# Bioenergy for Sustainable Local Energy Services and Energy Access in Africa

Demand Sector Report 1: Cement Manufacturing
Focus Country: Nigeria

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Cover photo: Alternative fuel conveyor system, Lafarge Africa Ewekoro Cement Plant, Ogun State, Nigeria. Credit: Linus Orakwe

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# EXECUTIVE SUMMARY


NIRAS-LTS partnered with Aston University, E4tech and AIGUASOL to research the opportunities and constraints for bioenergy development in sub-Saharan Africa (SSA) across seven shortlisted industries, through five interlinked themes: biomass resources, technology, economic competitiveness, commercial viability, and institutional, market and regulatory framework. This report, the first in the series, focuses on the bioenergy opportunities in the cement manufacturing sector in Nigeria.

Nigeria is Africa's largest cement producer. Its cement industry has traditionally used natural gas, petroleum products and coal to supply heat for processing limestone into clinker, the main ingredient for producing cement. While fossil fuels are plentiful in Nigeria, there is growing interest in the cement industry in 'co-processing' with alternative fuels (AF), including bioenergy. This drive has been led by Lafarge Africa and its AF subsidiary, Geocycle, which now co-process fossil fuels with biomass at four of its five plants. This research explored the wider commercial prospects for part-replacement of fossil fuels with biomass to provide heat in Nigeria's cement industry, based on the operational experiences of Lafarge's Ewekoro plant in Ogun State.

Biomass resources and technological considerations were not found to be barriers to the adoption of bioenergy for coprocessing. While there are some seasonality and aggregation considerations, with proper planning and sufficient diversification, there is sufficient feedstock available to satisfy potential demand from Nigeria's cement sector. On technology, the modalities for biomass pre-processing, handling and feeding are well understood within the industry, and the necessary equipment modifications can be undertaken using cement companies' own in-house engineering capacity.

The decision by individual cement companies to adopt bioenergy therefore depends upon the cost of establishing reliable, cost-effective supply chains for biomass fuels, compared with current fossil fuel solutions, and the cost of adapting or installing equipment to handles these fuels and utilise bioenergy. The need to set up supply chains with new, unfamiliar partners capable of delivering sufficient feedstocks at prices competitive with fossil fuels, and to undertake suitable technological modifications to incorporate biomass co-processing in cement manufacturing, are key factors for other producers seeking to adopt this bioenergy model. Although there are significant environmental and social co-benefits from adopting biomass fuels (such as sustainable agricultural processing, job creation, rural development through waste recovery and reducing greenhouse gas emissions), these may not be key motivating factors and are highly dependent upon cement companies' specific sustainability and social responsibility commitments.

Given the good business case for bioenergy adoption in this sector, sharing lessons from the experiences of companies such as Lafarge Africa can boost confidence amongst other players regarding the commercial and environmental benefits of such a transition. There is significant potential for wider adoption of bioenergy in the cement sector in Nigeria and in other target countries in SSA, where co-processing with biomass fuels is already practised to some extent. As more cement manufacturers adopt bioenergy, collective expertise will grow and this approach to heat production will become normalised and will facilitate further replication.

# Contents

# LIST OF ACRONYMS

| | |
|---|---|
| ABEX | abandonment expenditure |
| AF | alternative fuel |
| BSEAA | Bioenergy for Sustainable Local Energy Services and Energy Access in Africa |
| CAPEX | capital expenditure |
| CDM | Clean Development Mechanism |
| CHP | Combined Heat and Power |
| CKD | cement kiln dust |
| G&I | Gender and Inclusion |
| GBP | Pound Sterling |
| GHG | greenhouse gas |
| HCL | Hima Cement Ltd |
| IFC | International Finance Corporation |
| KPI | Key Performance Indicator |
| LCC | Life Cycle Cost |
| LCOE | Levelized Cost of Energy |
| MAN | Manufacturers' Association of Nigeria |
| MC | moisture content |
| MCA | Multi-Criteria Analysis |
| MEB | Mass Energy Balance |
| MMSD | Federal Ministry of Mines and Steel Development |
| Mt | mega tonne (1 million tonnes) |
| NESREA | National Environmental Standards & Regulatory Enforcement Agency |
| NGN | Nigerian Naira |
| O&M | Operations and Maintenance |
| OPEX | operational expenditure |
| PKS | palm kernel shell |
| RDF | refuse-derived fuels |
| SSA | sub-Saharan Africa |
| TEA | Transforming Energy Access |
| UNDP | United Nations Development Programme |
| UNEP | United Nations Environment Programme |
| UNFCCC | United Nations Framework Convention on Climate Change |
| USD | United States Dollar |
| WAPCO | West African Portland Cement Company |

# 1 INTRODUCTION

NIRAS-LTS partnered with Aston University, E4tech and AIGUASOL to implement a two-year project entitled 'Bioenergy for Sustainable Local Energy Services and Energy Access in Africa - Phase 2' (BSEAA2). BSEAA2 was part of the Transforming Energy Access (TEA) programme, which is funded with UK aid from the UK government. TEA is a research and innovation platform supporting the technologies, business models and skills needed to enable an inclusive clean energy transition. TEA works via partnerships to support emerging clean energy generation technologies, productive appliances, smart networks, energy storage and more. It increases access to clean, modern energy services for people and enterprises in sub-Saharan Africa (SSA) and South Asia, improving their lives, creating jobs and boosting green economic opportunities.

BSEAA2 was intended to identify and support the development of innovative, commercial bioenergy pathways and technologies to accelerate the adoption of bioenergy in SSA. Building upon BSEAA Phase 1, which took place in 2016/17, the second phase focused on opportunities for the development of anaerobic digestion (AD) and combustion for electricity and/or heat generation in the range 10 kW to 5 MW, with a Technology Readiness Level of 5+. That is, technologies that had been successfully piloted in a representative commercial setting.

The research team investigated the challenges and opportunities affecting the commercial deployment of these technologies in ten focus countries in SSA (Ethiopia, Ghana, Kenya, Mozambique, Nigeria, Rwanda, South Africa, Tanzania, Uganda and Zambia), investigated through six relevant themes: biomass resources, technology, economics, business models, institutional, market and regulatory frameworks, and gender and inclusion (G&I). The research targets bioenergy entrepreneurs, investors and policymakers, aiming to catalyse action for the further development of commercial bioenergy in SSA.

Commercial opportunities and constraints for bioenergy development were assessed within seven shortlisted industries, referred to as 'demand sectors'. These demand sectors and their associated bioenergy pathway and focus countries are presented in Table 1.1. This report, the first in the series, focuses on the bioenergy opportunity in the cement manufacturing industry in Nigeria.

*Table 1.1. Shortlisted demand sectors for BSEAA2 research*

| No. | Demand sector | Biomass resource | Technology | Country |
|---|---|---|---|---|
| **1** | **Cement manufacturing** | **Biomass residues, part-replacing fossil fuel** | **Combustion for heat** | **Nigeria** |
| 2 | Tea processing | Biomass briquettes, part-replacing fuelwood | | Kenya |
| 3 | Wood processing | Wood processing residues | Combustion for CHP | Tanzania |
| 4 | Palm oil processing | Palm oil mill effluent | AD for CHP | Ghana |
| 5 | Horticulture | Fruit & vegetable processing residues | | Kenya |
| 6 | Dairy | Cattle manure | | South Africa |
| 7 | Sisal processing | Sisal processing residues | AD for electricity | Kenya |

# 2 METHODOLOGY

## 2.1 OVERALL METHODOLOGY

During a 6-month preliminary assessment (2019-20), the research team screened a range of bioenergy 'pathways' in SSA involving AD or combustion, comprising a specific biomass feedstock, conversion technology, end use and demand sector. The aim was to identify the most promising pathways for the adoption of bioenergy-based combustion or AD across the target countries, for which the existence of at least one operational venture could be verified. This resulted in the shortlisting of the seven priority demand sectors in five countries. During the following 12 months (2020-21), these demand sectors were investigated in detail across the five research themes, to explore the experiences of both adopters and non-adopters of bioenergy technology.

Information was gathered from site visits to representative commercial operations and from other stakeholders active in bioenergy in SSA, from published literature and from partners of the TEA Programme, UK Energy Catalyst and Innovate UK. A bibliography is in Appendix 1 and a list of people consulted is in Appendix 2.

For each Demand Sector, a 'Base Case' and a 'Bioenergy Case' were identified:

- The **Base Case** refers to the industry standard for energy use in the given demand sector in the target country; that is, the default heat, power or combined heat and power (CHP) solution used by a majority of similar businesses.
- The **Bioenergy Case** refers to a specific enterprise (or 'flagship project') that has transitioned to the use of bioenergy for heat and/or electricity generation in the target demand sector, using either combustion or AD.

The Base Case and Bioenergy Case for the cement manufacturing sector are defined in Table 2.1.

*Table 2.1: Base Case and Bioenergy Case for the cement sector*

| Base Case | Bioenergy Case |
|---|---|
| Cement facilities using fossil fuels for generating heat for their manufacturing operations | Cement facilities co-processing[1] with biomass feedstock to generate heat for cement production<br>**Flagship project: Lafarge Africa cement plant at Ewekoro, Ogun State, Nigeria** |

This report analyses the Bioenergy Case flagship project across the six study themes of biomass resources, technology, economics, commercial viability, governance frameworks and G&I to identify the factors that have enabled the adoption of sustainable bioenergy. The findings are compared with Base Case examples to identify the opportunities and constraints for other enterprises in the same demand sector to adopt similar solutions. Based on this analysis, the potential and requirements for wider adoption of the Bioenergy Case in the chosen demand sector are assessed, both for the target country and for the other BSEAA2 countries.

[1] 'Co-processing' refers to the use of a mixture of two or more different fuels to generate heat for the industrial process, clinker calcination, in the production of cement clinker.

## 2.2 INSTITUTIONAL, MARKET AND REGULATORY FRAMEWORK ASSESSMENT

The institutional, market and regulatory framework for bioenergy in Nigeria's cement sector was assessed through web-accessed reports, journal articles, news reports and interviews with government, private sector and NGO informants, supplemented by field visits and team members' own extensive experience. Interviews were conducted remotely and in person with representatives of Geocycle (Lafarge Nigeria's alternative fuel supply company), the Standards Organisation of Nigeria, the Federal Ministry of Environment, the Renewable Energy Department of the Nigerian National Petroleum Company, the Lagos Waste Management Authority and the Cement Manufacturers' Association of Nigeria.

## 2.3 BIOMASS RESOURCE ASSESSMENT

The objective of the resource assessment was to determine resource availability, bioenergy potential, feedstock-technology interface and mass-energy balance (MEB) for the relevant feedstocks in each demand sector. The assessment considered the spatial distribution of feedstock, according to FAO's Global Agro-Ecological Zones (FAO, 2021b) and the UN Economic Commission for Europe's framework for land use and agro-ecological zoning. Existing data on agriculture, forestry and agro/forest processing were used, adopting biomass feedstock categories from FAO (2004) and IEA & FAO (2017). Country- and industry-specific resource potential was calculated based on the amount of crop or primary product generated, the residue-to-product ratio, the recoverable fraction, the fraction available (considering other uses) and its bioenergy potential (see source data in Appendix 3). An MEB model was also developed, to simulate the energy system using validated performance and efficiency data. Based on the known feedstock inputs of the flagship project, the model quantifies expected material flows and outputs of heat and power under optimised performance conditions, allowing replication potential to be estimated based on the preceding assessment of the biomass resource.

## 2.4 TECHNOLOGY ASSESSMENT

The objective of the technology assessment was to determine the technological implications of bioenergy use in each demand sector, in this case for generating heat for cement manufacturing sector in Nigeria, based on technical considerations and practical experiences at the Bioenergy Case flagship project, Lafarge Africa's Ewekoro cement plant in Ogun State. Lafarge's operations have been widely profiled as they were the first cement manufacturer in Nigeria to adopt alternative fuels. Exploring their experiences from a technical perspective required interaction with Ewekoro's contracted feedstock suppliers and with the management of Geocycle. The current technology and its supply chain landscape were characterised, and the opportunities and requirements for replication linked to technology were assessed.

## 2.5 ECONOMIC COMPETITIVENESS ANALYSIS

The objective of the economic competitiveness analysis was to compare energy costs under the Base Case and the Bioenergy Case, to investigate potential economic drivers for wider adoption of bioenergy in this demand sector. A 10-year discounted cash flow analysis was carried out using an Excel-based Life-Cycle Cost (LCC) modelling toolkit developed by AIGUASOL (see Appendix 4).[2] The main economic indicator considered was the Levelized Cost of Energy (LCOE), in USD/MWh. LCOE comprises CAPEX (upfront investment and other amortizable costs), OPEX (personnel, consumables and operating costs) and ABEX (abandonment expenditures). LCOE in this case was calculated for heat only. The LCC model was also used to perform sensitivity analyses on LCOE, considering a range of possible values for relevant input parameters.

## 2.6 Commercial viability assessment

The objective of this assessment was to determine the commercial case for the adoption of bioenergy in each demand sector, the factors affecting its successful adoption at the flagship project and the potential for wider uptake in the same sector, based on barriers, enablers, market potential and finance. The Bioenergy Case was analysed via the Lafarge Africa experience to identify elements for commercial success linked, for example, to supply chain operations, demand for heat, sustainability considerations and financing. Information was obtained from stakeholder interviews and literature review. This was followed by an analysis of the wider commercial potential in the cement sector, analysing the barriers and enablers for supplying heat under various scenarios. Taken together with an assessment of market size and conditions, the barrier analysis gave an indication of wider market potential. Finally, potential sources of finance and their relevance for bioenergy investments of this type were assessed.

## 2.7 Gender and inclusion assessment

The objective of the gender and inclusion research was to identify G&I-related issues in each demand sector, and to highlight potential areas for improved awareness, inclusion and participation of women. The research framework was adapted from a UNDP (2004) toolkit, and was structured around: access to assets; beliefs and perceptions; practices and participation; and institutional laws and policies. The research focused mainly on the production and supply of feedstocks, and, where applicable, the bioenergy conversion process. A literature review was also carried out, and further information was gathered through interviews with informants working in G&I and at the flagship project.

## 2.8 Multi-criteria analysis

A multi-criteria analysis (MCA) was carried out to summarise the degree to which each of the study's five key thematic strands (biomass resources, technology, economics, commercial viability and governance frameworks) are conducive or detrimental to the adoption of the particular bioenergy solution in each demand sector. Each theme was given an average 'score' from 1 to 10, based on the degree to which various factors (non-weighted) under each theme make a positive contribution (high score) or act as an impediment (low score) to the viability of the Bioenergy Case. The MCA results are presented in the report's concluding chapter as a multi-point spider diagram, to provide a graphical summary of the factors most likely to support or impede successful adoption of bioenergy in the demand sector in question. The input data for the MCA are in Appendix 5.

[2] 10 years is a standardised period chosen for economic analysis based on an averaging of longer periods generally applicable for sustainability assessments and shorter periods applicable for investors consideration, and is not necessarily indicative of the functional lifetime of a particular project.

# 3 Overview of the cement sector

## 3.1 Sector landscape

Nigeria is Africa's most populous country. It is also SSA's largest cement manufacturer, with an annual production capacity of nearly 50 million tonnes (Mt) in 2018 (Global Cement, 2018b), of which nearly a quarter is exported. Cement production is now Nigeria's leading manufacturing industry and leading industrial greenhouse gas (GHG) emitter (Federal Ministry of Environment, 2020). The sector is dominated by Dangote Cement, followed by Lafarge Africa (a subsidiary of the Holcim Group[3], the world's largest cement company) and the BUA Group. While being a more recent entrant to cement production, Dangote is now Nigeria's top cement producer accounting for over 60% of national cement production (Dangote Cement, 2020).

There are 11 cement plants at nine factory sites in Nigeria (see Figure 3.1). Lafarge Africa has five plants, with three in Ogun State (at Ewekoro I, Ewekroro II and Sagamu), one at Ashaka in Gombe State and one in Mfamosing in Cross River State. Dangote owns the country's largest factory at Obajana in Kogi State, as well as Ibese Cement in Ogun State and Gboko Cement in Benue State. BUA operates Obu Cement in Edo State (with two production lines) and Sokoto Cement in the far northwest at Kalambaina in Sokoto State.


*Figure 3.1 Locations of cement factories in Nigeria (Source: authors' compilation)[4]*

[3] Holcim Group became the official name of the LafargeHolcim international cement company in May 2021

[4] The palm oil belt is highlighted because of its significance as a source for biomass residues, elaborated later in the report.

## 3.2 Bioenergy in the cement sector

Nigeria's cement industry has traditionally used natural gas, imported coal and some domestic petroleum and coal[5] to supply heat for processing limestone into clinker, the main ingredient of cement. While fossil fuels are plentiful in Nigeria, cement companies are increasingly exploring 'co-processing' with alternative fuels (AF), primarily bioenergy. This drive has been led by Lafarge Africa and its AF subsidiary, Geocycle[6], which now co-processes biomass with fossil fuels at four of its five plants. Dangote is also planning to start co-processing fossil fuels with AFs at two of its plants, consistent with a corporate push towards AFs (Dangote Cement, 2020).

## 3.3 Institutional, regulatory and finance framework

### 3.3.1 Institutional framework

The key stakeholders in Nigeria's cement sector are government ministries and agencies at federal and state levels, as well as private sector manufacturers and non-government actors such as industry associations (Figure 3.2).

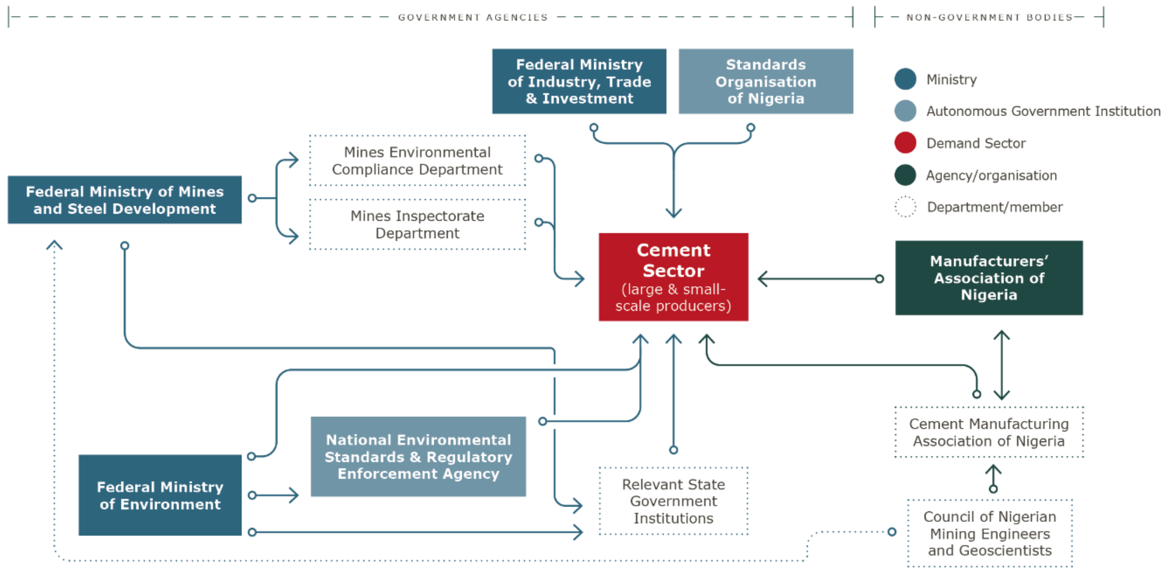



*Figure 3.2 Institutional framework for Nigeria's cement sector (Source: authors' compilation)*

The institutional framework for the industry is led by the Federal Ministry of Mines and Steel Development (MMSD), which licenses and oversees limestone extraction through its Mines Environmental Compliance Department and Mines Inspectorate Department. The Council of Nigerian Mining Engineers and Geoscientists advises the MMSD and sets professional standards for mining in Nigeria. The Standards Organisation of Nigeria sets and enforces standards for cement production, which has stimulated significant local investment. The Federal Ministry of Industry, Trade and Investment has been a champion for the expansion of the sector, given its contribution to industrial development, rural employment and foreign exchange-earning. Together with the MMSD, it has supported the rapid growth of cement production and exports.

[5] Nigeria is Africa's largest oil producer and second largest natural gas producer, and also has extensive coal reserves.
[6] Geocycle was set up over 30 years ago to provide international support for industrial, agricultural, municipal and other waste management services to Holcim's cement operations and to other public and private entities around the world.

The Council of Nigerian Mining Engineers and Geoscientists advises both federal and state governments on technical aspects of cement production, including fuel use and energy conservation. The Cement Manufacturers' Association of Nigeria is currently dormant, so there is no strong advocacy organisation specifically for the sector, but the Manufacturers' Association of Nigeria, in which cement companies have a strong voice, provides support and advocacy to all major companies.

Figure 3.3 shows the institutional framework for environmental management in Nigeria's cement sector at a federal and state level. State governments in the main cement-producing States of Ogun, Gombe, Ebonyi, Benue, Cross River and Sokoto have environmental protection agencies, departments of environmental conservation and resource management, and departments of mines, lands, water, industries, roads and other infrastructure support agencies.

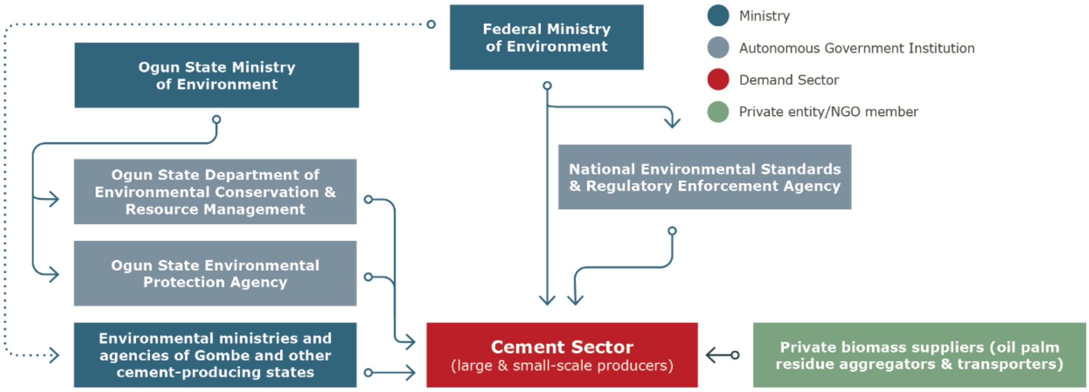



*Figure 3.3 Institutional framework for environmental management in Nigeria's cement sector (Source: authors' compilation)*

### 3.3.2 Policy and regulations

Until the early-2000s, it was cheaper to import cement to Nigeria than to produce it locally, so Nigeria's cement output was low and it was a net importer for several decades. Within the past 20 years, however, Nigeria has become the largest cement producer in Africa, producing over 50 Mt in 2018 and exporting more than 20%.

This turnaround was primarily the result of a far-sighted strategy called the Backward Integration Policy, which was set out in 2002 (Ohimain, 2014). This transformed a system that rewarded companies who imported cement to one that promoted investment in local production. It also focused on quality as much as quantity, encouraged energy efficiency, supported investment in state-of-the-art equipment and ensured access to international capital and technical support. This encouraged innovations such as the adoption of AF,[7] including bioenergy, to substitute for fossil fuels in cement production.

Combustion of fossil fuels and biomass results in emissions of carbon dioxide, carbon monoxide and particulates during calcination (the production of clinker from limestone). The National Environmental Standards & Regulatory Enforcement Agency (NESREA), a parastatal regulator under the Federal Ministry of Environment, enforces the discharge limits of such pollutants under the National Environmental (Non-metallic Minerals

[7] Alternative fuels explored by Nigerian cement companies include various bioenergy sources (wood and oil palm residues), refuse-derived fuels, used tyres, plastics and hospital waste.

Manufacturing Industries Sector) Regulations (Federal Ministry of Environment, 2014).The Regulations set maximum permissible levels of airborne pollutants from various energy sources, including organic carbon (e.g. from burning biomass). NESREA is responsible for overseeing Nigeria's Extended Producer Responsibility, which bears directly on the use of bioenergy and other AF in the cement industry (Anukam, 2018).

Those environmental policies and regulations that do exist relate to air and water pollution from the mining of limestone, the transport of limestone to the cement factories and the control of local emissions, primarily Cement Kiln Dust (CKD). CKD contains limestone dust, dust from the combustion of other additives and particulates from biomass and other fuel combustion. If not captured, CKD can be dispersed over large areas and pose a serious airborne health hazard.

Capturing CKD is an important environmental activity for Lafarge Africa, Dangote and BUA cement, but is essentially voluntary, rather than being dictated by national or state regulations. Lafarge's Ewekoro kilns are fitted with CKD recovery equipment to return the dust in a continuous cycle that also improves kiln efficiency.[8] Small amounts of CKD are nevertheless released into the atmosphere.

Emissions of other air pollutants (e.g. methane from natural gas transport and supply to the kiln, any other GHG emissions) are measured to ensure compliance with the National Environmental (Air Quality Control) Regulations (Federal Ministry of Environment, 2014).

### 3.3.3 Finance

Nigeria has an extensive and active banking sector. The most important institutions for supporting Nigerian industrial development are the Development Bank of Nigeria, the Infrastructure Bank of Nigeria and the Nigeria Export Import Bank. The Green Energy Fund Programme is a partial risk guarantee programme from the African Guarantee Fund to access local currency for renewable energy projects (particularly solar PV) through concessional loans. These are provided by three Nigerian development banks, namely, the Central Bank of Nigeria, the Development Bank of Nigeria and the Bank of Industry. These lend to renewable energy developers (primarily in the solar energy sector, with some hybrid technologies) through local commercial banks in Nigeria. These local banks include Zenith Bank, Access Bank, the First Bank of Nigeria and the Guaranty Trust Bank.

Nigeria's Rural Electrification Fund (REF), which started in 2002 with World Bank funding, is a fund administered by the Rural Electrification Agency (REA), Federal Government of Nigeria, to promote the expansion of the grid, and off-grid electrification. It is funded by government surplus, fines obtained by NERC, and gifts and donations from third parties including international development finance agencies including DEG (Germany), AFD (France) and KfW (Germany), among others.

Regional development banks that are active in renewable energy (again, primarily solar PV for rural electrification and supply to the grid) include the African Development Bank, the Banque Ouest Africaine de Développement and the ECOWAS Bank for Investment and Development. Bilateral international development finance institutions operating in Nigeria which provide finance for renewable energy investments include the UK's CDC

[8] Efficiency is improved because CKD has already been calcined, so, mixing it with limestone reduces the amount of energy necessary for calcination to produce clinker.

Group, Germany's KfW, France's AFD and the US Overseas Private Development Corporation. Further, international multilateral financial institutions active in Nigeria include the European Investment Bank, the World Bank and the International Financial Corporation (IFC). The IFC has been the most active international institution promoting non-fossil fuel use and improved energy efficiency in the cement sector in Africa, supported by the African Development Bank. Both have been active in providing finance in Ethiopia and Cote d'Ivoire for AF (including bioenergy) for co-processing with fossil fuels in cement production.

# 4 Overview of Bioenergy Case

## 4.1 Project summary

In 2013, Lafarge Africa began partially replacing fossil fuels with AF at its cement production facilities at Ewekoro (lines I and II) and Sagamu. Both plants previously relied exclusively on fossil fuels, principally natural gas. Due to the unreliability of gas supplies, there was also significant consumption of fuel oil and coal as back-up energy sources. The introduction of AF, including biomass, has required new storage and handling facilities, and retrofits to the cement production lines for co-processing.

This section describes the fuel sourcing and processing modalities for introducing biomass at Lafarge's Ewekoro plant, the technical aspects of plant modification, and the economic and commercial motivations. Information comes from published sources, as referenced, and from a site visit to Ewekoro Line II and local fuel sourcing areas in March 2021. A selection of photographs are provided in Appendix 6.

## 4.2 Technical details

### 4.2.1 History of AF at Lafarge Africa

Between 2010 and 2012, Lafarge Africa ran feasibility trials on a variety of AFs at Ewekoro and Sagamu, including agricultural residues, woody biomass from sawmills and plantations, used tyres and refuse-derived fuels (RDF) (ONF International, 2012). Though there are no clear specifications for AFs, the following minimum criteria have been developed by the cement industry to maximise performance and minimise environmental risks (Saleh & Abo-Elyazeed, 2017; Seboka et al., 2009):

- calorific value >14 MJ/kg (lower heating value, as received)
- moisture content <20%
- sulphur <2.5%
- chlorine <0.2%
- heavy metals <2,500 ppm
- polychlorinated phenyls <50 ppm

The most relevant parameters for biomass feedstocks are calorific value and moisture content (MC). Excessive levels of sulphur, chlorine, heavy metals and polychlorinated phenyls are mainly linked to the use of RDF, so do not usually arise with biomass. There are some exceptions, such as wheat straw and rice husks, which contain chlorine that may be a concern for slagging and corrosion in the kiln (Chinyama, 2011).

Initial plans to source fuelwood (FAO, 2004) from over-aged rubber and cocoa trees, and purpose-grown plantations (Lafarge WAPCO, 2012) were abandoned by 2015, due to high cost, and the majority of biomass supply by 2018 had switched to oil palm kernel shells (PKS), palm fruit fibre, cashew nut shells and sawdust (Lafarge Africa, 2019). This has since evolved further, and supply now comes almost entirely from PKS, with some limited use of palm fruit fibre.

AF currently accounts for 45% of energy supply at Ewekoro I (Lafarge Africa, 2020) and even more at Ewekoro II. The Ewekoro plant, with modern pre-calciner technology, could technically permit up to 70% substitution with AFs (Lafarge WAPCO, 2012).

### 4.2.2 Current biomass sourcing

A dedicated AF pre-processing facility was constructed at Ewekoro Line II in 2018 for the shredding and blending of solid waste. Figure 4.1 summarises the bioenergy sourcing and co-processing system.

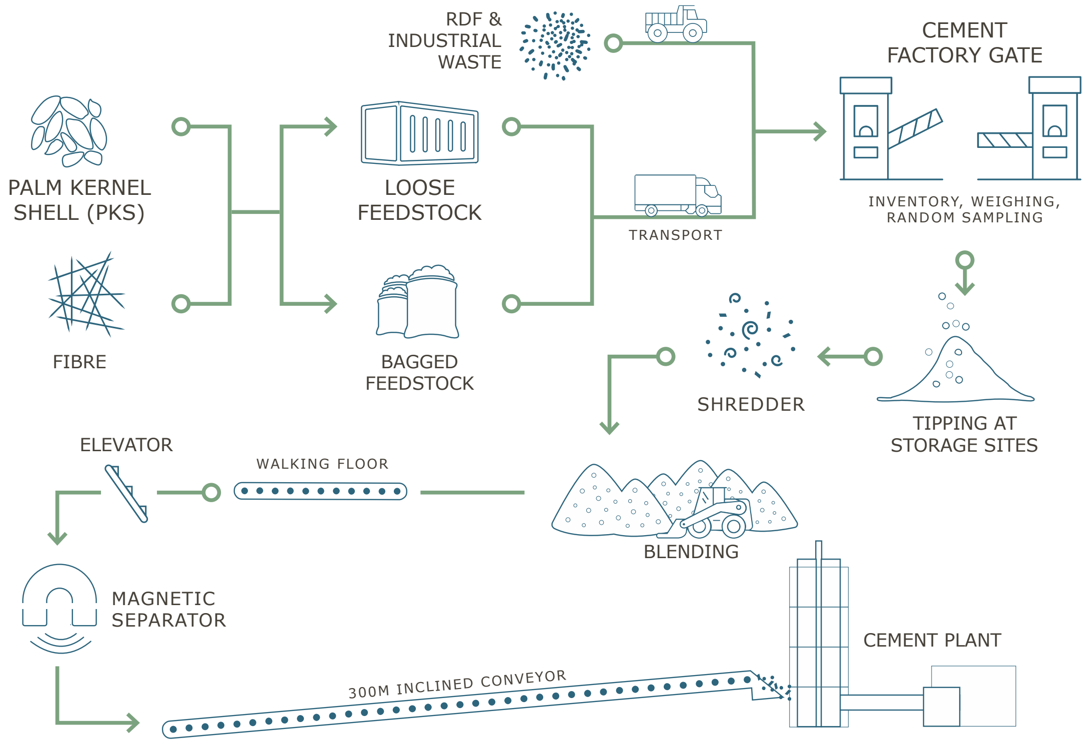



*Figure 4.1. Schematic diagram of AF supply at Ewekoro cement plant (Source: authors' compilation)*

Biomass is sourced and aggregated by a network of specialised companies contracted by Geocycle, who procure the feedstock from farmers or from farmer associations. The two biomass feedstocks currently used at Ewekoro are PKS and oil palm fruit fibre, with the PKS accounting for the vast majority:

- **Oil palm fruit fibre** (known in Nigeria as 'shafts') is the residue obtained after extracting the palm nuts from the fruits prior to oil extraction. In an industrial palm oil operation, this material would be burned at the mill to generate steam, but in Nigeria's artisanal sector, it is usually piled up and burned at the farm or sometimes used in households for domestic purposes, mainly to fire local stoves.
- **Palm kernel shells (PKS)** are the ligneous fractions left after the palm nut has been removed through manual or mechanised cracking. This fibrous material can be handled in bulk directly from the oil pressing location to the end user with no special treatment (BioEnergy Consult, 2020). PKS is a good quality fuel with uniform size distribution, low MC, high calorific value and low ash.

Both fruit fibre and PKS meet the above-stated standards for co-processing, with no need for drying or enhancement on-site. They are inherently well-suited to bulk feeding due to their physicochemical homogeneity, which facilitates handling and minimises the risk of heat fluctuation during combustion.

### 4.2.3 Feedstock storage and preparation

The cement process is most stable and efficient when the quantity of raw materials and fuels is kept constant. It is therefore important to have large capacity for on-site fuel storage, in order to sustain consistent supply throughout the year. Geocycle must balance this requirement with the high cost of excessive advance purchase, and the additional storage infrastructure and handling facilities that this requires.

The palm residues delivered to Ewekoro are stored outdoors close to the AF pre-processing facility. It had been envisaged that the feedstock might need to be dried, and a system was considered for blowing exhaust gas from the kiln chimney (at 100-200°C) onto a belt dryer, just before the AF was introduced (Lafarge WAPCO, 2012). This did not prove necessary, however, due to the low MC of PKS and palm fruit fibre.

For ease of handling and achieving uniform calorific input, some AFs require size reduction. For example, agricultural residues should be shredded to 5-30 mm (IFC, 2017), while solid woody biomass needs to be chipped and pre-dried, and unwanted materials such as stone and metal have to be removed (Nicholls et al., 2008). At Ewekoro, the PKS and fruit fibre are blended with other AFs at the pre-processing facility, in carefully measured proportions, and conveyed to the pre-calciner via a magnetic separator and a weigh-feeder.

### 4.2.4 Plant design

Pyro-processing to produce cement comprises three stages: pre-heating, calcining and clinkering. Ewekoro is a modern, dry process plant, where the raw materials (primarily limestone mixed with clay) are crushed and fed into a pre-heater tower, before the hot 'meal' (at 880°C and 90% calcined) enters a rotary kiln. Kiln systems with five- or six-stage cyclone pre-heaters and pre-calciners are considered standard technology for new plants today, as the extra cyclone stages improve thermal efficiency (Karstensen, 2006). Ewekoro has two kiln lines operating this multi-stage dry process, though other plants operate a single stage dry process or wet process.

There are three ways that biomass can be co-processed in cement plants. It can be burned directly in the pre-calciners or the kiln as either (i) loose or pulverized material, or (ii) as solid fuel in the form of pellets or briquettes; or (iii) it can be transformed into producer gas for co-processing in the kiln using a gas burner. The first option has been adopted at Ewekoro: direct combustion in loose form in the pre-calciner.

### 4.2.5 Feeding and control

The use of biomass and other AF requires adjustments to the air flow in the pre-calciner and calciner to ensure complete combustion, according to the carbon, hydrogen and sulphur content of the constituent fuels and their co-processing proportions. The AF feeding system at Ewekoro is fully automated to make dynamic changes to feed rate and air flow, based on real-time temperature and oxygen measurements.

Switching from conventional fuels to AFs presents additional challenges. These include poor heat distribution, unstable pre-calciner operation, blockages in the preheater cyclones, build-ups in the kiln riser ducts, higher $SO_2$, $NO_x$ and CO emissions, and dusty kilns (Chinyama, 2011). Fuel substitution also affects the chemistry of the cement. Ash is an important consideration. The main constituents of fuel ash are silica and alumina compounds. These combine with the raw materials to become part of the clinker. The percentage of silica in the ash in an AF therefore limits the level at which it can replace conventional fuels. For instance, rice husks can only replace 5-7% of traditional fuels as they contain up to 25% ash, which in turn contains 78-90% silica.

### 4.2.6 Technology sourcing

The technology for biomass coprocessing in cement kilns is well-established and can be purchased or custom-made in developing countries (Seboka et al., 2009). The infrastructure for receiving, storing and feeding AF at Ewekoro is a stand-alone addition that has had no effect on the existing systems for handling fossil fuels. The specialist equipment required for biomass feeding (such as shredders, conveyors, feeders and mobile machinery) was sourced internationally. The company's own engineers built the biomass pre-processing plant and made the necessary modifications to the pre-calciners, using a combination of internal capacity and specialist support from within the Holcim group. The constant process of repair, replacement and upgrade within a cement factory means that there is significant in-house expertise for such customisations.

The technological aspects of transitioning to AFs have been relatively straightforward for Lafarge, given this inhouse expertise and global experience (via Geocycle). Project management has focused as much on the identification and sourcing of biomass, as it has on the technical aspects of co-processing. In fact, the cost of sourcing and transporting biomass was expected to be around 20 times greater than the new equipment and retrofits over the first ten years of coprocessing (Lafarge WAPCO, 2012).

## 4.3 Economic assessment

Table 4.1 summarises the data used in the LCC model for co-processing with biomass fuels at the Ewekoro cement plant, as the Bioenergy Case, comparing it with a Base Case scenario of generating heat using only natural gas.

*Table 4.1: Key project data for economic modelling*

| Category | Parameter | Value |
|---|---|---|
| General parameters | Discount rate | 11.5% (Central Bank)[9] |
| | General growth rate | 11.3% (Consumer Price Index)[10] |
| | Energy price growth rate | 11.3% (Energy Price Index) |
| | Exchange rate | 383.27 NGN/USD (3 yr average) |
| Base Case | Specific energy consumption | 3.4 GJ/t of clinker (IEA, 2020b) |
| | Clinker production | 2.66 Mt/yr (IndustryAbout, 2019) |
| | Capacity factor | 70%[11] |
| | Fuel used | Natural gas USD 7/$MWh_{th}$[12] |
| Bioenergy Case | Additional CAPEX (biomass feeding equipment) | EUR 35/t/year of biomass burning capacity (UNEP-UNDP 2009) |
| | Additional OPEX | EUR 10/t of biomass burnt (UNEP-UNDP 2009) |
| | Biomass substitution rate | 35%[13] |
| | Feedstock used | Palm oil residues (LHV 18.4 GJ/t) |
| | Feedstock cost (factory gate) | USD 20/t |

[9] www.tradingeconomics.com/nigeria/interest-rate
[10] www.cia.gov/the-world-factbook/countries/nigeria/#economy
[11] The annual clinker production figure of 2.66 Mt/yr takes into account the estimated capacity factor of the plant.
[12] Paid in NGN, indexed to USD (D. Adedokun, personal communication, 1 June 2020).
[13] Biomass makes up 45% at Ewekoro Line I and an estimated 30% at Ewekoro Line II, weighted in favour of Ewekoro II as it has a cement production capacity of 2.5 Mt p.a., vs. 1.3 Mt p.a. at Ewekoro I (IndustryAbout, 2019).

Applying these input parameters, the LCC model shows that the Ewekoro plant has similar LCOE for heat under the Bioenergy Case and the Base Case (Figure 4.2). While the partial substitution of natural gas by biomass has resulted in a small increase in operation and maintenance (O&M) costs, this is offset by the reduced cost of biomass compared to natural gas, to give a similar final LCOE.

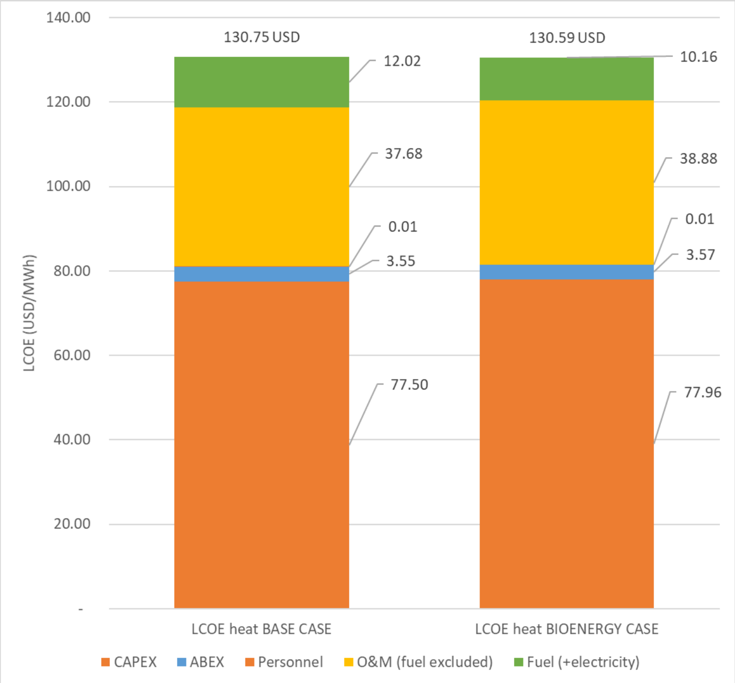



*Figure 4.2: LCOE comparison for heat, Base Case vs. Bioenergy Case*

## 4.4 Commercial success factors

Figure 4.3 summarises the supply chain for the Bioenergy Case at Ewekoro.

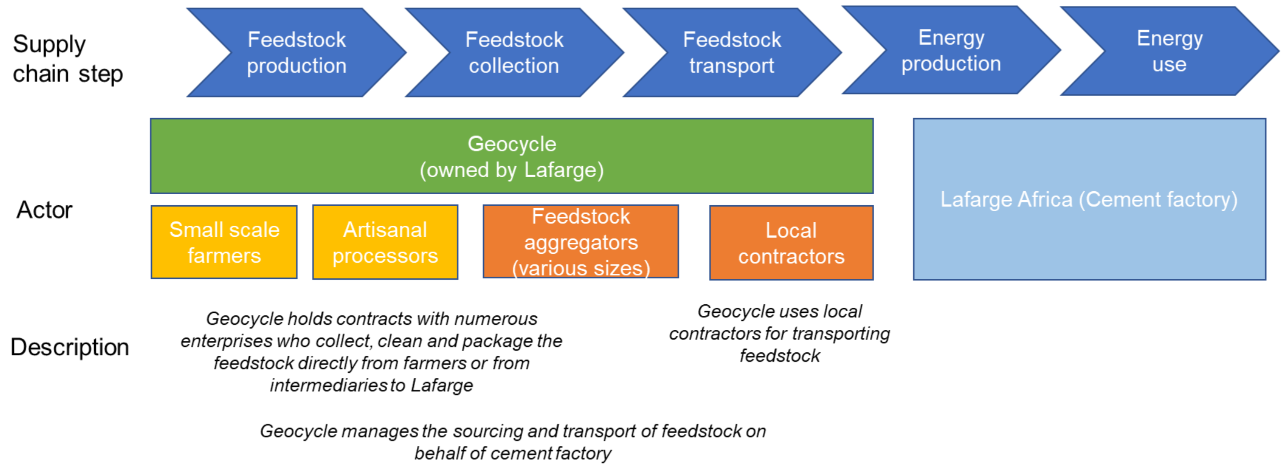



*Figure 4.3. Overview of the Ewekoro bioenergy supply chain*

As an indication of its long-term commitment to alternative fuels, Holcim's Geocycle Global created a subsidiary in Nigeria in 2018 as a specialist waste management service provider to serve both its own needs and those of other large energy consumers. Geocycle Nigeria initially serviced the Ewekoro and Sagamu plants, while also exploring new feedstock opportunities. Since 2018, it has also been facilitating the use of rice husk for co-processing at Lafarge's Ashaka cement plant in Gombe State.

It is not possible to isolate the cost of the biomass procurement and feeding systems at Ewekoro, as these were set up also to use non-biomass sources such as RDF and tyres. Taken together, and including the cost of equipment for storage, pre-processing, drying and feeding, the time and resources for establishing a biomass collection and logistical system, as well as setting up a dedicated tree plantation, capital costs were initially estimated at EUR 17m (Lafarge WAPCO, 2012). Given that final costs are not available from Lafarge, industry-standard CAPEX and OPEX costs based on AF throughput have been adopted in the economic analysis.

The main factors that have contributed to the commercial success of the Ewekoro coprocessing model have been the unreliability of existing fuel supplies, the availability of dedicated capacity (via Geocycle) to set up and manage new supply chains for AF (including biomass), the ability of Geocycle's aggregators to secure biomass fuels at competitive cost and sustainability incentives within the cement industry:

- **Unreliability of existing fuel supply:** Lafarge's plants in Nigeria were previously dependent upon fossil fuels, mainly natural gas, for thermal energy. Unreliability of supply meant that fuel oil and coal were often needed as back-up fuels, leading to energy supply risks and increased costs and emissions.
- **Dedicated resources to set up and manage supply chain:** There is a high cost in finance and resources to establish new energy supply chains for biomass fuels. A key component of the successful co-processing operation at Ewekoro has been the expertise of Geocycle, a Lafarge subsidiary dedicated to the aggregation and supply of feedstock. Other cement companies would also need to dedicate resources to establishing AF supply chains, allowing them to focus on their core business of manufacturing cement.
- **Competitive cost of biomass:** As evidenced in section 4.3 above, the cost of using biomass residues for co-processing at Ewekoro cement kilns is marginally lower than using natural gas. This is an important commercial motivation for Lafarge's adoption of the coprocessing model.
- **Sustainability incentives:** Cement is one of the largest emitting sectors globally, accounting for 7% of world energy sector $CO_2$ emissions in 2018 (IEA, 2020a). As a consequence, some multinationals operating in SSA, including Holcim, are prioritising the improved sustainability of their processes. With commitment from some of the largest players to sustainability in their operations, demand for bioenergy is only likely to rise, as cement demand in the region increases.

# 5 POTENTIAL FOR WIDER ADOPTION

This section assesses the replicability potential of the Bioenergy Case in the cement sector, considering the six research themes of biomass resources, technology, economic benefits, commercial potential, the institutional and regulatory framework, and gender and inclusion.

## 5.1 BIOMASS RESOURCE ASSESSMENT

### 5.1.1 Biomass potential from Cement sector

The cultivation of oil palm is an important economic activity in Nigeria, which is one of the world's top five palm oil producers, though lags significantly behind the leading four (see Figure 5.1). About 50% of the oil palm fruit is collected from wild groves or cultivated at small scale (PIND, 2011) with average oil yields of just 2.6 t/ha/yr, due to poor management, lack of agricultural inputs and over-aged trees (FAO, 2021b; PIND, 2011).

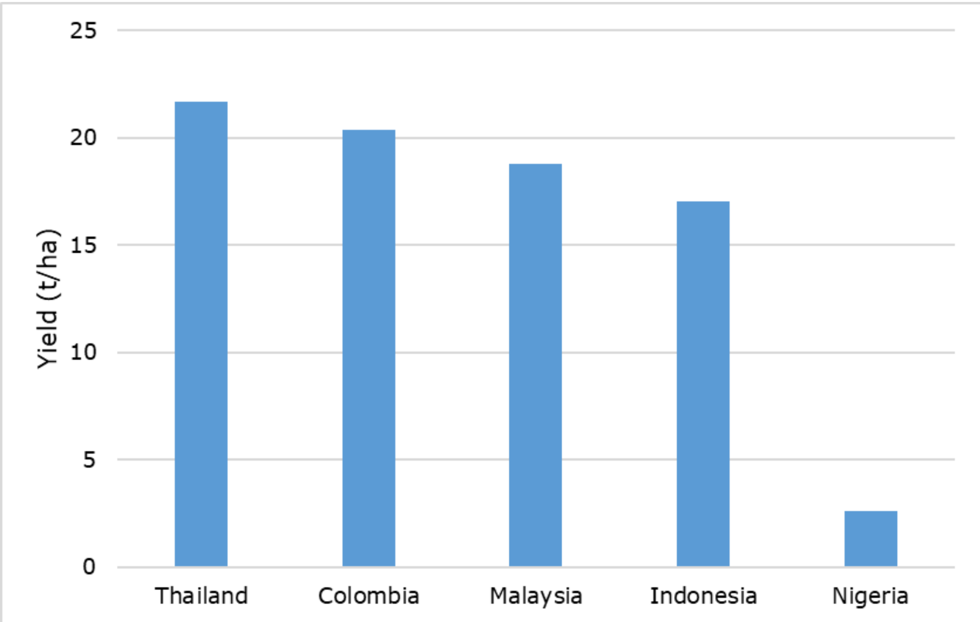



*Figure 5.1: Oil palm fruit yields of top-5 producers (t of fresh fruit bunch/yr) (FAO, 2021b)*

Some small-scale producers sell their oil palm fruits to commercial processors, who use the solid residues for energy generation at palm oil mills. Many others process their fruit locally using traditional technologies (PIND, 2011), where their residues are available to users such as cement companies and other industries.

Around 7.8 Mt of oil palm fresh fruit bunches are produced annually in Nigeria (FAO, 2021a). Considering this is mainly derived from small-scale production, and taking into account losses, contamination and competing uses (such as return to plantations and internal energy demand of palm oil mills), it is estimated that about 60% of the residues are recoverable. This implies a biomass potential of about 0.56 Mt of solid palm oil residues, and a bioenergy potential of about 11.6 PJ. The split by residue category (fibre, PKS) is shown in Figure 5.2. Empty fruit bunches represent an additional residue from palm oil processing, but are not used as biomass fuel in the cement industry.

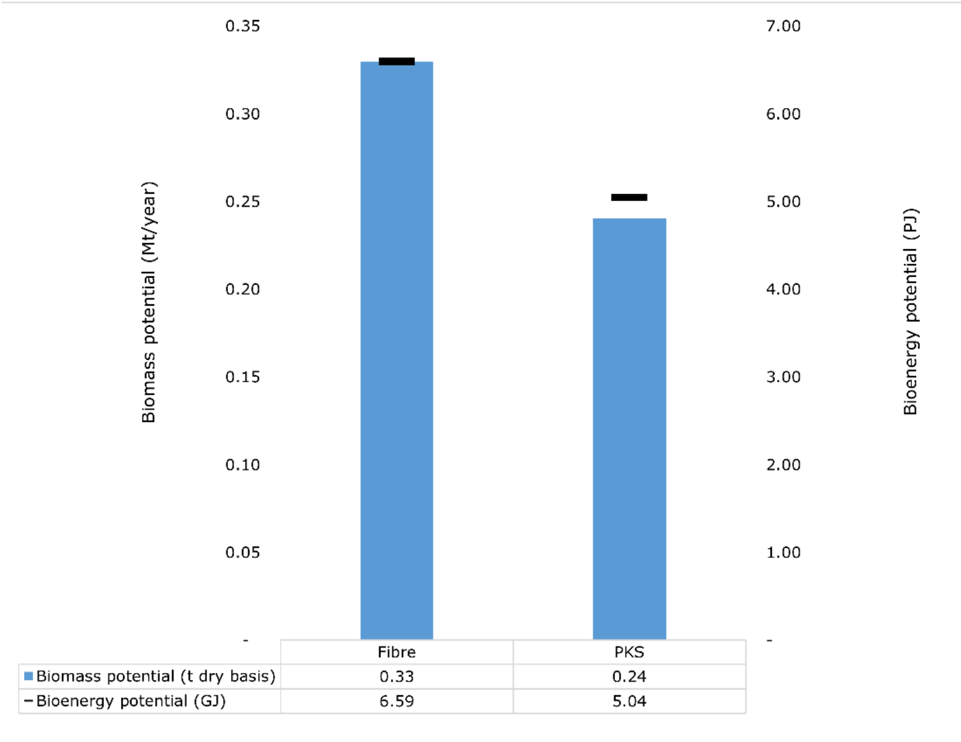



*Figure 5.2: Biomass and bioenergy potential from solid palm oil residues in Nigeria*

In addition to oil palm processing residues, Nigeria has significant quantities of other biomass feedstocks. As well as being Africa's largest producer of palm oil, Nigeria is also its leading producer of rice and the world's largest cassava producer. Cassava and other roots account for around 68% of total agricultural crop production. Other key crops are maize, vegetables and cereals (e.g. sorghum) (FAO, 2021a) (see Figure 5.3).

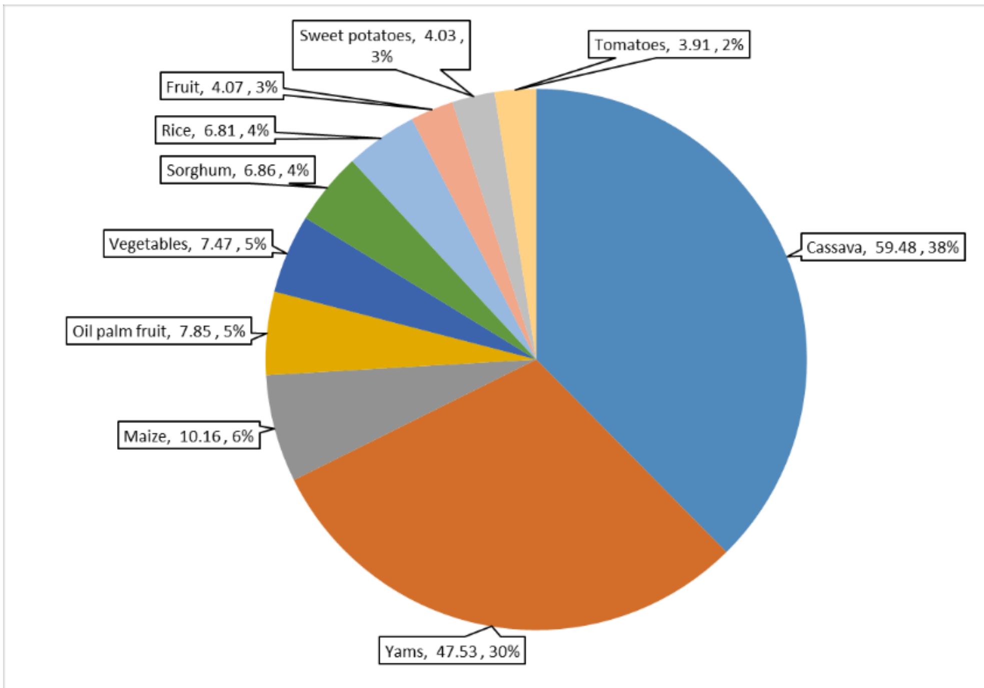



*Figure 5.3: Nigeria Top-10 agricultural crops as Mt and % (FAO, 2021a)*

While cassava and maize generate the largest quantity of biomass residues (~5.4 and ~3 Mt/yr, dry basis [d.b.], respectively), dispersed production means that mobilisation for commercial use would be very difficult, and these materials (and other small-scale crop residues) are used at household level only.

Figure 5.4 summarises the biomass and bioenergy potential from the main agricultural and processing residues that have commercial application potential.

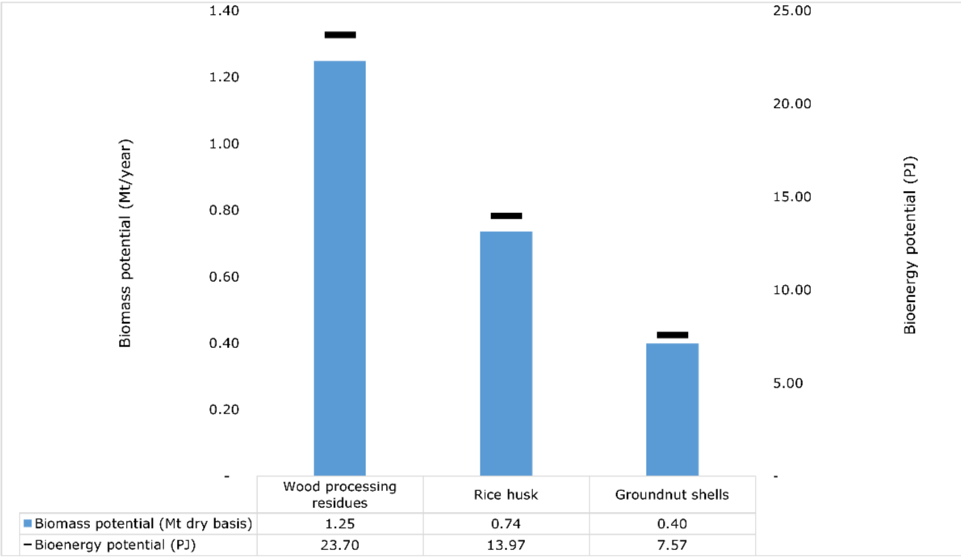



*Figure 5.4: Biomass and bioenergy potential from main agricultural residues in Nigeria*

As indicated, there is large potential for using wood processing residues, such as sawdust, wood chips and sawmill off-cuts, given that these residues are aggregated, and sawmills are generally close to road and transport infrastructure. The resource assessment suggest that wood processing residues have a biomass potential of about 1.25 Mt/yr. Rice husk has a biomass potential of about 0.74 Mt/yr and is already used in the dominant rice growing regions where the husk is aggregated at mills. Other biomass resources such as groundnut shells (~0.4 Mt/yr) are technically suitable, but barriers to collection need to be assessed in context, to confirm economic and sustainable sourcing. In total, these three biomass feedstocks could potentially provide 2.4 Mt/yr of feedstock with an energy content of 45.2 PJ.

### 5.1.2 Mass-energy balance

Table 5.1 shows the mass-energy balance (MEB) parameters for co-processing with biomass in cement manufacturing. The input data are based on the specifications of the Ewekoro plant.

*Table 5.1: Mass-energy balance, bioenergy for heat in cement production*

| Parameter | Units | Value |
|---|---|---|
| Biomass feedstock | PKS & oil palm fruit fibre | ratio 19:1 |
| **Input parameters** | | |
| Target capacity | $MW_{th}$ | 450 |
| Capacity factor | % | 70 |
| Annual operational hours | Hours | 6,132 |
| Process | Dry (multi-stage) | |
| Fossil fuel | Natural gas used for processing<br>Natural gas $Nm^3/y$ | |

| Parameter | Units | Value |
|---|---|---|
| | | 107,125,608 |
| Fossil fuel substitution by biomass | % | 35 |
| **Output of MEB** | | |
| Clinker | kg/s | 132.4 |
| | annual tonnes | 2,921,718 |
| Clinker:cement ratio | % | 75 |
| Cement | annual tonnes | 3,895,624 |
| Specific energy consumption | GJ/t of clinker | 3.4 |
| Biomass flow (total) | kg/s (d.b.) | 7.1 |
| | annual tonnes (d.b.) | 156,735 |
| Feedstock 1 (PKS) | kg/s (d.b.) | 6.8 |
| | annual tonnes (d.b.) | 148,899 |
| Feedstock 2 (oil palm fruit fibre) | kg/s (d.b.) | 0.4 |
| | annual tonnes (d.b.) | 7,837 |

The model demonstrates that the co-processing of fossil fuels with 35% biomass from oil palm processing residues would require a total of 156,735 t of residues per year. With estimated availability of ~570,000 t/yr of PKS and oil palm fruit fibre, there is more than sufficient potential to expand the use of these biomass types at Ewekoro and other facilities. 570,000 t of biomass could provide sufficient energy to produce about 10.6 Mt of clinker at a 35% substitution rate. With a current annual cement production of about 30 Mt (IndustryAbout, 2019) and a potential capacity of 60 Mt in Nigeria (The Guardian, 2020), this PKS and oil palm fibre availability could be sufficient for meeting just below 50% of the current Nigerian cement production and 25% of its potential cement production capacity at a 35% substitution rate.

Oil palm residues have relatively high calorific value and low ash content. The use of other agricultural residues would increase the input requirement as they have less favourable properties. For example, the MEB model shows that achieving the same 35% energy substitution rate would require 8.3 kg/s (183,206 t/yr) of rice husk, 8.4 kg/s (185,431 t/yr) of wood processing residues or 8.3 kg/s (184,068 t/yr) of groundnut shells. The viability of these feedstocks will depend on accessibility and cost at each cement plant.

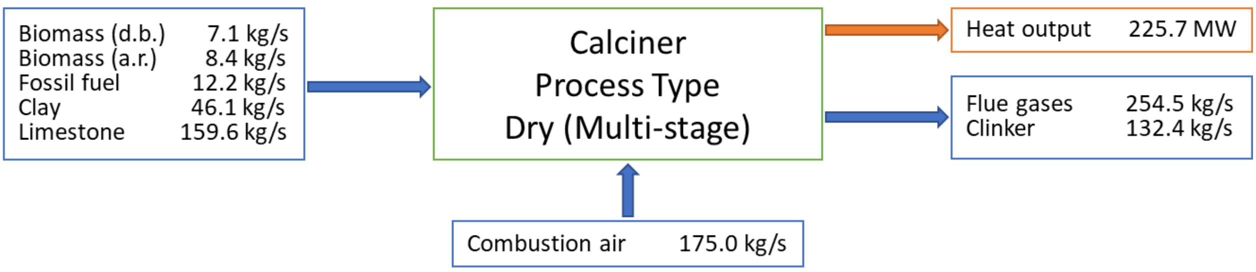



*Figure 5.5: Mass-energy balance for biomass-based heat generation at a cement plant, based on input specifications at Ewekoro*

## 5.2 Technology

Lafarge Africa has led the way in the progressive substitution of fossil fuels with AF for cement production in its Nigerian operations. By the time the company began to use AFs in 2012 (Lafarge Africa, 2018), it could already draw upon significant experience of co-processing from Holcim's own operations in SSA in Bamburi, Kenya; Hima, Uganda; Mbeya, Tanzania (Bamburi Cement, 2018) and from experiences from Southeast Asia specifically with oil palm residues.

After a period of experimentation with feedstocks that required pre-treatment at the cement plant, such as rubber wood and sawdust, the venture has evolved into a streamlined operation based on two relatively homogenous residues that are delivered to the factory in kiln-ready form. Coprocessing has therefore been possible with a minimum of well-tested technological adjustments to the plant.

The technical considerations around the introduction of biomass fuels in cement making are well understood and mainly concern MC, calorific content and particle size, which require adjustments to feed rates and air flow within the pre-calciner. Prudent selection of feedstocks, with a requirement for suppliers to deliver material in a form that is standardised and ready to burn, has meant that Lafarge has largely avoided the need for fuel cleaning and drying, and has consequently kept technological modifications and associated costs to a minimum (although shredding equipment has been needed for other AF, such as laminates and plastics).

Biomass feedstocks present few technical challenges for cement making as they are largely free of harmful chemicals and can be cleaned, dried and re-sized, if necessary, using standard equipment that is readily available. Modalities for storage, handling and feeding are well understood within the industry and the necessary modifications to pre-calciners and kilns for supplementary biomass feeding can be achieved using cement companies' own in-house engineering capacity, as add-ons to existing infrastructure. This applies even to relatively small cement plants, as the same principles and experiences are transferable. Scaling up the use of bioenergy in the cement industry is therefore constrained mostly by biomass suitability, accessibility and cost, and not by technical or technological limitations.

## 5.3 Economic competitiveness

The economic competitiveness of coprocessing with biomass and other AF is influenced by many factors, such as the price of natural gas and the price of biomass. In this section, the impact of these parameters on the LCOE is estimated through a multivariate sensitivity analysis. In each of the charts below, the linear regression lines are a best fit for the results from hundreds of simulated scenarios.

Figure 5.6 analyses the impact of natural gas price on $LCOE_{heat}$ for the Bioenergy Case, compared with the Base Case, for a range of natural gas prices from USD 6 to 10 per $MWh_{th}$ (vs. the current price of USD 7/$MWh_{th}$). The Bioenergy Case is naturally less sensitive to changes in natural gas price, since gas consumption is lower than it is in the Base Case. This shows that biomass coprocessing has the benefit of reducing exposure to changes in natural gas prices, which can be highly volatile.

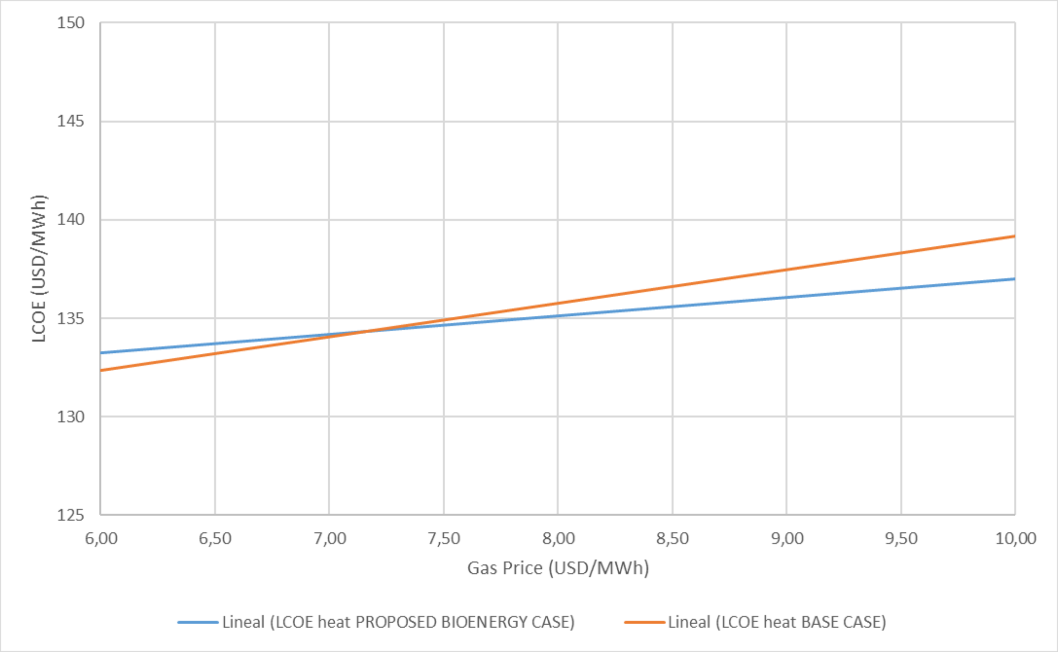



*Figure 5.6. Sensitivity of $LCOE_{heat}$ to gas price ($USD/MWh_{th}$)*

Finally, Figure 5.7 shows the sensitivity of $LCOE_{heat}$ in the Bioenergy Case to variations in the cost of biomass, for a range of feedstock prices from USD 10 to 70/t (vs. the current cost of USD 20/t). The LCC model identifies a tipping point at about USD 28/t for the cost of biomass, above which it is cheaper to continue using natural gas.

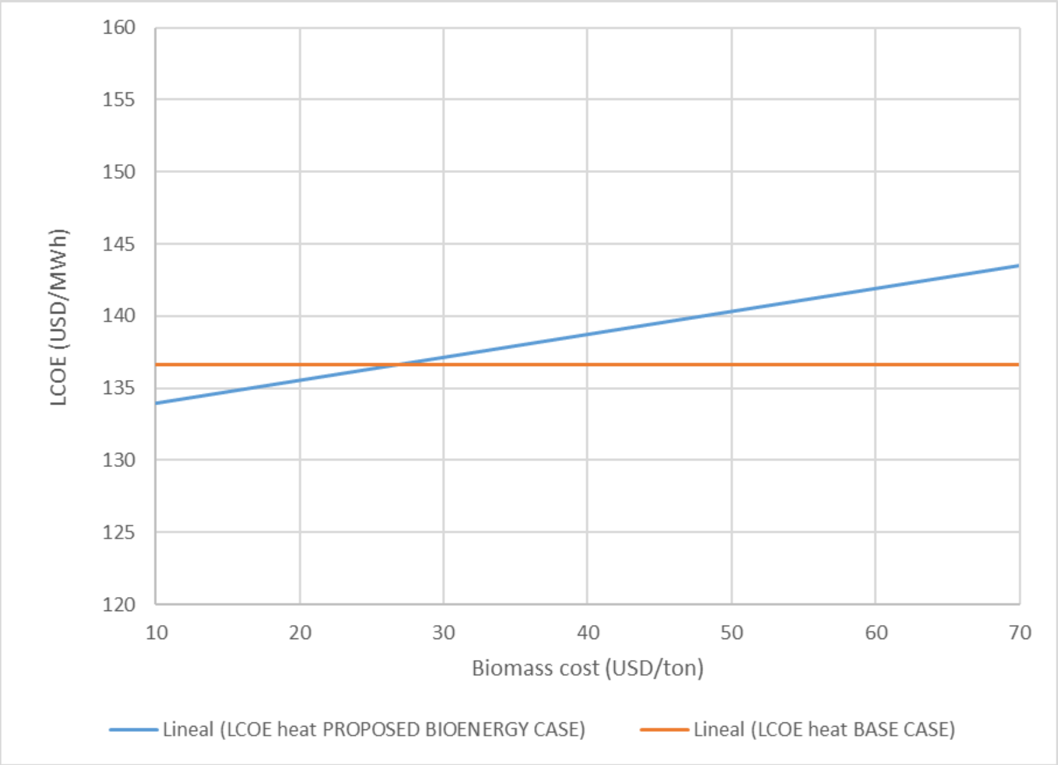
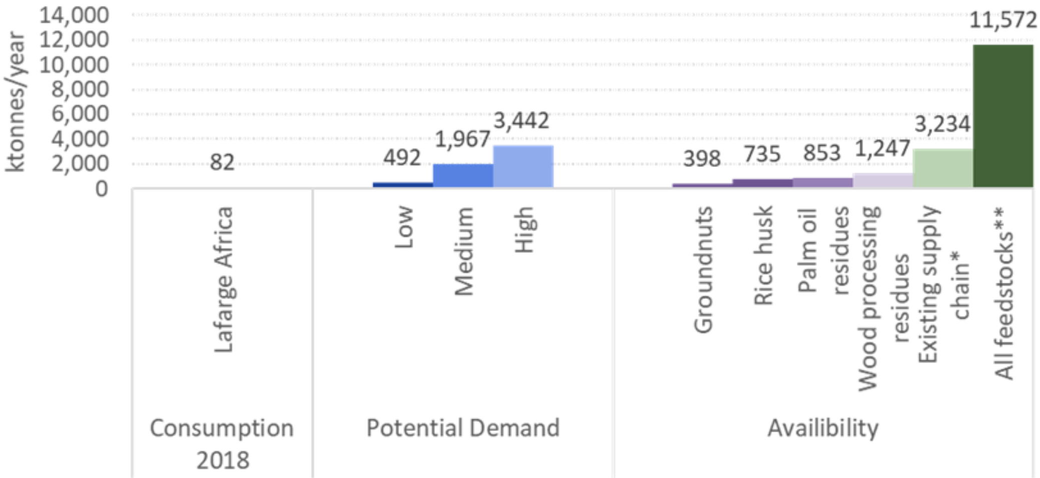



*Figure 5.7. Sensitivity of $LCOE_{heat}$ to biomass cost (USD/t)*

## 5.4 Commercial prospects for replication

### 5.4.1 Market potential

The potential biomass demand in the Nigerian cement sector is shown in Figure 5.8, for substitution rates from 10% up to 70%, and compared with the biomass resource availability that was quantified in section 5.1.1. Demand was estimated based on the cement production capacity of all Nigerian cement factories (United Capital, 2019) and industry-standard parameters.[14]




**Feedstocks with pre-existing supply chains: groundnut shells, rice husk, palm oil residues and wood processing residues.*

*All feedstocks: groundnut shells, rice husk, palm oil residues, wood processing residues, cassava stalks and maize cobs & stalks.*

*Low scenario – 10% biomass substitution, based on existing practices; Medium scenario – 40% biomass substitution, corresponding to maximum for wet process; High scenario – 70% substitution, corresponding to maximum achievable substitution in a modern pre-calciner.*

*Figure 5.8 - Market potential for biomass co-firing in Nigerian cement industry*

The analysis suggests that there is sufficient feedstock availability to satisfy demand, although at the highest possible substitution rates, additional sources may be required.

The Nigerian construction market is expected to grow by 160% from 2015 to 2030 (Betts et al., 2015), driven by population growth, urbanisation and industrialisation, and cement demand across Africa is expected to double by 2040 (IEA, 2019). This may indicate an opportunity for greater use of bioenergy in cement manufacturing, assuming that major producers follow Holcim's lead, but competition for feedstock also poses a threat to resource supply and price. In addition, further market growth will increase potential demand compared to the scenarios based on existing capacity (Figure 5.8). High demand scenarios in a growing market will therefore require the establishment of additional biomass supply chains.

### 5.4.2 Market barriers

The key barriers and enablers that will determine the wider adoption of biomass co-processing in the cement sector are mostly linked to the feedstock supply chain and availability.

[14] Assumptions: Clinker-to-cement ratio 0.75; Thermal energy demand 3.4 GJ/$t_{clinker}$; Biomass LHV 18.4 GJ/t

*Table 5.2: Barriers and enablers to the use of biomass residues in the cement sector*

| Barrier to business model | Enabling conditions |
|---|---|
| **Lack of pre-existing biomass supply chains**<br>Most cement factories in SSA are in areas lacking pre-existing supply chains for industrial-scale supply of biomass. It is costly (high upfront capital costs) and complex for cement companies to set up such supply chains, and not all have the necessary expertise and resources, despite the potential for long-term financial savings. | **Dedicated resources to set up and manage supply chain**<br>Lafarge used its specialist Geocycle subsidiary to set up and manage the supply chain, to ensure technical competence and a capital-light approach.<br><br>**Availability of local feedstock aggregators**<br>The co-processing initiative has benefitted from the presence of local sourcing companies, with experience in rural supply chains and on-the-ground presence. |
| **Feedstock aggregators lacking capital**<br>Small-scale feedstock providers are likely to lack sufficient capital to sustain a consistent supply of feedstock in the required volumes. | **Seed capital may be needed to kickstart supply chains**<br>Funds may be required to 'prime the pump' and get supply chains working, especially with new and unfamiliar actors working together for the first time. |
| **Not all cement factories have unreliable fossil fuel supplies**<br>Lafarge's dependence on costly and unreliable fossil fuel was a key driver for the co-processing initiative. Although other cement factories in Nigeria have also reported shortages of fossil fuels, sometimes caused by theft or sabotage of supply infrastructure, this driver may not exist at all factories e.g. Dangote has factories located close to the company's own petroleum refineries and coal mines | **Stronger policy support for use of low carbon feedstocks**<br>Whilst it appears that this is unlikely in the short term in Nigeria, policy measures to promote the use of biomass or other low carbon feedstocks for co-processing could provide a significant financial incentive for cement producers to adopt this concept |

Based on this analysis, the market potential for biomass co-processing for cement manufacturing in Nigeria is large and growing. Unlocking this potential requires diversification and development of feedstock supply chains, higher awareness of the opportunities presented by biomass and additional investment.

Experiences of two of Lafarge's biggest aggregators indicate the profitability of such ventures for themselves and those involved in their supply chain. These suppliers have diversified into supplying PKS and palm fruit fibres to other industries, thus securing and further strengthening their incentives to operate in this space. Such a transition presents a win-win for cement factories, local aggregating companies and their rural suppliers, presenting encouraging prospects for similar undertakings by other cement companies making further supply chain development easier in future.

### 5.4.3 Financing approach

The entire biomass sourcing, collection and transport operation is owned by Lafarge. No external funding was sourced to set up Geocycle and the biomass supply chain. Lafarge prepared a Clean Development Mechanism (CDM) Project Design Document that was registered with the UNFCCC (UNFCCC, 2012), but has never claimed CDM credits – perhaps because CDM verification can be expensive and time-consuming. Lafarge Africa are therefore thought to have financed the bioenergy investments with their own capital, both from their own international sources and from Nigerian commercial banks.

The bulk of Lafarge Africa's investment in bioenergy is understood to have been made in local currency, without recourse to international finance. This includes financing the purchase of biomass feedstocks, aggregation of those feedstocks and transportation to four of the company's factories. Construction of facilities for storing, sorting, blending and feeding biomass residues, as well as the necessary modifications to pre-calciners and kilns, were made by Lafarge using their own design and construction resources.

Given the size of Dangote's and Bua Cement's operations, as well as their other national operations and infrastructure investments, both should have access to sufficient resources (from their own capital, local banks and ability to raise finance on Nigeria's Stock Exchange) to fund any similar bioenergy substitution and conversions, without the need for international financing.

In general, given the profile of cement industry investors in SSA, most of their finance would come from local sources. However, these companies have strong relations with regional finance institutions (such as the West African Development Bank for Ghana and Nigeria; the East African Development Bank for Ethiopia, Kenya, Uganda and Tanzania; and the Development Bank of Southern Africa for South Africa, Zambia and Mozambique) should their own local industrial development banks and commercial banks not have access to the necessary foreign exchange.

## 5.5 Gender and inclusion

This section describes key issues and considerations around G&I in the oil palm sector in Nigeria, to highlight areas of interest or concern on feedstock supply for bioenergy in the cement sector. The cement industry itself is not addressed.

Palm oil is an important cash crop in rural areas of Nigeria, but in common with many agricultural sectors, it exposes G&I inequalities, most notably toward women and children, and for estate-scale oil palm cultivation there are additional risks to land rights and local ecological resources (Baiyewu-Teru, 2017). Nigeria has the highest rate of children out of school globally, many of them required for domestic and farm labour. Women are unable to reap the full benefits of palm oil production due to cultural beliefs and perceptions that inhibit their inclusion in decision-making or accessing profits, despite their high engagement in production and processing. This is exacerbated by the fact that women in Nigeria cannot be owners of land, and can therefore be excluded in policy development or negotiations on how land is used or managed (Baiyewu-Teru, 2017).

From in-country consultations, while there appears to be a high level of involvement of women in oil palm residue supply chains, this does not necessarily mean the positions are of good quality, nor that women have safeguards to minimise risks. From field interviews, it appears that gender roles within small-scale oil palm processing sector is generally split in the following ways: manual separation of nuts and fibre is often conducted by women. Women and children also seem to be responsible for other manual jobs such as cracking the kernels and breaking off the shells. Where this is mechanised, however, it is usually handled by men. Men are also seen to be involved in jobs requiring heavy lifting such as loading trucks with sacks of biomass residues. Regarding the brokerage or sale of such residues, men are often the decision makers or leaders on this. However, some cases of women leaders in such decision-making positions were also observed from the field visits.

Overall, more supportive processes and policies are required to ensure that those managing the supply chains down to producers and processors of the feedstock, should have targets to enable progress to be monitored on ensuring G&I is mainstreamed into all procedures, beyond total numbers of employed women. Asserting that some positions require 'heavy lifting' is insufficient reason for not engaging with G&I issues. Effort should be made by any company involved in biomass feedstock sourcing to include community or smallholder consultation, in order to gather thoughts and perceptions of both male and female farmers and processors, so as to gain a picture on what positive or negative socio-ecological effects could be caused by any purchasing operations.

Capacity-building efforts should be introduced, as appropriate, to highlight issues related to unskilled or informal labour, and how this has wider effects on G&I. To support this capacity building, research should gather information on the extent to which education or training opportunities are inhibiting women entering into decision-making roles. The capacity building efforts should be targeted at current decisions makers, who appear to be predominantly men.

## 5.6 Institutional, regulatory and market framework

Lafarge Africa began substituting natural gas with locally-sourced biomass for cement processing at its Ewekoro and Sagamu plants in 2012 (Lafarge Africa, 2018). This was driven by a combination of unreliable gas supplies, a Holcim commitment to reduce GHG emissions in its cement production,[15] and the ability to develop the necessary supply chains for bionergy at a price that is competive with current fossil fuels supply.

The aim was to shift as much as possible to sustainable, locally-sourced energy, improving reliability of supply, reducing emissions and stimulating rural development. Among the AFs trialled, oil palm residues have now replaced more than one third of previous natural gas consumption at Ewekoro and Sagamu, while rice husks meet an increasing share of energy needs at Lafarge's Ashaka plant.

A combination of factors, none of which were driven by government or Nigeria's regulatory framework, therefore contributed to Lafarge Africa making a commercial decision to adopt bioenergy. The experience has been extremely successful from a commercial perspective and in terms of GHG benefits, and is supporting sustainable

[15] Cement production generates more than 5% of global GHG emissions. www.iea.org/reports/cement See Lafarge Africa's Annual Reports (2018 and 2019) and Sustainability Reports (2017, 2018 and 2019).

small-scale agri-processing by valorising ‘waste’ biomass. There are strong indications that Dangote, Nigeria’s largest cement producer, is closely examining the use of AFs at two of its three production sites, including Obajana and Ibese. If Dangote follows the same route as Lafarge Africa, it is likely to be driven primarily by commercial factors and secondarily by increasing growing corporate commitments to addressing climate change, namely ”modern, efficient factories producing the highest quality cement for local market needs” (Dangote Cement, 2020).

The Government of Nigeria has aspirational objectives to reduce GHG emissions in its petroleum, gas and heavy industries (with cement being one of the largest), which are set out in its Nationally Determined Contribution submitted to the UNFCCC in 2015 (Federal Republic of Nigeria, 2015). But there are currently no regulatory or policy drivers to incentivise the cement sector to shift to bioenergy for co-processing with fossil fuels.

## 5.7 Replication potential in other target countries

### 5.7.1 Introduction

This section explores the potential for wider adoption of the Bioenergy Case in the other BSEAA2 target countries. The intention is to summarise the prospects for replication of the model, based on the commercial environment in each of those countries and their respective cement manufacturing sectors, where applicable, but not to quantify either total energy demand in the sector, or the potential scale of the replication opportunity.

### 5.7.2 Country analysis

Cement is produced in all ten of the BSEAA target countries. After Nigeria, the largest producers (ranked by production) are South Africa, Ethiopia, Tanzania, Ghana, Kenya, Uganda, Mozambique, Zambia and Rwanda. Cement production is increasing in most SSA countries. However, the pace of growth has slowed in several of the project’s target countries, including Kenya, Tanzania, Uganda, Rwanda and Mozambique, as local production has been hit by imports, particularly from Egypt and from the newly consolidated African Free Trade Zone, which brings together the East African Community (EAC), the Southern African Development Community (SADC) and the Common Market for Eastern and Southern Africa (COMESA) which covers eight of the target SSAs and the Economic Community of West African States (ECOWAS) which covers Nigeria and Ghana.

South Africa, Ghana, Mozambique, Zambia and Rwanda do not use bioenergy for cement production. Fossil fuels are dominant in cement production in SSA, with coal being the largest fuel source, followed by fuel oil, natural gas (in Nigeria and Ghana) and pet coke. South Africa also uses some municipal solid waste to substitute for fossil fuels.

**Ethiopia:** Ethiopia is one of SSA’s largest cement-producing countries, with 20 factories and total output of around 16 Mt p.a. None of its cement plants use bioenergy on a systematic basis. One cement plant, Massebo Cement Company in Mek’ele (Tigray Region), has used municipal solid waste, coffee husks, cotton stalks and other biomass on an opportunistic basis. The Ethiopia Cement Association, representing 14 producers, has completed a major feasibility study to harvest invasive *Prosopis juliflora* (‘mesquite’) in the Afar Region and transport the wood chips by rail for co-processing with fossil fuels in eight of the largest cement facilities (Green Climate Fund, 2018).

**Kenya:** Kenya produces nearly 7 Mt p.a. of cement, of which more than 90% is consumed domestically and the balance is exported within East Africa. There are six cement companies: Lafarge Kenya (which includes Bamburi Cement and the Nairobi Grinding Plant, Athi River), Mombasa Cement, East Africa Portland Cement, Savannah Cement, Athi River Mining Cement and National Cement.

Bamburi accounts for a third of Kenya's national cement production and is the leading producer in East Africa. It has two plants (in Mombasa and Athi River), for which 12% of electricity needs are generated from biomass, mainly coffee, rice and coconut husks, as well as confiscated cargoes from the port of Mombasa. Using bioenergy is important for the company to stem losses arising in part from high electricity costs (Takouleu, 2019). Rice husks from the Mwea irrigation scheme in central Kenya are used as an AF, substituting 60% of fossil fuel consumption at Lafarge Kenya's Nairobi Grinding Plant (Bamburi Cement, 2018; Global Cement, 2018a).

**Tanzania:** Tanzania produces over 7 Mt p.a. of cement, of which nearly 60% is consumed domestically and the rest is exported to neighbouring countries, mainly DR Congo and Burundi. There are a number of large and small-scale producers, of which Tanzania Portland, Dangote, Tanga and Mbeya are the largest. Mbeya and Tanga use bioenergy for cement production from time-to-time. Mbeya is a part of Holcim. Through Geocycle, it has started using agricultural residues as fuel, mainly rice and coffee husks. This ensures that no organic waste from nearby coffee and rice farms is dumped and generates income and employment for people living in the surrounding communities (LafargeHolcim, 2019).

**Uganda:** Uganda has a cement production capacity of about 7 Mt p.a. The leading producers are Tororo, Hima, Simba and Kampala. Tororo and Hima (part of Kenya's Bamburi Cement, itself part of the Holcim Group) co-process with bioenergy. The fossil fuels substitution rate at Hima Cement Ltd (HCL) is currently around 56% (Bamburi Cement, 2018) at its two plants in Kasese and Tororo, mainly from coffee husk, groundnut husks, rice husk, bagasse and sawdust. HCL has also established tree plantations for the supply of fuelwood for its kilns (Bamburi Cement, 2020). In 2011, HCL, through Geocycle, started the Hima Coffee Development Project in Kasese and Kamwenge. Geocycle partnered with the Uganda Coffee Development Association and farmers' associations in the areas around the two plants, to produce coffee seedlings for sale to farmers at one sixth of their normal price, together with a package of technical support (Geocycle Worldwide, 2018). HCL distributed 16.7 million seedlings to 45,000 farmers between 2012 and 2015, with total resulting income expected to reach approximately GBP 40m by 2020 (Geocycle, 2018). In addition to enhancing farmers' livelihoods, the project was to help HCL to access renewable energy from coffee husk.

### 5.7.3 Summary of replication potential in other target SSA countries

There is a significant potential for wider adoption of bioenergy in the cement sector in Nigeria and in the other target countries in SSA, where co-processing with biomass fuels is already practised to some extent. Bioenergy has already been used as fuel to co-process with fossil fuels for cement manufacturing in five of the BAEAA2 target countries (Nigeria, Kenya, Uganda, Tanzania and Ethiopia). Its adoption has the longest history in Uganda (Hima Cement/Lafarge), followed by Kenya, then Tanzania, Nigeria and

Ethiopia. Quantitatively, Nigeria uses more bioenergy than any of the other target SSA countries, followed by Uganda, Kenya, Tanzania and Ethiopia, in that order.

However, with the exception of Holcim's bioenergy use in Nigeria, Uganda and Kenya, with a small amount being used in Tanzania, the team could find no evidence, other than on an opportunistic basis at one cement factory in Ethiopia, that there was any bioenergy use among non-Holcim factories in the other target SSA countries. The Ethiopian Cement Association conducted an extensive study on the use of *Prosopis julifora,* which was presented to the Green Climate Fund in 2016, but which has not progressed. Thus, there is little evidence that bioenergy is being viewed as an alternative to fossil fuels by most companies, in the other target SSA countries.

The leader in the adoption on bioenergy to substitute for fossil fuels is clearly Holcim, who are active in eight of the ten target SSA countries. Lafarge Kenya led the way in the early-2000s with Bamburi Cement, along with Hima Cement Uganda (plants at Tororo and Hima), and in Rwanda, and at Mbeya Cement, Tanzania. All except Hima Rwanda, which is a distribution company, co-process bioenergy in their clinker production. Of the other major producers, only Heidelberg, in Tanga, Tanzania, has co-processed bioenergy in cement production. All other plants use only fossil fuels.

# 6 SUMMARY AND CONCLUSIONS FOR REPLICATION

Based on the analysis of Lafarge Africa's experiences with biomass co-processing, a multi-criteria analysis (MCA) was carried out to summarise the degree to which each of the study's five thematic strands are conducive or detrimental to the successful adoption of bioenergy in cement manufacturing in Nigeria. The results are presented in Figure 6.1, with a low score indicating an impeding factor and a high score indicating an enabling factor (see Appendix 5 for scoring details).

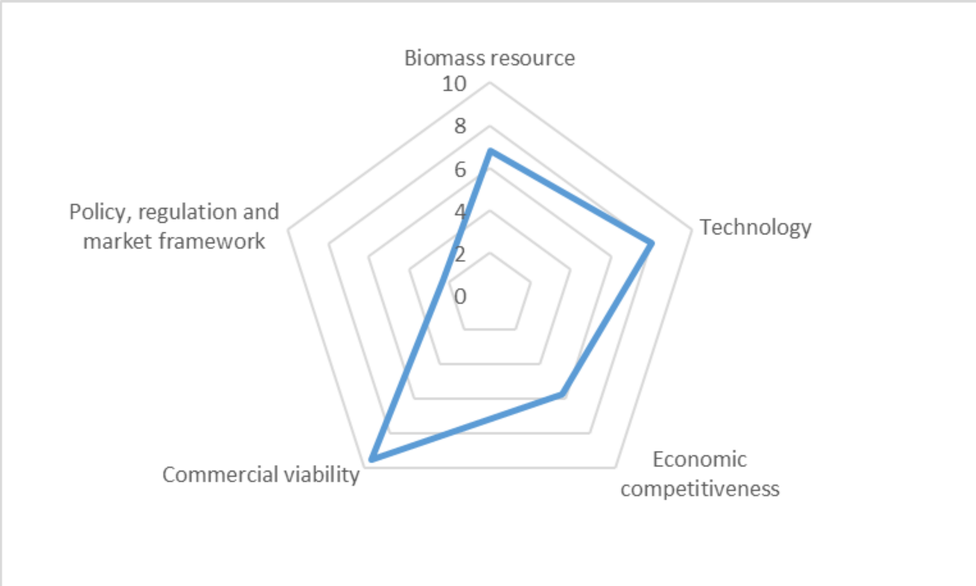



*Figure 6.1: Impact of key factors on wider adoption of Bioenergy Case*

Assessments of biomass resources indicate sufficient feedstock availability within existing supply chains in Nigeria to satisfy demand for cement production. While palm oil residues are estimated to be sufficient to meet just below 50% of the demand from Nigeria's cement sector (assuming a 35% biomass substitution rate), the availability of other biomass-based AFs such as wood processing residues, groundnut shells and rice husks further increase the potential for the use of bioenergy, although context-specific barriers to access and collection may exist. While there are some seasonality and aggregation considerations, with proper planning and sufficient diversification, the availability of sufficient biomass resources for co-processing with fossil fuels is not a bottleneck to wider adoption within the cement industry.

Based on Lafarge Africa's experience, technology selection, sourcing and operation is also not a constraint to the adoption of bioenergy in cement manufacturing. Biomass feedstocks present few technical challenges for cement production as they are largely free of harmful chemicals and can be cleaned, dried and re-sized, if necessary, using standard equipment that is readily available domestically and internationally. Modalities for biomass storage, handling and feeding are well-understood within the industry, and the necessary modifications to pre-calciners and kilns for biomass feeding can be achieved using cement companies' in-house engineering capacity. This applies even to relatively small cement plants, as the same principles and experiences are transferable. Scaling up the use of bioenergy in the cement industry is not, therefore, constrained by technical or technological limitations. However, Geocyle in Nigeria sees an upper limit of co-processing oil palm residues in their Ewekoro facilities at 70%, and rice husks at their Ashaka plant at around 25%, due to technical and chemical limitations. There are no cement plants in SSA using 100% bioenergy for these same reasons.

The economic analysis indicates a slightly more favourable economic case for bioenergy than fossil fuels in cement production, based on operating parameters at Lafarge's Ewekoro plant. Sensitivity analysis reveals that the economic case strengthens as the bioenergy substitution rate increases, provided that biomass can be procured for less than USD 65/t. Coprocessing also reduces exposure to fossil fuel price fluctuations and supply interruptions, which are common in Nigeria and other SSA countries.

The commercial case for part substituting natural gas with locally-sourced biomass for cement manufacturing was driven by unreliable gas supplies, the competitive cost of biomass and Lafarge Africa's commitment to reducing GHG emissions. A critical enabling factor has been the presence of a specialised resource handling entity (Geocycle) and experienced bioenergy aggregation companies, which have together been responsible for the development of biomass supply chains. This model has been successful in achieving commercial viability and contributing to corporate climate change and sustainability targets. It also stimulates sustainable agricultural processing and contributes to rural development through waste recovery, job creation and increased incomes to farmers, enterprises and communities.

The institutional, market and regulatory framework in Nigeria was not a driver for Lafarge Africa's decision to pursue a shift to bioenergy. While policy or regulation could support wider adoption of their approach, particularly if used to de-risk the development of biomass supply chains, this has so far been neither a barrier nor an enabler for investment in bioenergy for cement manufacturing in Nigeria.

In sum, there is a strong potential for the wider adoption of this bioenergy opportunity in the cement sector in Nigeria and other target countries in SSA, where co-processing with biomass fuels is already practised to some extent. Geocycle is already successfully supplying bioenergy to Holcim's cement plants in Kenya (wood residues, rice husks, etc.), Uganda (coffee residues) and Tanzania (wood residues, coffee residues, etc.), and some plants in Ethiopia use small quantities of biomass (including coffee husks and wood residues).

The decision by individual cement companies to adopt bioenergy will depend upon the local cost of developing reliable, cost-effective and sufficient bioenergy supplies, relative to current fossil fuel solutions, and the cost of adapting or installing equipment to handle biomass fuels. The need to set up supply chains with new, unfamiliar partners capable of delivering sufficient feedstocks at prices competitive with fossil fuels, and to undertake suitable technological modifications for biomass co-processing, are key factors requiring careful consideration by other cement producers looking to enter this space. The environmental drive to 'green' cement by using renewable energy is important, but not necessarily a key motivating factor, and is highly dependent upon cement companies' own sustainability and social responsibility commitments.

Given the good business case for bioenergy adoption in this sector, sharing lessons from the experiences of companies such as Lafarge Africa can build confidence amongst other players regarding the commercial and environmental benefits of such a transition. As more cement manufacturers adopt bioenergy, collective expertise will grow and this approach to heat production will become normalised and facilitate further replication.

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# Appendix 2: People consulted

| Organisation | Full Name | Position | Mode of contact |
|---|---|---|---|
| Al-bari Nigeria | Akinrinlola Akinwumiju | GM | Calls, in-person (PKS processing centres at Okitipupa LGA, Ondo State) |
| Cement Manufacturers' Association of Nigeria | Eng. Joseph Makoju | Chairman | Call |
| Dept. for Climate Change, Federal Ministry of Environment | Dr. Peter Tarfa | Director | Call |
| | Amudi Chioma | MRV & NDC Coordinator | |
| Geocycle | Daniel Adedokun | Head | Calls, in-person (Ewekoro, Ogun State) |
| | Greg Salami | Operations Manager | |
| Lagos Waste Management Authority | Dr. Nsuabia Essien | Asst. GM, Operations | Calls, in-person (Lagos) |
| | Ayotunde Amodu | Asst. GM, Eng. Services | Call |
| National Electricity Regulatory Commission | Dr Chikwerem Obi | Head, Statistics Division | Call |
| Nikoy | Lucky Musa | GM | Calls, in-person (head office, Ibadan; farms & PKS processing centres at Iwo LGA, Osun State) |
| Renewable Energy Division, Nigerian National Petroleum Corporation | Yusuf Abubakar | Renewable Energy Specialist | Call |
| Standards Organisation of Nigeria | Eng. Obi Manafa | Director, Standards | Call |
| | Justin Bartholomew Nickaf | Abuja Director | Call |

## Appendix 3: Assumptions in biomass resource assessment

The country-specific residual biomass potential was calculated based on amount of crop or primary product generated, the residue-to-product ratio, the recoverable fraction and the fraction of biomass available, considering other uses:

$$BMP=Cp*RPR*RF$$

Where: BMP = available residual biomass in tonnes per year
Cp = crop production in tonnes per year
RPR = residue-to-product ratio in tonnes of residues per tonnes of product
RF = recoverable fraction per tonnes of product after considering other uses per tonne of product

The theoretical bioenergy potential of this biomass resource was calculated considering the available residual biomass and its energy content.

$$BEP= BMP*(1-MC)*HHV$$

Where: BEP = bioenergy potential in GJ
BMP = available residual biomass in tonnes per year
MC = moisture content
HHV = higher heating value in GJ per tonne

The results of the resource assessments and energy potential calculations are summarised in the tables below.

*Biomass resource assessment data*

| Crop | Feedstock | Production of crop (t/yr) [1] | Area of crop (ha) | Total biomass (t) | Recoverable fraction | Biomass potential (t wet basis) | Moisture content as received [2, 3, 4] | Biomass potential (t dry basis) | HHV (MJ/kg) [2, 3, 4, 5] | Bioenergy potential (GJ) |
|---|---|---|---|---|---|---|---|---|---|---|
| Oil palm fruit | EFB | 7,850,000 | 3,015,530 | 1,177,500 | 0.6 | 706,500 | 60% | 282,600 | 17 | 4,804,200 |
| | Fruit fibre | | | 785,000 | 0.6 | 471,000 | 30% | 329,700 | 20 | 6,594,000 |
| | PKS | | | 471,000 | 0.6 | 282,600 | 15% | 240,210 | 21 | 5,044,410 |
| Cassava | Cassava stalks | 59,475,202 | 6,852,857 | 29,737,601 | 0.6 | 17,842,561 | 70% | 5,352,768 | 18 | 96,349,827 |
| Maize | Maize stalks & cobs | 10,155,027 | 4,853,349 | 7,108,519 | 0.6 | 4,265,111 | 30% | 2,985,578 | 17 | 50,754,825 |
| Sawlogs & other industrial roundwood | Wood processing residues | 4,950,000 | n/a | 2,970,000 | 0.6 | 1,782,000 | 30% | 1,247,400 | 19 | 23,700,600 |
| Rice | Rice husk | 6,809,327 | 3,345,969 | 1,361,865 | 0.6 | 817,119 | 10% | 735,407 | 19 | 13,972,739 |
| Groundnuts | Groundnut shells | 2,886,987 | 2,911,705 | 721,747 | 0.6 | 433,048 | 8% | 398,404 | 19 | 7,569,680 |

| Crop | Feedstock | Production scale | Current use | Existing supply chain | Mobilisation |
|---|---|---|---|---|---|
| Oil palm fruit | EFB<br>Fruit fibre<br>PKS | Small scale (dominant) & large scale | Residues returned to plantations as fertilizer; often disposed to land; increasingly used for bioenergy (onsite for palm oil processing) | yes | Can be mobilised as part of the palm oil processing supply chain, but requires additional handling and potentially storage of feedstocks. |
| Cassava | Cassava stalks | Small scale individual | Stalks used as cuttings for new planting; stalks are also used as firewood in domestic setting; leaves are also used for food; unused stems and leaves left on field or disposed to land | no | Very scattered feedstock, mainly available at small scale lacking infrastructure and resources for collection and transport. The ad-hoc harvest at small scale rather than a dedicated harvest/season can further limit availability. Potentially more feasible for use at HH/community level. |
| Maize | Maize stalks & cobs | Small scale individual | Used as animal fodder; returned to field as fertiliser/nutrient/organic matter; unused residues left on field or disposed to land | no | Very scattered feedstock, mainly available at small scale, lacking infrastructure and resources for collection and transport. Seasonal availability further limits mobilisation. Potentially more feasible for use at household/community level. |
| Sawlogs & industrial roundwood (other) | Wood processing residues | Small and large scale | Used for wood processing (kiln drying); used by other industries and commercial sector for processing energy; unused residues disposed to land or burned | yes | Mobilisation depends on scale of wood processing facility and demand from other sectors |
| Rice | Rice husk | Small scale individual | Used as fuel for rice drying in mills; unused husk disposed or burned; increasingly used by other industries for energy generation, which means knowledge and experience, but also competition exists | yes | In the case of small-scale processing scattered availability, with limited infrastructure and resources for collection and transport. More feasible if large-scale commercial processing as easier to collect or used on-site |
| Groundnuts | Groundnut shells | Small and large scale | Used as fuel for groundnut oil production; large amounts unused and disposed to land or burned | yes | In the case of small-scale processing, lacking infrastructure and resources for collection and transport. More feasible in large-scale commercial processing |

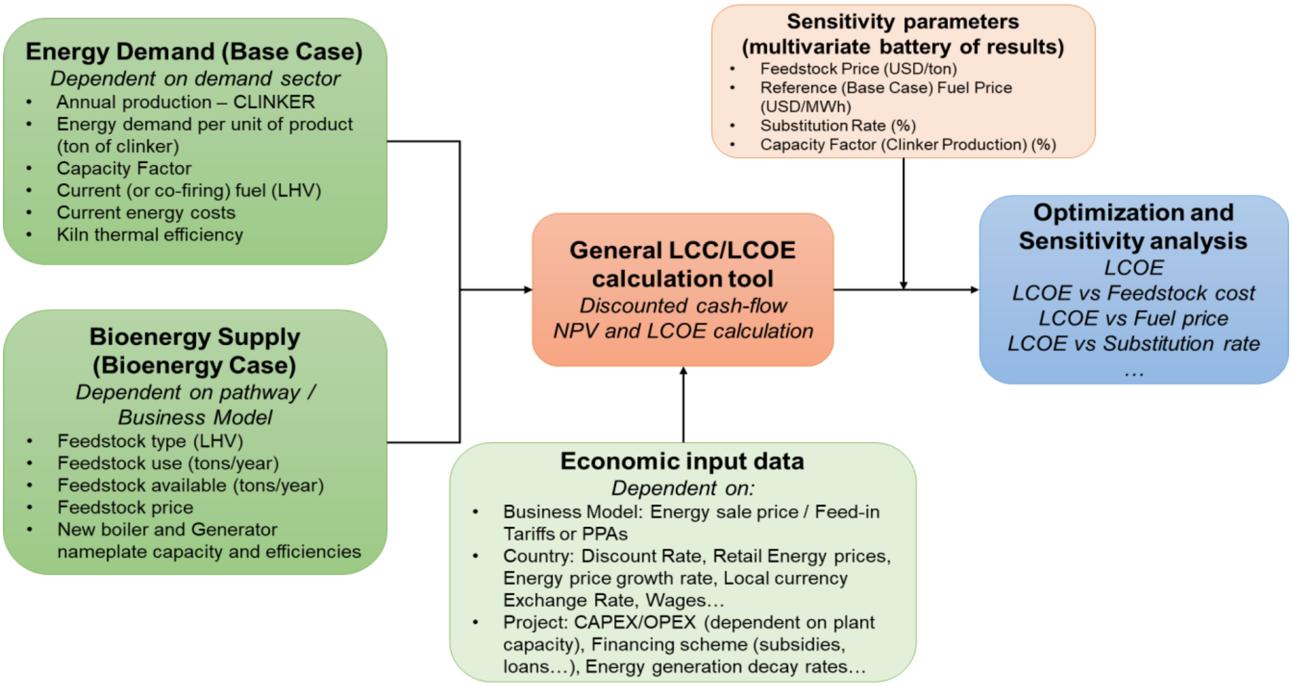
*Residue-to-product ratios*

| Crop | Residue type | Residue-to-product ratio |
|---|---|---|
| Oil palm | EFB residues | 15% of fresh fruit bunch [2] |
| | Fibre residues | 10% of fresh fruit bunch [2] |
| | PKS | 6% of fresh fruit bunch [2] |
| Cassava | Cassava stalks | about 50% of root weight (wet) [3] |
| Maize | Maize stalks & cobs | Ratio maize grain to residues ~1:0.7 [6] |
| Sawlog/roundwood | Wood processing residues | ~40% of logs are sawn wood, 30% chips, 15% offcuts, 15% sawdust [7] |
| Rice | Rice husk | 0.2 kg husk per kg milled rice [8] |
| Groundnuts | Groundnut shells | 25% of fruit are shell [9] |

Sources: [1](FAO, 2021a) ; [2] (Elbersen, 2013); [3] (Zhu et al., 2015); [4] (TNO, 2021); [5] (Forest Research, 2021); [6] (Dafrallah et al., 2010); [7](AEBIOM European Biomass Association, 2013); [8] (IRRI, 2020); [9] (Perea-Moreno et al., 2018)

# Appendix 4: Life-Cycle Cost toolkit functions

A flow diagram of AIGUASOL's Life-Cycle Cost (LCC) modelling toolkit functions is provided below:




The main economic indicator considered is the Levelized Cost of Energy (LCOE), in USD/MWh:

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{C_t}{(1+DR)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+DR)^t}(1+IR)^t}$$

Where: $C_t$ = costs incurred in year t
DR = discount rate
$E_t$ = energy consumed in year t
IR = annual inflation rate

# Appendix 5: Multi-Criteria Analysis input data

| Criteria | Score | Scoring criteria (min=1, max=10 | |
|---|---|---|---|
| **Biomass** | | | |
| Availability | 10 | low | high |
| Seasonality | 7 | short | long |
| Aggregation | 7 | scattered | centralised |
| Proximity | 3 | far | close |
| Technical feasibility | 7 | low | high |
| **Average** | **7** | | |
| **Technology** | | | |
| Technology track record in same sector | 9 | low | high |
| Availability of a turnkey technology solution | 8 | limited | well established |
| Ease of operation and maintenance with in-house capacity | 7 | limited | well established |
| Supplier reputation, engagement and partnership | 8 | not engaged | engaged |
| Access to technical support & spares | 8 | low | high |
| **Average** | **8** | | |
| **Business model** | | | |
| Energy self-consumption drivers | 9 | limited | significant |
| Grid and 3rd party export drivers | n/a | limited | significant |
| Waste disposal drivers (based on cost for disposal) | n/a | limited | significant |
| Market potential (replicate business model) | 10 | low | high |
| **Average** | **10** | | |
| **Policy, regulation and market** | | | |
| Bioenergy policy | 5 | unsupportive | supportive |
| Bioenergy policy implementation | 1 | not implemented | implemented |
| Agriculture/Forestry policy | 3 | unsupportive | supportive |
| Agri/Forestry policy implementation | 3 | not implemented | implemented |
| Demand sector specific policy | 2 | unsupportive | supportive |
| Environmental policy | 2 | unsupportive | supportive |
| Environmental policy implementation | 2 | not implemented | implemented |
| Technology-specific fixed price (e.g. FIT) | 1 | unattractive | attractive |
| Demand sector specific governance practice | 2 | weak | strong |
| Biomass/processing-specific governance practice | 2 | weak | strong |
| **Average** | **2** | | |
| **Cost** | | | |
| LCOE heat total | 7 | cost increase | cost reduction |
| LCOE heat CAPEX | 4 | cost increase | cost reduction |
| LCOE heat OPEX non-fuel | 4 | cost increase | cost reduction |
| LCOE heat OPEX fuel or electricity | 8 | cost increase | cost reduction |
| **Average** | **6** | | |

# Appendix 6: Photos of bioenergy sourcing and Ewekoro cement plant

Credit: Linus Orakwe, except where otherwise stated

Manual separation of oil palm fruit fibre from nuts, Osun State

Manual cracking of oil palm nuts to remove shell, Osun State


Drying palm fruits before milling, Ondo State

Mechanical cracking of oil palm nuts, Ondo State


Water pit for float separation of shell from nuts, Ondo State

Oil palm fruit fibre ('shafts')[16]

[16] archive.ump.edu.my/asivr/images/mesocarp%201.jpg

Palm kernel shell[17]

Geocycle container for PKS collection, Ondo State

Loading bagged PKS, Osun State

PKS storage at Ewekoro II

Blending PKS with other alternative fuels, Ewekoro II


Sieve and walking floor for AF feed, Ewekoro II

[17] www.briquetting-machine.com/upLoad/news/month_1509/20150913004753999.jpg

Lift from walking floor to magnetic separator, Ewekoro II

AF entering magnetic separator, Ewekoro II

300 m inclined conveyor from AF plant to pre-calciner, Ewekoro II