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Built for net-zero: analysis of long-term greenhouse gas emission pathways for the Nigerian cement sector

María Yetano Roche

Wuppertal Institute for Climate, Environment and Energy, Döppersberg, 19, 42103, Wuppertal, Germany

A R T I C L E I N F O

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A B S T R A C T

Nigeria is Africa's top cement producer and could be on course to be one of the top producers globally. The goal of this study is to identify and critically examine the pathways available to Nigeria to meet its decarbonisation goals in the cement sector. Based on a literature review, the study assesses demand drivers and decarbonisation potentials for the sector. It then presents two different quantitative pathways for growth in production of cement by 2050, and three different pathways for decarbonisation of the sector. Using published data and a scenario analysis tool, the study calculates how the sector's emissions might evolve under each of these pathways. The results indicate that, in the most ambitious scenario, emissions from the sector can plateau by the late 2030s, resulting in an overall increase of 21% by 2050 (compared to 2015 levels). Achieving this scenario is necessary in order to put the sector on a path to net zero emissions beyond 2050. The scenario is driven by reductions in both energy-related and process emissions, as well as a small share of carbon capture and storage and demand management. A moderately ambitious scenario that relies mostly on savings on energy-related emissions results in an 84% increase in emissions by 2050. Finally, the Business-as-Usual scenario results in an almost tripling of emissions by 2050. The results indicate a strong potential for policies to drive improvements in energy efficiency and clinker-to-cement ratio. Critical areas of uncertainty within the assumptions include the production rates (including the evolution of the export market) and the fuel mix.

1. Introduction

The industry sector was the leading source of greenhouse gas (GHG) emissions worldwide in 2019, once indirect emissions are considered (Bashmakov et al., 2022; Bataille et al., 2018). Industry decarbonisation is now considered one of the next frontiers in the fight against climate change. Across the world, ambitious long-term transition plans for industry decarbonisation are being developed, such as the G7 Industrial Decarbonisation Agenda (G7 Germany, 2022) or the Industrial Deep Decarbonisation Coalition (UNIDO, 2022).

Cement production is one of the key contributors to emissions from the industry sector. It is the fastest-growing industry sub-sector in terms of emissions, currently accounting for up to 8% of global emissions (Bashmakov et al., 2022; Minx et al., 2021). Decarbonising the cement sector poses a challenge in the transition to a net zero world due to process emissions, which are particularly difficult to avoid (ETC, 2018). A radical reduction in emissions from the cement sector will entail making use of different decarbonisation levers, including energy efficiency, fuel switching and demand management. To this end, cement producers and governments are devising sectoral strategies and commitments. Key ones include the 2050 Net Zero Global Industry Roadmap of the Global Cement and Concrete Association and the World Economic Forum (GCCA, 2021; Mission Possible Partnership, 2022). Cement decarbonisation has been a key focus of the 2022 COP 27 Summit (Conference of Parties) (WEF, 2022), building on the success of the international commitments of the steel industry that were reached at COP26.

A range of long-term scenario studies for the cement sector project that, with ambitious measures, achievement of net zero emissions in the sector in the long term is within reach (Cembureau, 2020; ETC, 2018; GCCA, 2021; IEA, 2018, 2021). However, the majority of the research is centered around developed countries and China, where cement production is projected to stay relatively flat or decline in the next decades. Countries such as India, and other emerging and developing Asian and African countries, are still in the process of urbanising and building up key infrastructure. In these countries, cement demand is projected to grow significantly and begin to stabilize only around 2050 (IEA, 2020a). Achieving emission reductions in the sector in emerging and developing economies is projected to be far more challenging than in the industrialised economies.

In Africa specifically, cement demand per capita is projected to

E-mail address: maria.yetano@wupperinst.org.

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List of abbreviations

BAU	Business as Usual
GNR	Getting Numbers Right
BECCS	Bioenergy with Carbon Capture and Storage
IEA	International Energy Agency
BIP	Backward Integration Policy
GDP	Gross Domestic Product
GHG	Greenhouse Gas
CCS	Carbon Capture and Storage
NEEAP	National Energy Efficiency Action Plan
COP	Conference of Parties
NDC	Nationally Determined Contribution
ETP	Energy Transition Plan
EU	European Union
SSA	Sub-Saharan Africa
GCCA	Global Cement and Concrete Association
TNZ	Towards Net Zero

double or triple in the mid-term, and local production is expected to increase greatly as well (IEA, 2019). There is however a lack of detailed emission scenario studies that assess the feasibility and pathways for achieving deep decarbonisation of the sector in specific African countries. Despite the rapid ramping up of investment and cement production capacity, the prospects for demand growth and the potential for carbon mitigation measures in African countries are not well understood. In general, research in the area suffers from strong data inadequacies and limitations in gaining access to expert knowledge that is available but fragmented. The following sections describe the novelty of this study and its key goals.

1.1. Novelty of the study

The novelty of the present study against existing studies in the field is that it is the first study to provide a detailed analysis of the prospects for cement sector decarbonisation at the national level for a country in the African region. It focuses on Nigeria, already the top cement producing country in the region and on course to becoming one of the top producers worldwide. The analysis is more in depth than previous studies, because it considers the underlying drivers of cement demand for Nigeria, as well as the full range of decarbonisation options for the sector, including demand-side measures. The assumptions regarding the evolution of these drivers are based on a review of existing historical data, literature regarding decarbonisation potentials, and expert opinion.

1.2. Motivation and objective of the study

The goal of this study is to identify and critically examine possible pathways available to Nigeria to transition to a decarbonised cement sector, in the context of the country's recently announced net zero targets (Climate Action Tracker, 2022; FGN, 2021b, 2021a). Drawing from socio-technical transition studies, and using the method of scenario analysis, the study identifies plausible future changes in underlying drivers of cement production (e.g. demographics, economic growth) and cement decarbonisation (e.g. technological improvements, policies, investments) and tests how they would interact and lead to outcomes in terms of the GHG emissions of the sector in the long-term.

1.3. Research gaps

The study aims to address the following research gaps:

- Lack of validated historical data regarding cement demand, sector energy intensity and emissions from the sector in Nigeria, Africa's top cement producer.
- Poor understanding of the prospects for growth in demand for cement and the potential for different decarbonisation measures in the specific context of Nigeria, which differs from the context of industrialised economies. Key differences between Nigeria and these more widely studied contexts include the prospects for rapid demand growth in the short term, the young cement production infrastructure fleet, the technological maturity of the sector, a distinct energy mix, and the market characteristics, among others. Knowledge in this area is strongly limited by data inadequacies and limitations in gaining access to expert knowledge.
- A scarcity of coherent and published datasets available for use in the analysis of future scenarios in the sector.

1.4. Study contribution

This study contributes to:

- Advancing scientific knowledge on the Nigerian cement sector structure, dynamics, prospects for growth and the pathways available for this key sector to contribute to the goal of achieving net zero emissions by mid-century.
- Enhancing the understanding of the sector in comparable African economies: Nigeria, Africa's top cement producer, provides a suitable case study of the prospects of growth in demand in Sub-Saharan Africa (SSA) as well as possible approaches to decarbonisation in the region.
- Providing an evidence basis for national strategy development, in particular to inform:
  - A roadmap that can guide the transformation of the sector and prepare it to comply with more stringent climate regulation in the future, and therefore remain competitive in international markets.
  - An investment plan that can prioritise and help attract the considerable financing needed both in mature technologies (e.g., clinker substitutes), non-commercial technologies (e.g., Carbon Capture and Storage (CCS)), and new value chains (e.g., bioenergy).
  - Goal setting for the sector, as part of the country's climate commitments under the Paris Agreement (Nationally Determined Contribution (NDCs), and long-term decarbonisation goals).
  - Policy and regulation for the sector, including standards and financial incentives.
- Identifying key areas of uncertainty and remaining data gaps, that can guide future research efforts in this field.

1.5. Orientation of the manuscript

The following section reviews relevant recent cement decarbonisation scenario studies as well as literature regarding demand projections and decarbonisation potentials for the Nigerian cement sector. Section 3 presents the methodology including the scenarios, key assumptions, and modelling approach. Sections 4 and 5 present the results and discussion, respectively.

2. Literature review

2.1. Scenario studies on cement decarbonisation

A small number of studies analyse decarbonisation scenarios in the African and Nigerian contexts specifically. These are summarised in Table 1 below, together with a set of key global studies.

In its decarbonisation pathways study for African industry, McKinsey (2021) finds that the cement sector can potentially reach net-zero by 2050. For this, three strategies (Bioenergy with Carbon Capture and

Table 1
Review of recent relevant scenario studies on long-term cement sector decarbonisation.

Reference and *Geographical scope*	Key mitigation levers	Key results	Net-zero sector by 2050?
Climate Action Tracker (CAT, 2017), *Nigeria*	• Demand reduction by 20% by 2050 via material substitution • 100% decarbonised power and fuels by 2050 • Reduction of the clinker/cement ratio to 70% • No CCS	Sector emissions continue to increase in 2050, even in most ambitious scenario	No
Energy Transition Plan (FGN, 2021b, 2021a), *Nigeria*	• Clinker substitution with calcined clay by 50% • Applying biomass combustion and CCS (BECCS) to 50% of production post 2030 • No demand-side measures	Emissions reduced by 92% against BAU in net-zero scenario (62% via BECCS and 30% via clinker substitution)	No (but yes by 2060)
Africa green manufacturing (McKinsey, 2021), *Africa*	• BECCS (most kilns fired by biomass and fitted with CCS in 2050) • Demand reduced by 40% in 2050 due to uptake of cross-laminated timber in commercial and residential construction • Clinker substitution with energetically modified cement where available, 50% calcined clay elsewhere	Emissions reduced by 91% against BAU in net-zero scenario (62% via BECCS and 30% via clinker substitution)	Yes
Africa Energy Outlook (IEA, 2022a), *Africa, SSA*	• Fuel mix (coal and gas) for cement production remains largely stable, but bioenergy and waste replace some of the coal • Substantial use of calcined clay as substitute	Production per capita in Africa and SSA increases to 100–150 kg by 2030 and then slows down	No
World Energy Outlook (IEA, 2022b), *Global*	• Clinker-to-cement ratio 0.56 b y 2050 (globally) • Use of coal, oil and natural gas in cement production is fully replaced by bioenergy, electricity and hydrogen between 2030 and 2050 (globally) • 8% of emissions from cement are captured by 2030, and 95% by 2050 (globally)	Africa sees overall increase in demand industrial materials but material efficiency tempers growth in net-zero scenario	Yes in Net-Zero scenario (globally)
Concrete Future Roadmap (GCCA, 2021), *Global*	• Largest share of emission reductions (36%) achieved via CCS, starting post 2030 • Demand-side measures, e.g. efficiency in design and construction, also contribute a very significant share (22%) • Smaller role for other measures: efficiency in production, fuel switching, etc. • Cement as a carbon sink (recarbonation)	Global demand increase from current 14.0 billion m^3 of concrete to 20 billion m^3 in 2050, taking into account large increases in Africa, India and Latin America	Yes
Cement industry roadmap (IEA, 2018), *Global*	• Global cement production is set to grow by 12–23% by 2050 from the current level. • Africa more than triples its current cement production by 2050 • Carbon capture and reduction of clinker content provide largest emissions reductions by 2050, complemented by fuel switching and energy efficiency • Material efficiency and demand management only marginal	By 2050, sector's direct emissions reduced by 24% compared to current levels (in most ambitious scenario)	No
Mission Possible (ETC, 2018), *Global*	• Full spectrum of measures required to reach net zero: • Demand management: improved demand management and material efficiency, circularity, use timber as a substitute. • Energy efficiency: especially clinker-to-cement ratio • Switch from coal to gas (particularly in China), use of biomass and hydrogen. • Innovations: new cement chemistries, use of carbon capture and heat electrification	Sector decarbonisation will imply a significant increase in cement prices and could account for circa 60% of the global costs of decarbonizing all the harder-to-abate industrial sectors	Yes
Indian cement decarbonisation roadmap (WBCSD, 2018) - *India*	• Demand for cement expected to increase three- to six-fold • Roadmap's goal is to reduce emissions intensity to 0.35 tCO_2 per tonne of cement	Direct emissions can be reduced by 45% compared to 2010 levels by 2050	No
Indian cement sector 1.5 °C scenario (Dhar et al., 2020), *India*	• Industrial GDP growth as driver for cement demand growth • In BAU scenario, demand increases 5-fold from current levels by 2050 in, but in 1.5 scenario it is 25% lower than BAU, thanks to demand management • Significant role for material efficiency and demand management in order to meet 1.5 goal • Widescale deployment of CCS	Most ambitious scenario results in a 30% increase in emissions by 2050, compared to the base year.	No

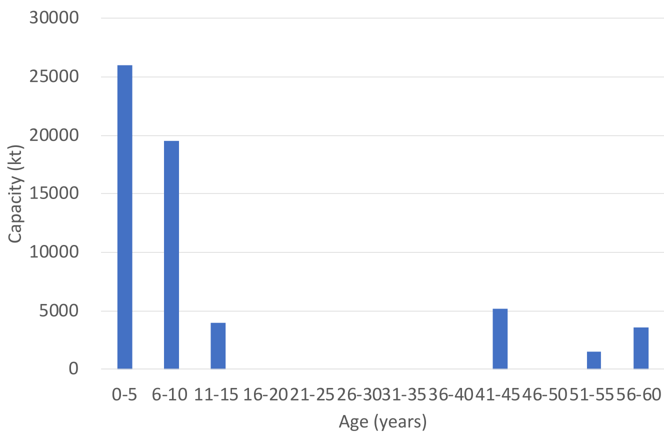


Fig. 1. Plant installed capacity by age. Source: GID (2021).

Storage (BECCS), clinker substitution, and demand reduction) would need to be pursued aggressively in the sector. More recently, Nigeria's Energy Transition Plan (ETP) (FGN, 2021b, 2021a) highlights two key levers for the full decarbonisation of the sector by 2060. On the other hand, it assumes a strong reduction of the clinker-to-cement ratio through the substitution of 50% of clinker with calcined clay. This assumption would drive 30% of the emissions reductions by 2060. The ETP also identifies BECCS as an option for the cement sector post-2030, and estimates that applying it to half of Nigeria's cement production could abate 62% of emissions from the sector. Finally, an earlier scenario study by CAT (2017) found that emissions in Nigeria's cement sector would be in the range of 110MtCO_2 by 2040 in an ambitious scenario that considers material efficiency, and around 200 MtCO_2 under a Business-As-Usual (BAU) scenario.

The next section sums up the state of knowledge on the Nigerian cement sector, to provide the needed context for the scenarios.

2.2. Nigeria's cement industry

Nigeria produced 21.5 million tonnes of cement in 2015 (FMEnv, 2018). It is unclear how much of this was destined for export. Cement production in the country grew at an average rate of 18% per year between 2000 and 2015. As a point of comparison, China's production between 1990 and 2014 grew at an average rate of 11% per year (CAT, 2017).

Current production capacity is estimated to stand at 56.8 Mt, making it the second-largest installed capacity in Africa after Egypt. The capacity utilisation level thus stands at around 40%, slightly lower than the world average (CemNet, 2021b, 2022; United Capital, 2019). As can be seen in Fig. 1, 44% of installed capacity has been installed in the last 5 years, and 83% in the last 15 years (Fig. 1). The average age of the fleet is thus lower than the Chinese and Indian average of 12–13 years (IEA, 2020a; Tong et al., 2019). Major plants are listed in Table 2 and mapped in Fig. 2.

Nigeria's manufacturing and construction sectors currently contribute around one-tenth of the nation's Gross Domestic Product (GDP) (CBN, 2022). The sector's contributions to foreign exchange earnings, employment and government revenue remain relatively low, in particular in comparison to the oil sector. The contribution of non-oil sectors to the economy has consistently grown in the last fifteen years, though at a relatively slower rate since the 2016 recession. Within the manufacturing sector, the cement sector is one of the main contributors to growth in GDP terms (CBN, 2022).

The current market in Nigeria is oligopolistic in nature and dominated by three key players: Dangote Cement Plc is the leader with 32.3 Mt per year of installed capacity (concentrated in just two plants, Obajana and Ibese), followed by Lafarge Africa Plc and the BUA Group (BUA Group, 2022; Dangote Cement Plc, 2020). This is in line with a global trend, where large companies dominate the market. It is estimated that over half of African production capacity is owned by nine pan-regional firms (Byiers et al., 2017).

Table 2
Cement production plants in Nigeria and estimated capacities. Sources: CemNet (2021a), GID (2021), SFI-ALD (2021).

Main owner	City and state	Capacity (Mt/year)
BUA	Okpella 1 and 2, Edo	3
	Kalamaina, Sokoto	5
Dangote Cement PLC	Gboko, Benue	4
	Ibese, Ogun	12
	Obajana, Kogi	16.3
Lafarge Africa PLC	Ashaka, Gombe	1
	Ewekoro 1 and 2, Ogun	2.7
	Sagamu, Ogun	1.8
	Mfamosing, Cross River	5
	Calabar, Cross River	3

1 All plants are integrated (meaning they include clinker production), and all are in operation except Calabar which is under construction.

The oligopolistic nature of Nigeria's cement industry has been criticized for causing price rises and obstructing economic recovery, calling for new policies to attract new entrants (Reuters, 2021). The current dominance of the three large firms is indeed a result of previous policies: in 2002, when domestic production was unable to meet demand and the country relied on the importation of cement to meet domestic construction needs, the government implemented the Backward Integration Policy (BIP), requiring cement import licenses be allocated only to importers who could prove they were building factories for local cement manufacturing in Nigeria. Incentives under the policy include waiver of VAT and custom duty for importation of cement production equipment (Akinyoade and Uche, 2016).

The following two sections delve into the key drivers for cement demand and the potentials for decarbonisation in the sector.

2.3. Drivers of demand

The relationships between cement demand, economic development and urbanisation are complex, but some patterns can be distinguished (Zhang et al., 2018). Cao et al. (2017) identified an S-shaped evolution of cement stock per capita as a function of income and urbanisation, where four stages can be distinguished: an initial stage with a slow linear growth in developing economies, an accelerated "take-off" stage, a slowdown stage, and finally a shrinking stage (found in a limited number of countries with very high incomes and urbanisation levels). Van Ruijven et al. (2016) tested different linear and non-linear models for GDP growth and also found that an S-shaped relation is the best fit to historical data. Bleischwitz et al. (2018) also find that historical data from developing economies tend to show a linear fit, and that at higher levels of GDP per capita consumption tends to decouple. However, they find the decoupling pattern can vary considerably, depending on the infrastructure intensity, consumption patterns and technological choices of developed economies. Three areas of relevance for cement demand are analysed below: demographic changes, economic development, and infrastructure growth drivers.

2.3.1. Demography and urbanisation

Extended demographic changes are expected over the coming decades in SSA countries. The projected growth in population is led by West Africa. Between 2020 and 2050, Nigeria's population will have doubled in size, reaching 401 million and making it the world's third most populous country (Fig. 3).

Regarding urbanisation, Nigeria is expected to show growth rates that are above the regional averages (Fig. 3). Urban population in SSA has more than doubled since 2000 to reach 440 million today. The share

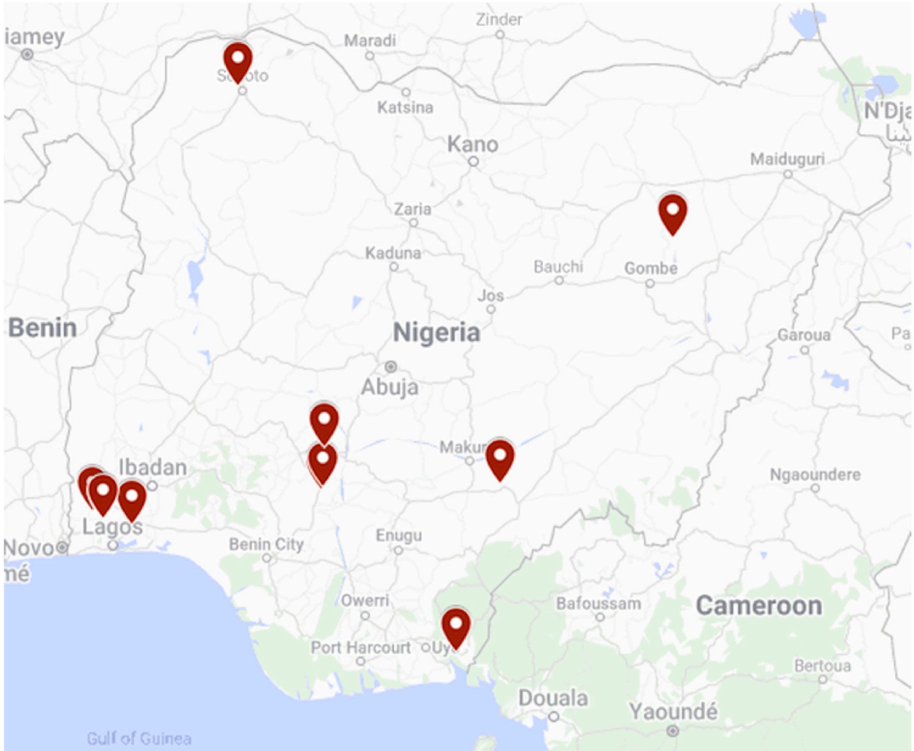


Fig. 2. Location of cement plants. Source: SFI-ALD (2021) (created with Google Maps).

of population currently living in cities in SSA is now 40.4%, up from 31.4% in 2000. In Nigeria, this proportion is now well over 50%. By 2040, there will be 520 million more people in cities in SSA than there are today. Around 115 million of these will be in Nigeria. For comparison, between 1990 and 2010 China saw the population of cities increase by 360 million (and cement production grow nine-fold). Urbanisation of this scale and speed has never been seen before, and is expected to be twice as large as the projected growth of urban population in India over the next two decades (IEA, 2019).

2.3.2. Economic growth and industrialisation

In the period 1990–2020, Nigeria's average GDP per capita growth rate was 1.4% per year (World Bank, 2022a). There is currently strong uncertainty on economic trends in Nigeria and no studies on how they would affect cement demand. Despite being Africa's largest economy in terms of size of GDP, Nigeria is not likely to be among the fastest growing economies in SSA in the next years (World Bank, 2022b). Mid-term estimates for growth of GDP in Nigeria are highly uncertain. The government's post-pandemic recovery economic plan foresees an average GDP growth rate of between 3 and 5% per year could be achieved by 2025, depending on different oil price and economic stimulus scenarios (ESC, 2020; FMFBNP, 2021).

Regarding industrialisation, SSA is projected to increase its global share of manufacturing, although the timeframe and speed of this increase are debated. Some of the factors that could make SSA manufacturing more globally competitive include: an increase in wage levels in Asia, suitable skill base development, and growing trade between SSA and other emerging economies (Hogarth et al., 2015).

2.3.3. Infrastructure and housing

Cement use for infrastructure, and particularly transport infrastructure, is expected to be a key driver of cement demand in emerging economies up to 2050 (IEA, 2020a). Infrastructure deficit severely undermines the prospects for economic growth in Sub-Saharan Africa. For example, Nigeria's road network spans around 195,000 km, of which an estimated 81% are unpaved (Bello-Schünemann and Porter, 2017; Ubi and Udah, 2019). Both paved and unpaved road network density in Nigeria is more than twice as high as those of the peer group of resource-rich African countries, although still only half of the levels found in Africa's middle-income countries.

As a result of demographic trends, demand for housing in Nigeria is also high. It is estimated that up to 780,000 housing units in different market segments are needed annually in Nigeria to keep up with demand (OBG, 2018b; Wong et al., 2016). However, current production is below 100,000, resulting in an overall accumulated deficit of around 17 million units as of 2013. As a result, it is estimated that Nigeria would need to build 1.5 million new units per year to meet its needs.

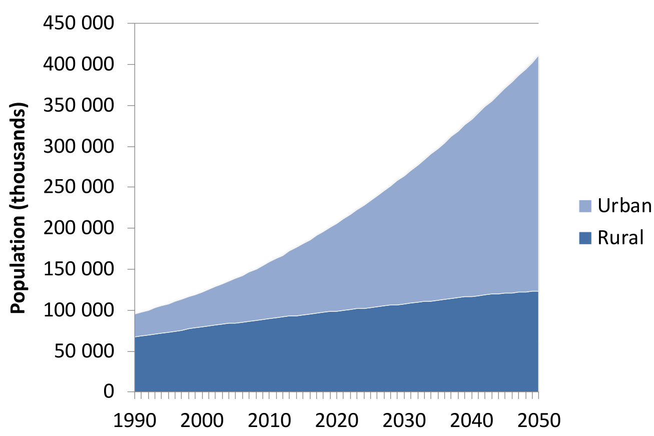
2.4. Decarbonisation potentials

Historically, Nigeria has contributed very little to climate change. Nevertheless, in 2021, Nigeria passed the Climate Change Bill which includes a net zero target for 2050 to 2070 and has since further committed to net zero emissions by 2060 (Climate Action Tracker, 2022; FGN, 2021a, 2021b).

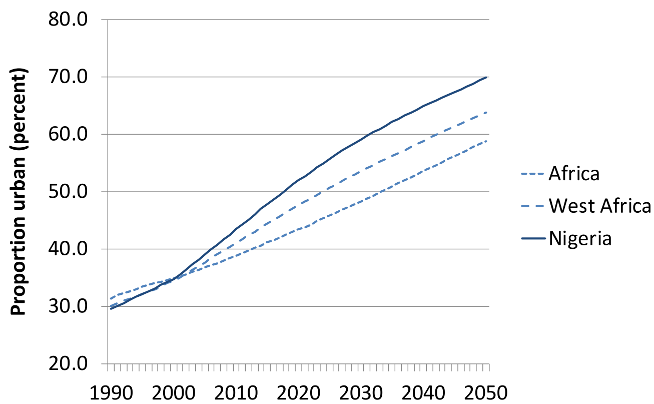
There are three key levers for decarbonisation of the cement sector: (1) reducing demand for cement (chiefly through material efficiency and material substitution); (2) improving energy efficiency (including reducing the clinker-to-cement ratio), and (3) deploying decarbonisation technologies such as cleaner fuels or carbon capture and storage (ETC, 2018; Korczak et al., 2022). The following sections sum up existing knowledge on their potentials as well as ongoing initiatives and example projects in Nigeria.

2.4.1. Demand management

The IEA (2019) assumes that Africa could follow a different trajectory for cement demand than China and other emerging economies thanks to demand-side measures. While no studies could be found regarding the potential of demand-side measures for SSA and Nigeria, the greatest opportunities are likely to lie in material efficiency and



(a)



(b)

Fig. 3. Population projections for Nigeria (a) and projections for proportion of urban population in Nigeria compared to the region (b). Source: UNDESA (2018).

circularity.

Regarding material efficiency, measures to extend the lifetime of buildings account for the largest reductions in demand from material efficiency in global scenarios, followed by improved building design and construction and reduced material losses (IEA, 2020a). Recycling of cement is currently challenging but innovation efforts are underway to recycle production waste and end-of-life cement.

Usage of alternative low-carbon building materials could impact cement demand in the long term. There is a large potential for use of engineered timber and traditional materials (e.g. adobe) rather than concrete in construction. This could not only deliver net reductions in emissions, but also potentially constitute a permanent carbon sink, offset some of the growth in demand for cooling and make cities more resilient to climate change (ETC, 2018; IEA, 2019). McKinsey's net-zero decarbonisation path for Africa suggests that cement demand could be reduced by 40% against business-as-usual by 2050 due to the uptake of cross-laminated timber (McKinsey, 2021) and adds that job creation in this sector would compensate for the job losses in the cement sector. However, there are no studies examining the cost or available supply of timber or other materials for this purpose in Nigeria nor its potential impact on water or biodiversity (Klasa, 2018).

2.4.2. *Energy efficiency*

Cost of energy is a strong driver for energy efficiency in Nigeria, with energy costs being the single largest variable production cost at a cement plant (Oni et al., 2017). As depicted in Fig. 1, most capacity has been installed in the last 10 years. Full refurbishments of these young kilns are unlikely. However, there is a large potential to improve energy efficiency of existing kilns in the next investment cycle (the typical lifetime of a cement kiln is 40 years). Njoku et al. (2017) constructed energy conservation supply curves for three Nigerian cement manufacturing plants and showed that thermal energy savings of between 19.8 and 52%, and electrical energy savings of between 35.2 and 43.1% were possible with respect to the global benchmark plants. With respect to Chinese benchmark plants, thermal energy savings of 10.7–47.3%, and electrical energy savings of 20.9–30.2% could be achieved.

Moreover, studies show a large room for cost-effective investments in partial retrofits. A recent audit in a major plant indicates there is potential for 10% savings in primary energy consumption against the benchmark, with an average payback of four years for the necessary investments. The calcination process is the biggest energy consumer and has the highest potential for savings, followed by the on-site electricity generation losses (NESP, 2020).

It is important to remember that energy efficiency improvements may be partly offset by additional energy requirements related to the use of other carbon mitigation measures, for example, use of alternative fuels or installation of carbon capture equipment. Policies and standards may also impede efficiency improvements (for example, electricity consumption in cement grinding is very dependent on grain size requirements).

Clinker production is the most energy- and emission-intensive process of cement production. Decreasing the clinker-to-cement ratio through the use of blended cements and clinker substitutes can substantially reduce the energy requirements and direct emissions of cement production. The "Getting Numbers Right" (GNR) project of the Global Cement and Concrete Association (GCCA, 2022) estimates the average clinker-to-cement ratio for Africa was 79–75% over the 2012–2019 period. Most decarbonisation scenarios for the sector rely on the clinker-to-cement ratio declining to between 60 and 70% in the mid-term (Cembureau, 2020; IEA, 2018; WBCSD, 2018), though the lower range is not yet commercially viable.

In Nigeria, Lafarge cement has implemented projects (including some with CDM finance) to reduce the clinker to cement ratio and introduce a new blended cement standard (FMEnv, 2021), but there is no recent information on their progress. Almost all the steel production in Nigeria is through scrap steel recycling and therefore the potential of Nigeria's steel sector to provide slag to the growing cement sector is likely to be very limited.

Nigeria has abundant deposits of kaolin clays (Raheem et al., 2021). Their use for replacing up to 50% of the clinker in cement has been successfully tested though not developed (Akindahunsi et al., 2020). There are other viable natural clinker substitutes available, such as rice husk ash, but they are presently not used (Abubakar, 2018; Tijani et al., 2022). The development of sustainable supply chains, standards for alternatives to clinker, and construction standards has an important part to play in unlocking the potential of clinker alternatives.

2.4.3. *Decarbonisation technologies*

Two key levers to reduce the emission intensity of cement production are fuel switching and CCS.

The IEA projects that the share of gas in the calcination process across Africa will grow significantly, in line with global trends (IEA, 2019). Nigeria's IEA balances state that coal represents 100% of the direct energy input in the cement industry (IEA, 2020b). These national statistics stand in contrast with company reports that indicate a mix of fuels. For example, the market leader Dangote (Dangote Cement Plc, 2020) reports that its plants currently use between 30% and 50% local coal, with the rest being supplied by gas. In one plant, petroleum coke represents about 10% of the fuel mix. According to one report (United Capital, 2019), key Dangote plants (Obajana and Ibese) which were originally designed to run on gas were retrofitted to operate with coal.

Despite the lack of coherent data, there are indications that in recent years cement manufacturers in Nigeria are increasingly using locallymined coal in heat-related processes. This is because oil products and gas have proven to be more expensive and, in the case of gas, susceptible to foreign exchange volatility and supply disruptions (United Capital, 2019). Moreover, earlier studies suggest that the shortage of natural gas supply in the northern part of the country may have restricted its use in plants located in this region (Ohunakin et al., 2013).

One other major player, Lafarge Africa, currently leads in the use of alternative fuels, which they use at four of their five plants (NIRAS-LTS et al., 2021). Alternative fuels currently account for 45% of energy supply at its Ewekoro plant, and a reliable supply chain has been set up over the last decade. The feedstock is almost entirely from palm kernel shells, with some limited use of palm fruit fibre. A recent study estimates that these two bioenergy feedstocks, together with peanut shells, rice husk, and wood processing residues (all of which also have relatively established supply chains) could meet up to 70% of the energy demand of the current Nigerian cement plant installed capacity. The use of waste as a fuel source, such as tyres, seems to be minimal in the Nigerian cement sector.

Technology developments may allow increasing the electrification of kilns in the mid-term. The lack of sufficient power from the grid drives all Nigerian cement plants to install their own power generation plants on site. This is potentially an opportunity for increasing the share of renewables-based electricity in heat-related processes as well as in general operations.

CCS is likely to be the only route to achieving total decarbonisation of cement production (ETC, 2018). The IEA's latest net-zero scenario projects that by 2070, about 90% of all the CO_2 emitted globally in cement sector is captured (IEA, 2021). However, the first commercial applications in the cement sector are not expected until 2024–2026 (IEA, 2020a).

In Nigeria, carbon capture has mainly been studied for the oil and energy sectors. The biggest bottleneck for use of CCS in Nigeria is likely to be storage and transport. The Oil and Gas Climate Initiative (IEA and OVP, 2021) has identified four storage hubs in Nigeria amounting to ~42 Mt/year of CO_2, but the feasibility of their use for the cement sector has not been investigated.

With regards to capture technology, investment costs in Nigerian cement plants are high (Betiku and Bassey, 2022), which suggests that pilot projects are very unlikely to start in the next ten years. It is likely that only new plants in future investment cycles will incorporate capture technologies, due to the high costs and efficiency losses related to retrofitting options. Moreover, Nigeria will need strong policy and regulatory frameworks for CCUS deployment.

Based on the data and trends reviewed in this section, the next section describes the approach to developing the scenarios and accompanying assumptions.

3. Method

3.1. Scenario analysis

The study draws from socio-technical transition studies, and other theoretical frameworks that delve into the management and governance of complex transitions toward sustainability, including transition management, strategic niche management, and the multi-level perspective (Markard, 2018; Markard et al., 2012). Nigeria's cement sector is a socio-technical system that consists of different elements: infrastructure, knowledge, markets, regulation, etc. Scenarios are a tool used within transition studies to improve the understanding of the complex interactions within socio-technical systems and the dynamics of the transition from one system state to a future one. The long-term, system-level foresight provided by scenarios can anticipate key features of transitions, as well as key risks and uncertainties. A scenario is a coherent and plausible description of a possible future state of a socio-technical system. It incorporates internally-consistent assumptions about the drivers, relationships, and constraints in the system (Thompson et al., 2012). Scenario analysis in climate change mitigation research in general, and in this study in particular, helps to evaluate the implications of different approaches to mitigation as well as critical areas of uncertainty (Moss et al., 2010).

This study analyses three possible transition scenarios for Nigeria's cement sector:

- Business-as-Usual: a pessimistic scenario where decarbonisation potentials are not pursued.
- Ambition: a scenario that sees significant improvements, but does not put the sector on the path towards deep decarbonisation.
- Towards Net-Zero (TNZ): a best-case scenario where all current decarbonisation levers are used to a high degree, leading to a substantial transformation of the sector. This scenario relies on significant investments, improvement in finance, policy, and enabling environment measures as well as continued reductions in the cost of decarbonisation measures that are not currently cost-competitive in Nigeria.

The following sections delve into the rationale behind the chosen cement production and decarbonisation pathways.

3.2. Production pathways

As a basis for the development of the transition scenarios, two different quantitative pathways for growth in production of cement were developed (Fig. 4). The baseline scenario follows a 3% growth rate consistently until 2050. This is based on a mid-point of current GDP growth projections. It is slightly lower than the 3.75% rate of urbanisation that UNDESA projects for Njoku et al. (2017) and the 3.5% yearly growth rate that the top-down model by van Ruijven et al. (2016) obtained for growth in cement demand in West Africa, and which was used in an exploratory modelling exercise for the Nigerian cement sector (CAT, 2017).

The second production scenario assumes that cement production starts to slow down from 2035 onwards and settles at a 1.5% growth rate. This is based on the decoupling of demand from economic growth that has been identified by global models (reviewed in section 2) as well as on the introduction of demand-side measures that drive down demand for cement.

A further two projections are given in Fig. 4 for illustration purposes: one assumes a production growth rate that only follows population growth (2.5% per year). The other one assumes a significantly higher growth rate (of 5% per year) and illustrates a potential path where domestic production grows faster than GDP and where Nigeria significantly increases its exports of cement to the region. It is interesting to note that some market analysis studies foresee higher demand growth in the short term (of up to 6% in total) (ARM, 2018; Research and Markets), but it is unclear whether this would be the case for Nigeria nor for how long.

It is important to note that the growth rates chosen do not dramatically increase production on a per capita basis. As Fig. 4(b) shows, the current low levels of 120 kg per capita would increase by 27%, to 151 kg per capita, in 2050 (and only 14%, or 135 kg per capita, in the scenario with demand-side measures). These values are still significantly lower than emerging economies (e.g., per capita cement consumption in India currently stands at around 200 kg).

3.3. Decarbonisation pathways

The three scenarios hinge on different key strategies for emission reductions from the sector. The key assumptions for each scenario are shown in Table 4 below.

The assumptions on historical values, potential fuel mix and energy efficiency improvements (including clinker-to-cement ratio) draw strongly on the GNR database (GCCA, 2022), the IEA National Energy

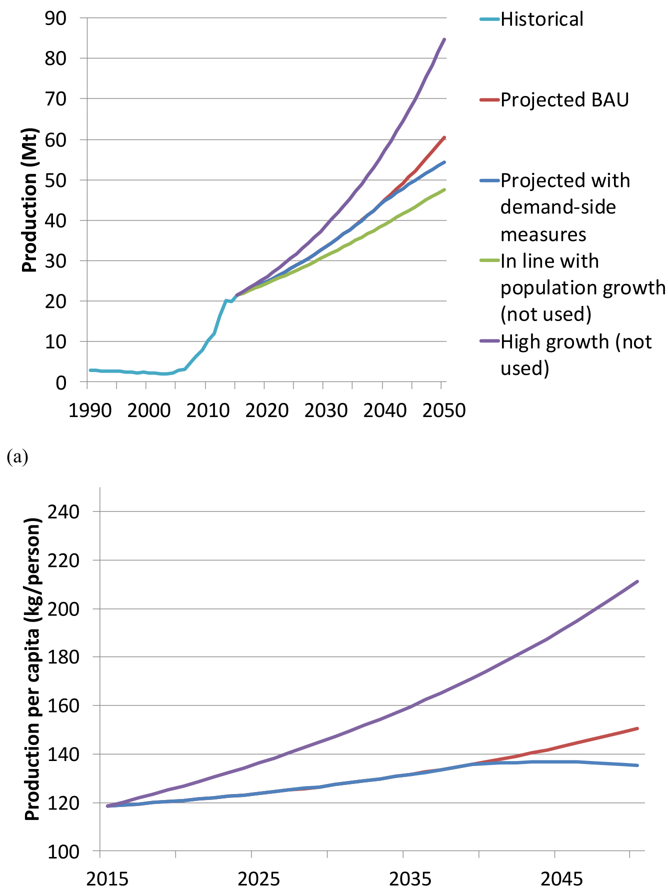


Fig. 4. Cement production (historical data and assumptions under the scenarios), total (a) and per capita (b). Source of historical data: 1990–1999 from Ohimain (2014), 2000–2015 from FMEnv (2018).

Balances (IEA, 2020b), and the IEA's regional estimates for cement decarbonisation potentials (IEA, 2018). However, the values derived from these datasets are qualified in light of the literature reviewed and expert interviews.

3.4. Scenario simulation tool

The analysis was performed using the open access PROSPECTS + tool, which captures the basic activity and intensity factors driving emissions in the cement sector (ICAT and NewClimate Institute, 2022). This excel-based tool allows building sectoral emissions scenarios by multiplying activity metrics (chiefly cement production) and intensity factors (see Equation 1). The calculation variables are described in Table 3 whereas a schematic view of the links between the variables is shown in Fig. 5. The input data that were altered in the calculation are indicated in the legend. PROSPECTS+ is particularly useful for creating a high-level, long-term vision of how a sector may plausibly evolve under certain assumptions. The tool does not have an optimisation functionality nor does it include cost estimates for different technology options or scenarios.

Equation 1. Calculation of Greenhouse Gas (GHG) emissions in the three scenarios

$$E = \sum_{n=0}^{N} (DEE_n + PE_n + EE_n) \quad (1)$$

Where:

$$DEE = DED \bullet DEEI$$
$$DED = A_{clinker} \bullet DEI$$
$$A_{clinker} = A_{cement} \bullet r$$
$$PE = A_{clinker} \bullet (PEI \bullet k)$$
$$EE = ED \bullet EEI$$
$$ED = A_{cement} \bullet EI$$

The following section describes the results of modelling the three scenarios with the above-mentioned assumptions and modelling approach.

4. Results

The scenario calculations are given in Figs. 6 and 7. The Business-as-Usual (BAU) scenario results in a strong increase in emissions from 2015 levels, from 15.2 Mt to 41.6 Mt CO_2e per year in 2050. This represents a 174% growth, driven equally by energy- and process-related emissions. The emissions per ton of cement decrease marginally, from 0.71 tCO_2e/t cement in 2015 to 0.68 tCO_2e/t cement in 2050.

The Ambition scenario sees an increase to 27.9 Mt, or 84% from 2015 levels, with most of the increase driven by process emissions, which grow by 137%. The emission factor decreases from 0.71 in 2015 to 0.46 tCO_2e/t cement in 2050.

Finally, the "Towards Net Zero" scenario reaches a peak of 19.6 Mt in 2038 and decreases slightly to 18.4 b y 2050. This represents only a 21% growth from 2015 levels and puts the sector on the path to deeper emission reductions, including through CCS, which avoid 3.1 Mt up to 2050. The TNZ scenario sees a doubling of process emissions and a 25% decrease in energy-related emissions. The emission factor is halved, reaching 0.34 tCO_2e/t cement in 2050.

The assumptions on demand management measures in the TNZ scenario drive a small proportion of the decrease in emissions. It is important to remember that the scenarios assume that cement demand per capita would only increase to 135–151 kg per capita, which is still significantly lower than other emerging economies.

The following section presents the results in light of existing literature and lays out caveats and critical uncertainties.

5. Discussion

The results share some common points with existing literature on potential pathways for deep decarbonisation in Nigeria's cement sector. The Energy Transition Plan (FGN, 2021b, 2021a) assumes a strong reduction of the clinker-to-cement ratio through the substitution of 50% clinker with calcined clay. This is broadly in line with the assumption of the Towards Net Zero scenario in the present study, which assumes a 60% ratio is achieved by 2050. The report states this would reduce

Table 3
List of variables.

Variable	Description	Unit
E	Total Emissions	MtCO_2e
N	Number of historical years in estimation	years
DEE	Direct Energy Emissions	MtCO_2e
PE	Process-related Emissions	MtCO_2e
EE	Electricity-related Emissions	MtCO_2e
DED	Direct Energy Demand	PJ
DEEI	Direct Energy Emissions Intensity	MtCO_2e/PJ
$A_{clinker}$	Activity (Clinker Production)	Mt clinker
A_{cement}	Activity (Cement Production)	Mt cement
r	Clinker-to-cement ratio	t clinker/t cement
DEI	Direct Energy Intensity	MJ/t clinker
PEI	Process-emissions Intensity	MtCO_2e/Mt clinker
k	% of process emissions captured by CCS	%
ED	Electricity Demand	TWh
EEI	Electricity Emissions Intensity	tCO_2/TWh
EI	Electricity Intensity of cement production	kWh/t cement

Table 4
Key assumptions of scenarios.

Parameter	Unit	Starting point (2015)	Scenarios (2050)			Affects which strategy?
			BAU	Ambition	Towards Net-Zero	
Direct energy intensity	MJ/t clinker	3.81[a]	Stays constant	Linear decrease to 3.3[b]	Linear decrease to 3.2[b]	Energy efficiency (primarily)
Direct energy emissions intensity	$MtCO_2e$/PJ	0.09[c] (fuel mix 100% coal)	Stays constant	0.06 (Coal 35%, Gas 50%, Biofuels and waste 15%)	0.04 (Coal phased out, Gas 75%, Biofuels and waste 25%)	Fuel mix
Clinker-to-cement ratio	%	77.23%	Stays constant	65%[d]	60%[d]	Clinker-to-cement ratio
Electricity intensity	kWh/t cement	98[e]	Stays constant	86[f]	83[f]	Energy efficiency
Electricity emissions intensity	tCO_2/TWh	0.42 [g] (fuel mix 82% gas, 17% RES)	Stays constant	0.23 (65% gas, 35% RES)	0.32 (45% gas, 55% RES)	Fuel mix
CCS	% share of direct emissions avoided/ year	0%	0%	5% (starting in 2040)	15% (starting in 2035)	CCS
Demand	Mt/year	21.5	60.5 (3% yearly growth rate until 2050)	60.5 (3% yearly growth rate until 2050)	54.3 (3% yearly growth until 2035, then linear decrease to 1.5%)	Demand management

[a] 2015 value for Africa from GNR database, indicator 93AG (GCCA, 2022).
[b] Based on expert interview and 2040 values from IEA 2DS scenario (IEA, 2018).
[c] Nigeria's IEA balances state that coal represents 100% of the direct energy input in the cement industry (IEA, 2020b). These national statistics stand in contrast with company reports that indicate a mix of fuels.
[d] 2015 value for Africa from GNR database, indicator 92AGWce (GCCA, 2022). Decrease to 70%/68% by 2030, 67%/63% by 2040, based on RTS and 2DS scenarios, respectively (IEA, 2018). Extrapolate to 2050.
[e] 2017 value for Africa from GNR database, indicator 93AGW (GCCA, 2022) (2015 value not available).
[f] Based on 2040 RTS and 2DS scenarios, respectively (IEA, 2018).
[g] 2015 value from Nigeria IEA energy balances (IEA, 2020b).

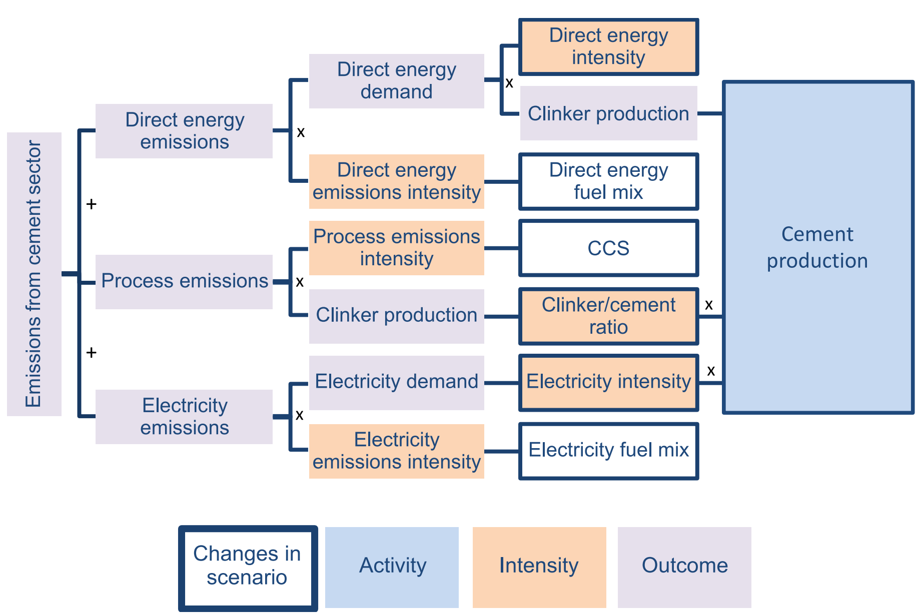


Fig. 5. Depiction of calculation variables and links in PROSPECTS + tool (ICAT and NewClimate Institute, 2022). Activity variables are centered around cement and clinker production, whereas intensity variables refer to energy consumed or emissions produced per unit of activity. Those variables with a thick outline are modified in the scenarios (as described in Table 4), whereas those with no outline remain unchanged.

cement emissions by 8 Mt by 2050, a 30% reduction from the base year levels.

The ETP also identifies BECCS as an option for the cement sector post-2030, and estimates that applying BECCS to half of Nigeria's cement production could abate 62% of cement emissions. This is a much higher value than that considered in the current study and is not in line with the likely timeline of CCS commercialisation in Nigeria, given that the world's first commercial applications in the cement sector are not expected until 2024–2026 (IEA, 2020a). Further comparisons are limited as the study gives no consideration to demand-side measures and no details are provided regarding the assumptions on demand growth. In its Africa-wide scenario for the cement sector, McKinsey (2021) does consider a strong decrease in demand in the long term due to the uptake of cross-laminated timber as an alternative material. However, this does

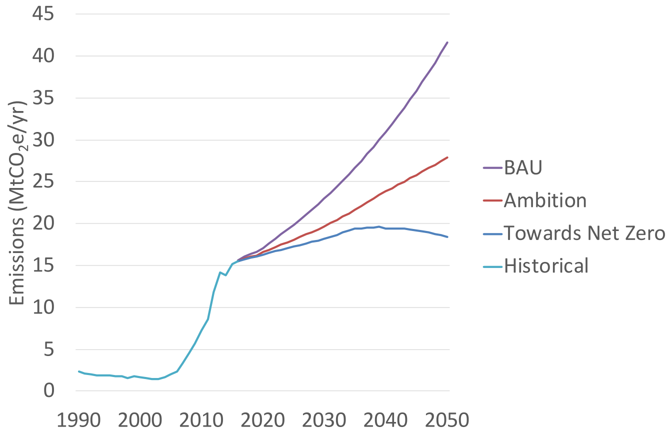


Fig. 6. Emissions from cement sector in Nigeria, 2015–2050, under the different scenarios.

not seem in line with current market and policy trends in Nigeria.

The scenarios by CAT (2017) find that emissions in 2040 would be in the range of 110–200 $MtCO_2$, depending on the scenario. Their scenarios are driven by an assumption of there being 60 Mt of cement produced in Nigeria in 2015 but this figure was obtained from a media report and does not align with current government data. The scenarios in the present study foresee a slower growth in production and emissions. However, the evolution of emission intensity of cement production in the moderate and business-as-usual scenarios is comparable across both studies (in the range of 0.60–0.45 tCO_2/t of cement).

This study's findings are broadly aligned with studies in comparable contexts. For example, Dhar et al. (2020) find no absolute decrease in emissions from the base year in any of the scenarios for the Indian cement sector. Even the most ambitious scenario results in a 30% increase in emissions by 2050, compared to the base year. This is due to a highly certain increase in cement demand.

It is important to remember that the Ambition and Towards Net Zero scenarios rely on substantial investments, improvement in finance, policy, and enabling environment measures. However, Nigeria's industry faces significant barriers to investments: inadequate power and infrastructure (including high cost of transportation of cement), and limited access to finance are key barriers for all industry sectors in Nigeria, including cement. The incentives for the cement industry to transition towards net-zero are an immediate need to reduce its energy costs, and, in the future, compliance with more stringent regulation to avoid competitive disadvantage in international markets.

The Nigerian market and policy environment for industrial energy efficiency is still in its infancy. However, in the last ten years, there have been significant developments. In particular, the development and formal adoption of the NEEAP (National Energy Efficiency Action Plan) which sets energy efficiency targets for industry, and makes energy audits compulsory in all energy-intensive sectors (FGN, 2016). The ISO 50001 standard has been adopted in Nigeria, industrial energy efficiency networks have been set up and a series of capacity-building programmes and energy audits are underway (GIZ, 2020). As a result of recent efforts, awareness on energy efficiency in industry has risen among policy makers and industry. A survey of energy consumption

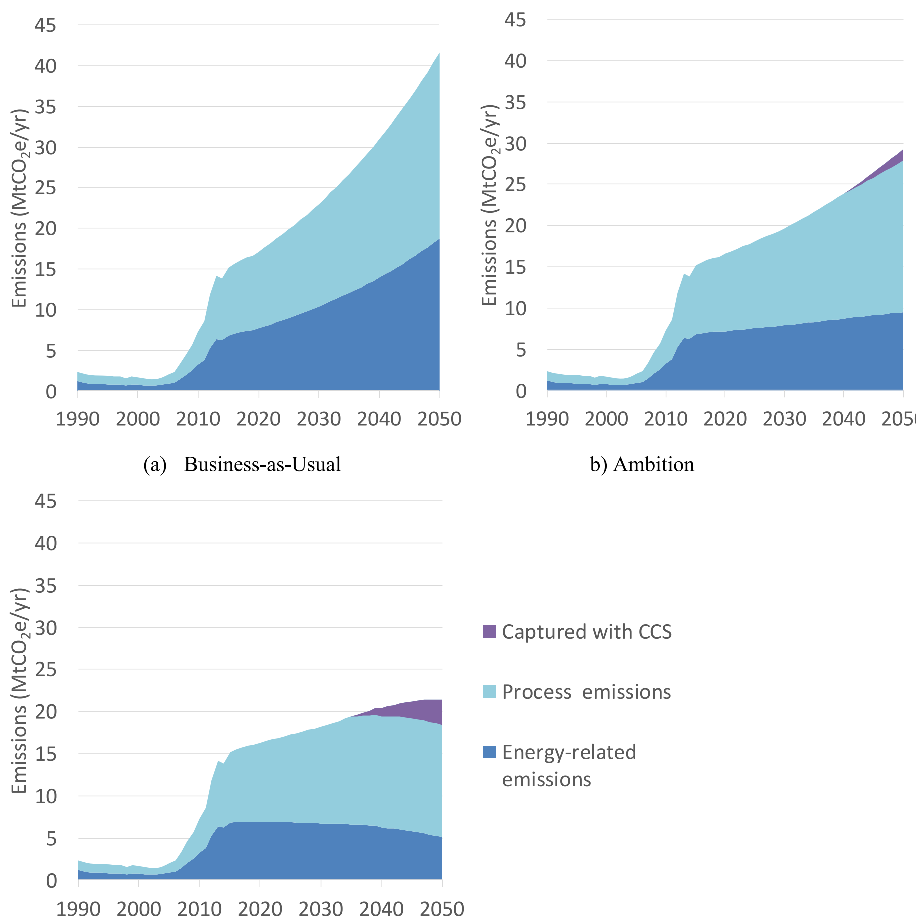


Fig. 7. Emissions by type, under the Business-as-Usual (a), Ambition (b), and Towards Net Zero (c) scenarios.

across multiple large-scale cement plants is however still lacking.

The results indicate a strong potential for policy that could drive improvements in the clinker-to-cement ratio. The uptake of blended cements in national cement standards is an area of high potential, but it is highly uncertain how fast it could happen. Moreover, the value chains for alternative materials for clinker are still to be developed.

Finally, literature on the potential of material efficiency and circularity in the cement sector in Nigeria and comparable economies is extremely scarce. Incentives to material efficiency are likely to act indirectly – for example, requirements for industry to reduce emissions lead to somewhat higher prices, which provide an incentive for construction companies and other industries to use materials more efficiently. Policy-driven changes occurring in other sectors also contribute to lower material demand, for example by encouraging the renovation rather than the replacement of old buildings.

5.1. Key caveats

The key caveats of the present study are of two types: those related to the availability or reliability of published data that informs the assumptions, and those related to the approach chosen for the development and analysis of scenarios. Furthermore, there are limitations related to the applicability of the findings in other contexts in the African region.

With regards to the data availability, the first major area of uncertainty is the assumption for current electricity mix and thermal energy mix. As stated in section 2, Nigeria's IEA balances are in contrast with company reports regarding the use of coal in the sector for heat generation. Moreover, Nigeria's manufacturing sector relies heavily on self-generation of electricity. Using the electricity mix of grid-based electricity (such as the one provided for the International Energy Agency (IEA)) is therefore not a suitable proxy. The coverage of the GCCA database on energy intensity and clinker-to-cement ratio is also rather low for Africa (29% coverage in 2017, cf. 86% for the European Union (EU)) and this diminishes the reliability of the data used.

The second key area of uncertainty concerns the energy efficiency potentials. A public survey of energy consumption and saving potentials across multiple large-scale cement plants is still lacking in Nigeria. The present study makes use of international literature and expert opinion, but future scenario studies should seek to enhance the database on energy and emissions saving potentials in Nigeria, through the use of on-site energy audits.

The third critical source of uncertainty are the assumptions for growth in demand and the potential for demand-side measures. The BAU and Ambition scenarios follow a 3% growth rate consistently until 2050, in line with GDP projections, rate of urbanisation, and findings of integrated models (van Ruijven et al., 2016). The Net Zero scenario assumes that cement production starts to slow down from 2035 onwards due to demand-side management, and settles at a 1.5% growth rate. These growth rates assume that production will mainly meet domestic demand and that demand per capita stays at relatively low levels (up to 135–151 kg per capita by 2050, which is still significantly lower than emerging economies where per capita cement consumption stands at around 200 kg). However, it is important to remember that several Nigerian cement manufacturers have plans to develop a strong export market. For example, several companies have built port facilities for exports (World Cement, 2018). In 2020 Dangote Cement exported 27,800 tonnes of clinker to Senegal and Lafarge Holcim began exports to Ghana in 2017 (OBG, 2018a; Olowookere, 2021).

Growth in production and in exports remains very difficult to forecast based on past trends and published literature and would merit further research through stakeholder engagement and the creation of a detailed dataset for planned production capacity in the next decades, which reflects expected stock turnover and investments. The present study indicates that Nigeria's cement plant fleet stock today is very young but, at the same time, that much of the 2050 stock is yet to be built. As of today, 44% of installed capacity is less than 5 years old, and 83% is less than 15 years old. The average age of the fleet is thus lower than the Chinese and Indian average of 12–13 years (IEA, 2020a; Tong et al., 2019). Despite slight overcapacity at the moment, the sector is likely to need new capacity from 2025 onwards.

A number of limitations emerge from the scope of the study and the approach chosen. Most importantly, the present study does not analyse the economic costs and benefits of the transition, nor its effect on cement pricing and the related distributional impacts. Future studies should use data on upcoming investments in plant capacity for an analysis of the cost and emission implications of different technology choices. For example, calculating the overall costs of delivering certain emission goals, a comparison on the cost of new plant investment vs. retrofits of existing plants, analysing the savings that can accrue from investing in the most efficient kilns available (rather than in outdated technology) or examining the effect of different scenarios on the price of cement products, and the impacts that this would have on consumers (construction sector and cement end-users). An interesting avenue for further research would be the study of the effects of carbon prices on the economic feasibility of different transition scenarios. Finally, a study of the economic externalities of the scenarios is warranted. For example, in terms of the co-benefits that could result from pursuing deep decarbonisation: health, productivity or employment creation (in the cement sector or in alternative value chains).

The scenarios analysed in this study are based on qualitative assumptions about near-term developments in finance, policy, and enabling environment that would drive each scenario. Future studies should seek to build on these underlying storylines and elaborate them further, ideally with the input from key industry stakeholders and relevant institutions. Examples of near-term developments which could be analysed in greater detail are the barriers to investment (such as the risk of further devaluations of the local currency), or the greater availability of finance for energy efficiency investments. A stronger set of qualitative assumptions regarding demand-side measures would also require a study of supply chains for alternative materials, and the policy needs to incentivise uptake Finally, understanding the potential of technologies that are currently not commercial, such as CCS, requires a more detailed analysis of global technological trends and the likely time ranges in which the use of the technology could be tested in Nigeria.

Finally, there are limitations related to the applicability of the findings in other contexts. This study sheds light into the prospects for growth in cement demand and decarbonisation pathways for the sector in other major cement-producing countries in Africa, especially in those characterised by oligopolistic markets with large-scale cement production facilities. However, it is important to keep in mind that macroeconomic factors such as population and GDP growth can significantly differ in other contexts and this may affect the potential of different approaches to decarbonisation.

6. Conclusions

In conclusion, this study finds that an ambitious yet feasible scenario could put Nigeria's rapidly growing cement sector on a path towards net zero emissions. The results indicate that, under a best-case scenario, emissions from the sector can plateau during the 2030s and grow by 21% by 2050 (compared to 2015 levels). This is despite an almost tripling of demand for cement, due to a doubling of the population and an increase in cement demand per capita to the levels of other comparable economies. Achieving this scenario involves action across all three key levers for decarbonisation of the cement sector: demand management, energy efficiency (including reducing the clinker-to-cement ratio), use of cleaner fuels, and carbon capture and storage. Realising each decarbonisation measure will require substantial investments, improvement in finance, policy, and enabling environment.

The findings also shed light into alternative scenarios where not all decarbonisation levers are implemented: a moderately ambitious scenario that relies mostly on savings on energy-related emissions results in an 84% increase in emissions by 2050, far from the path towards net zero emissions. Finally, a Business-as-Usual scenario results in an almost tripling of emissions by 2050.

The cement sector is characterised by long investment cycles and slow stock turnover. Most of Nigeria's cement production capacity has been installed in the last decades, and full refurbishments of relatively young kilns are unlikely. However, there is a large potential to improve energy efficiency of existing kilns via partial retrofits. Moreover, new kilns constructed in the next major investment cycle can incorporate best-available technology. This will likely take place in the mid 2020s and represents a window of opportunity which can either lock in outdated technology or put the sector on track for deep decarbonisation.

The findings of the present study provide an evidence base that can guide the development of a roadmap for the decarbonisation of the sector that seizes this upcoming investment window. The results also demonstrate the strong potential for policies to drive improvements in energy efficiency and clinker-to-cement ratio. Furthermore, Nigeria provides a suitable case study for understanding the potential for decarbonisation in similar contexts, as demand for cement and capacity to produce locally continues to rise in SSA in the mid-term.

Literature around decarbonisation of the cement sector in Nigeria and comparable economies is extremely scarce. The scarcity of published data on the sector limits the applicability of the findings. Some of the central assumptions in the present study are also some of the major sources of uncertainty. Critical areas of uncertainty include:

- The assumptions on production growth rates (including the potential of demand reduction, and the evolution of the export market), and
- The assumptions on energy efficiency potentials and fuel mix, with national statistics standing in contrast with company reports regarding the use of coal in the sector for heat generation.

Conducting on-site energy audits and the creation of a detailed dataset for planned capacity investments would help overcome this limitation. Moreover, updated and industry-validated historical data regarding cement production is required.

Furthermore, a detailed study into the cost implications of different scenarios, which quantifies the investment needs and key investment windows, is warranted. Future studies should also look into the impacts of the scenarios on the price of cement and any related equity implications. Finally, future research on the long-term prospects for decarbonisation of the Nigerian cement sector should seek broad stakeholder engagement and input, including from the cement producing firms, institutional actors, financing bodies, consumers and other affected parties.

Credit author statement

María Yetano Roche: Conceptualisation, Methodology, Formal analysis, Investigation, Data curation, Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available on https://doi.org/10.5281/zenodo.7403393.

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