further reductions in CO_2 emissions • Further reductions of disposal of fly ash and GGBS • Further reduction of industrial waste products being disposed of as alternative fuel use increases • Conservation of resources by utilising low grade limestone as SCM • New jobs created in service offering by cement companies • New revenue streams available from new customer service offering • Support change in downstream design of buildings and infrastructure as well as material usage resulting in an overall decline in the quantity of cement and concrete demanded • Support demand for downstream eco-friendly substitute materials

Developing next generation of technologies (novel cements)	*Firms:* • R&D and commercialisation of novel cements • Invest in new productive assets and plants • Increase customer support and product dissemination to users of cement • Collaborate on testing and performance standards and regulation development *Government:* • Support R&D of novel cements • Support R&D of new building techniques and software development to minimise cement demand • Change public procurement and tender specification to utilise novel cements • Invest in large scale infrastructure demonstration projects using novel cements • Regulations on the embodied carbon content of buildings and structures expanded • Agreement on application and performance based standards for novel cements	• Existing clinker based cement factories close and unemployment in decentralised rural locations close to quarries increases • Capital costs in building next generation plants for manufacture of novel cements. • High cost in educating and skilling workers for new industry upstream and downstream • Electricity usage may increase given intensity of use in production of alkali activators • Education and upskilling of downstream construction workers to deal with use of GPCs and other novel cements	• Decrease of CO_2 emissions related to clinker production • Decrease in industrial waste products disposed of as now used in GPCs and other novel cements • Possible decrease in CO_2 levels as novel cements become carbon negative • Development of new businesses and new jobs • New entrants to market may increase level of competition in the market

*Assumes uptick in CO_2 emissions between 2015 and 2016 is not indicative of an upward trend and that the DEA-cited 41% substitution rate is maintained.

Source: Author's own compilation

The first barrier relates to enhancing the availability of the supply of inputs for clinker substitution. At present, this includes GGBS and fly ash. As part of a 30-year strategy, both of these inputs would become less readily available and alternate sources to SCMs would need to be identified and their supply secured. The supply chain for clinker substitutes is heavily influenced by regulations (National Environmental Management: Waste Act, 2008), market access to available supply, processing and quality standards, and commercial viability. If substitution rates for cement are to rise, regulatory changes would be required on the handling and disposal of industrial waste, access to consistent quality and volumes of waste and hence incentivising the processing of waste.

If the South Africa's iron and steel and power generation industries follow a decarbonising pathway, the supply fly ash and GGBS would likely decrease closer to 2050. As such, if Pathway 2 is to be viable, research needs to be started in the immediate short run to consider alternative materials for substitution. This would most likely be calcined clay. Calcined clays are not commonly used as they need to be heated to 700°C to 800°C and are hence very energy intensive and no specialised processing capital and equipment has been developed for the key steps of drying, calcining and grinding the clays. As such an entirely new input value chain would need to be developed.

The second issue which requires attention if a pathway shift is to be manifested deals with technical aspects: both in terms of product performance and standards. Cements with high levels of SCMs to OPC clinker perform differently to traditional Portland clinker cements. They tend not to flow as well, which slows down the application process and thus increases labour inputs and construction costs. Setting times tend to be slower and there are delays in developing strength, which once again slows down construction times. Finally, in terms of performance there is uncertainty regarding long-term durability as there has been limited in-field use of high substitution cement blends over the past five decades. Given that the construction industry is liable for the safety and performance of the structures it erects, it is unsurprising that it is conservative by nature and reluctant to use products whose safety performance over time has not been tested and proven. Leanne and Preston (2018) offer a particularly insightful take on this challenge. They suggest that the root to shifting from Pathway 1 to Pathway 2 (and eventually Pathway 3) is to move away from the idea of standardisation.

One of the reasons why OPC is the most produced product on earth is because it is so flexible and can be used in so many different applications (from skyscrapers to home DIY projects). Researchers such as Leanne and Preston (2018) suggest that there may not be a single low-carbon cement that provides all the functions that OPC does. They see this current one-size-fits-all approach as the lead barrier to the adoption of more blended and novel cements into the future. The current construction industry paradigm, reinforced by the current approach on setting standards for cement and concrete, are all based on high blend cements and future novel cements matching the characteristics of OPC for the majority of applications. Rather what is required is a shift away from prescriptive standards towards standards focused on whether a cement can demonstrate a performance sufficient for a given application in a given context. Ideally, this would allow the lowest-carbon cements to be matched to their most viable use cases with high-carbon cements being reserved only for applications where they might still be needed.

If this is the direction of the industry in the long term, it implies a fundamental shift in how cement and concrete are considered. They are no longer commodities but become niche market products bespoke for given applications in given contexts. Such a shift fundamentally changes the business model for the cement industry. The industry would shift from being commodity suppliers to service-orientated companies working intimately with clients on a one-on-one basis to determine the best and most applicable product for a given use.

A third barrier to overcome is fostering demand for new low-carbon products. As shown earlier, to increase demand for new products, buy-in is required from the commissioning client, the design team of architects and structural engineers, and the contractors responsible for putting up the structure. There are three core activities which would shift the preferences of these players. The first and most important is enhanced information through better indicators and regulations. Users need to be able to easily compare and contrast embodied carbon levels of competing products and understand their performance levels. This would require a new approach to standards setting and information dissemination, consistent industrywide methodologies followed by all materials suppliers and a central database and new labelling requirements.

A second approach to support fostering demand for new low-carbon products is to use software, artificial intelligence and new information modelling to allow stakeholders in the construction chain to work out optimal design and material usage for a given project within the parameter of minimising the structures carbon footprint.

A third and crucial action to support the uptake of new low-carbon cements is the support of early mover consumers. In a triangle of different users, with large projects at the apex of the triangle (dams, bridges, airports) and small mass projects at the bottom of the triangle (house renovations, new residential builds) the literature suggests that the transition to new pathways will be led by the apex users of cement and concrete. These large projects are typically undertaken by only a handful of users (central government, provincial government, state-owned enterprises) that are well-educated and sophisticated users. Government could take the lead in utilising speciality cements and concretes, thus providing in-field usage and establishing a track record for high blended and novel cement performance and usage. In the middle of the triangle, medium sized users such as industrial and commercial property developers could be incentivised to use high blended and novel cements especially when tendering for government contracts. In the Netherlands for example, government tenders for housing projects allow suppliers to get a reduction in project costs based on how carbon efficient their design is. Proposals with low-carbon impacts thus achieve a competitive advantage over other proposals. In the United Arab Emirates, all government housing tenders specify cement with a minimum of 60% GGBS or fly ash be used (WWF, 2007). In both examples, increased demand for reduced carbon cements has been achieved. Almost all current research concurs that selling high blended and novel cements to mass users (at the bottom of the pyramid) is not feasible as it will require too much education and service support to be viable. Rather it is suggested for this segment of the market that activity be focused on selling these users finished concrete products which have been fabricated using low-carbon cement and concrete. Selling finished concrete products to this mass-market segment would reduce the volume of raw cement demanded by contractors servicing this market. By optimising CO_2 emissions reduction at the factory level, increased use of finished concrete products can achieve lower emissions ratings of buildings constructed in the mass market.

Arp, Bole-Rentel and Jakuja (2018) identify six key risks in moving from Pathway 1 to Pathway 2 in South Africa. The first risk identified is the technical risk related to the level of substitution of SCM to clinker. Under current South African regulations, 35% substitution is permissible. There is substantial experience in using cements with these substitution levels and hence there is no risk in technical performance. For any level of substitution above 35%, there is an insufficient track-record to prove durability performance in the field. This technical risk weighs heavily on those responsible for the safety of a structure during its lifetime and hence hinders the uptake of higher substitution cements and the commercialisation of high blend cements or products fabricated using high blend cements.

The second risk in shifting towards higher blended cements in South Africa relates to the skills risk. Risks related to skills exist across the spectrum from concrete design mixers and structural engineers to on-site construction managers who have little experience of working with high blend cements and their distinctive performance properties. All current teaching syllabuses and site best practices are based on OPC and cements with a maximum of 35% SCMs.

Arp, Bole-Rentel and Jakuja (2018) believe that the third risk is a supply risk faced when migrating from Pathway 1 to Pathway 2 in South Africa is related to the quality of SCMs rather than the availability of SCMs in the future. Given the use of coal-based electricity generation until at least 2050 they argue that sufficient volumes of fly ash would be available to support a shift to Pathway 2 but that substantial investment would need to be undertaken to improve waste collection and treatment by waste generators and waste processing facilities.

The fourth risk is economic. It relates to the overall health of the economy and hence the level of construction industry activity over time. Poor GDP growth and overall macroeconomic performance would decrease the demand for cement and thus make it increasingly less viable for the industry to migrate from Pathway 1 to Pathway 2.

Similarly, the fifth risk is that political instability increases locally, resulting in a decrease in confidence by investors and consumers. These decreased confidence levels would reduce the demand for cement and hence make it less viable for the cement industry to move to Pathway 2.

The sixth and final risk identified in the Arp, Bole-Rentel and Jakuja (2018) report relates to social risk and specifically a lack of environmental consciousness. This would hinder the uptake of low-carbon cements and cement-based products and at worst lead to resistance to change due to views of low-carbon products being lower quality products (Leanne and Preston 2018). As mentioned earlier, change would be required among consumers but also (and especially) civil engineering firms which fear litigation if low-carbon cements do not perform.

7. CONCLUSION

The research has shown seven key interventions which could decrease the GHG emissions of the cement industry moving forward. Decreasing electricity usage, thermal efficiency and increased use of alternative fuels are all elements of the current South African cement industry. They are predominantly driven by cost considerations and the pursuit of margins and profits but nonetheless they have contributed to decreasing CO_2 emissions nationally from 1996 to 2015. A fourth contributor to lowering emissions domestically has been the increased production of blended cements up from 20% to 41% in 2014. Current standards allow for blended cements in terms of constituent percentages but technical risks exist for new eco cements with higher levels of clinker substitution. The risk is the result of a lack of in-field performance of durability over the lifespan of a structure.

A fifth intervention to decrease the carbon footprint of the domestic cement industry lies in disrupting the built environment and essentially increasing the demand for more environmentally friendly building materials. Case studies show that there is some interest in “going green” on the margins and periphery of the construction industry but that in the main eco cements and substitute low-carbon building materials would struggle to enter the mainstream market until their performance over time has been established, thus changing the conservative attitudes of those responsible for the long-term safety of built structures. South Africa does, however, have a dynamic niche market for innovative and low-carbon cement and concrete products, as seen by three South African examples being cited in the Zero Carbon Australia research document.

Finally in terms of novel cements and CCS, long-term potentiality is noted and explored in the document but moving to a pathway based on these future technologies is viewed as viable only in a period of 30-plus years. Currently, there is no large-scale research and development being undertaken by South Africa’s current cement producers for either of these future technologies.

South Africa’s path towards a more climate friendly pathway for the cement industry is filled with opportunity and potential but the limited number of cement producing firms, their market power and the lack of market competition all suggest that fundamental change would in all likelihood be driven by the public sector and encounter substantial resistance. A non-negotiable dimension in any future pathway is that the construction of buildings and infrastructure must be safe over the entire lifespan of the structure. As such, steps to establish a performance track record of high SCM eco blend and novel cement products is crucial and should be undertaken as soon as possible, given the time periods involved.

The recent COVID-19 pandemic has, in the immediate short run, provided a huge challenge to the country’s cement companies as the construction industry ceased all work during Level 5 and Level 4 lockdown. The post-lockdown infrastructure-led recovery plan, however, provides an extraordinary opportunity for high visibility demonstration projects financed by the state using cutting-edge approaches to blended cements, material optimisation construction techniques, and circular economy approaches to the design. Globally there is a push to ensure that “brown” economic recovery options are replaced by green alternatives and the South African government should not miss this opportunity to meaningfully increase the climate compatibility of the local construction industry (and specifically cement makers) as it invests in its post COVID-19 infrastructure projects.

REFERENCES

Association of Cementitious Materials Producers (ACMP) (2018). Imposition of Carbon tax and Associated Impacts in the Cement Sector: A High Level Overview, Presentation to the National Council of Provinces (NCOP).

ACMP (2011). Cementing a Sustainable Future. Johannesburg: Association of Cementitious Materials Producers.

Arp, R., Bole-Rentel, T. and Jakuja, N. (2018). Greenhouse Gas Emissions Reduction Options for the South African Cement Sector. Emerging Climate Smart Business Opportunities. Technical Report. WWF South Africa.

Berriel, S. (2016). Assessing the environmental and economic potential of limestone calcinated clay cement in Cuba. *Journal of Cleaner Production*. Vol 124.

Brown, N. and Hasson, R. (2016). Overview of the South African cement Industry. Quarterly Strategy Note. Electus Fund Managers.

Centre for Competition Regulation and Economic Development (CCRED) (2015). Consolidation and Entry Changing Dynamics in Regional cement. Briefing Note prepared by Modliwa, P. and Zengeni, T. Johannesburg.

Celadyn, W. (2014). Durability of Buildings and Sustainable Architecture. Technical Transactions 7A.

Department of Environmental Affairs (DEA) (2014). South Africa's Greenhouse Gas Mitigation Potential Analysis. Republic of South Africa, Pretoria.

DEA (2016.) GHG National Inventory Report South Africa 2000-2015. Department of Environmental Affairs Republic of South Africa, Pretoria

Engineering News (2019). Cracks in the Wall. By Dineo Faku. 16 October 2019.

Eskom (2011). Concrete Steps Towards Profitability: Solid Ways to Ensure Energy Efficient Cement Production. Eskom Brochure 128251.

Getting the Numbers Right (GNR Indicator) (n.d.). Database. Available at: https://gccassociation.org/gnr/world/GNR-Indicator_59cAGWct-world.html. Accessed 27/06/2020.

International Energy Agency (IEA) (2018). Technology Roadmap – Low-Carbon Transition in the Cement Industry.

International Finance Corporation (IFC) (2017). Improving Thermal and Electrical Energy Efficiency at Cement Plants: International Best Practice. World bank Group.

InEnergy (2010). Concrete Industry Greenhouse Gas Emissions. Prepared for The Concrete Institute, Johannesburg.

Leanne, J. and Preston, F. (2018). Making Concrete Change: Innovation in Low Carbon Cement and Concrete. Chatham House Report, United Kingdom.

Lewis, Y., Cohen B. and Cloete B. (2017). South Africa's Greenhouse Gas Pathways. Unpublished mimeograph by The Greenhouse.

Maqhawe Technical & Financial Services (2006). To create business opportunities that can use ash as an input material. Feasibility Report prepared for the Waterberg District Municipality.

McLellan, B.C., Williams, R.P., Lay J., Van Riessen, A. and Corder, G. (2011) Cost and Carbon Emissions from Geopolymer Pastes in Comparison to Ordinary Portland Cement. *Journal of Cleaner Production*.

Naqui, A. and Jang, J. (2019) Recent Progress in Green cement Technology Utilizing Low Carbon Emission Fuel and Raw Materials: A Review, Incheon National University, Korea

Perrie, B. (2014) Overview of the South African cement Industry. Presented to the ConSem14 Seminar on behalf of The Concrete Institute.

Pretoria Portland Cement (PPC) (2018). Annual Report 2018.

PPC (2019). Annual Report 2019.

South African National Standards (SANS) (2020). SANS 50197 Common Cements. Part One: Specifications; Part Two Conformity Criteria. https://store.sabs.co.za/catalog/product/view/_ignore_category/1/id/224242/s/sans-50197-1-2013-ed-2-00/. Accessed 30/06/2020.

South African Reserve Bank (SARB) (n.d.) Fixed investment data set. Available at: www.resbank.co.za/Research/Statistics/Pages/Statistics-Home.aspx. Accessed 27.06.2020.

Scrivener, K. (2014). Options for the future of cement. *Indian Concrete Journal.*

Shekovtsova, J. (2015). Using South African Fly Ash as a Component of Alkali Activated Binders. Faculty of Engineering, Built Environment and Information Technology. University of Pretoria.

Shi, C., Jimenez, A.F. and Palomo, A. (2011). New cements for the 21st century: The pursuit of an alternative to Portland Cement. *Cement and Concrete Research*, No. 41.

Tempest, B., Snell, C., Gentry, T., Trejo, M. and Isherwood, K. (2015). Manufacture of full scale geopolymer cement concrete components: A case study to highlight opportunities and challenges. *PCI Journal.*

The Concrete Institute (2020). Cementitious Materials for Concrete: Standards, Selection and Properties.

Theron, N. and Van Niekerk, A. (2018). Impact of Competition Enforcement in the Cement Industry in South Africa. Paper prepared for the Biennial Conference of the Economic Society of South Africa in 2017.

Turner, L.K. and Collins, F.G. (2013). Carbon Dioxide equivalent Emissions: A Comparison between Geopolymer and Ordinary Portland Cement and Concrete, *Construction and Building Materials* No. 43.

Vosloo, J. and Mathews, M. (2017) Analysis of Energy Consumption and Cost Distribution on South African Cement Plants. North West University.

WWF (2007). A Blueprint for a Climate Friendly Cement Industry. Report prepared for the WWF by the Lafarge Conservation Partnership, Switzerland.

Zero Carbon Australia (2017). Zero Carbon Industry Plan. Rethinking Cement, Victoria, Australia.