



# Modelling Nigerian residential dwellings: bottom-up approach and scenario analysis

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RESEARCH

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## ABSTRACT

Nigeria's residential buildings consume a substantial amount of the country's energy, so achieving a net-zero building sector with a rapidly growing population is a key challenge. To bridge the gap in research at a national level and support Nigeria's commitment to an unconditional 20% reduction in emissions by 2030, this study develops bottom-up archetype models of different residential building typologies to estimate the energy and material use of Nigerian residential buildings. This creates an overview of the residential stock and how different archetypes perform. The study calculates a baseline energy and material use of Nigeria's residential building stock using the BuildME tool and converts these data into CO<sub>2</sub> emissions using a life-cycle assessment. Scenarios are modelled for 2020. Nigeria's residential dwellings use approximately 0.3 kt of material per dwelling over a lifetime of 50 years and 2404 kWh/yr of energy per dwelling. Annualised, dwellings emit 2500 kgCO<sub>2</sub>-eq per dwelling due to material and energy use. Scenarios proposed for meeting Nigeria's emissions targets will require improved energy efficiency, decarbonising the building envelope through a shift in construction materials and decarbonising grid electricity.

## POLICY RELEVANCE

This study provides a comprehensive analysis of the energy and material use of residential buildings in Nigeria, focusing on achieving the country's commitment to a 20% reduction in emissions by 2030. It employs a bottom-up approach to model energy and material use, revealing the peculiarities of the dwelling stock across Nigeria's four climatic zones. The study explores the implications of different policy scenarios on sustainable housing. The research suggests that meeting Nigeria's emissions targets requires improved energy efficiency, a shift in construction materials and decarbonisation of grid electricity. It also highlights the potential benefits of a policy switch to materials such as timber, earthen blocks, adobe bricks and clay, which could significantly reduce construction-related emissions. These changes could improve the quality of life of households in Nigeria, combat climate change on a global scale and bring economic advantages to Nigeria.

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## 1. INTRODUCTION

### 1.1 ENVIRONMENTAL IMPACTS AND ASPECTS OF BUILDINGS

Shelter provided by buildings is an essential human need (Zhong *et al.* 2021). This might explain in part why the building sector alone accounts for one-third of the final energy consumed and nearly 40% of the energy-related greenhouse gases (GHG) emissions worldwide (UNEP 2023). This trend places buildings at the centre of climate change mitigation and adaptation efforts as they provide low-cost and short-term opportunities for achieving set goals. They offer many opportunities for material and energy efficiency, improved health and wellbeing of citizens, and economic growth (Müller *et al.* 2013; WRI 2016). Several global goals emphasise reducing energy consumption, promoting sustainable construction and moving towards net-zero carbon operations, all while ensuring affordable, safe and inclusive housing (UN DESA n.d.; Pauw *et al.* 2020; UNEP 2022; WGBC 2019). Delay in planning concerning the built environment is dangerous as this delay can lead to a possible lock-in because of the long lifetime of buildings and their persistent energy use (Davis *et al.* 2010).

Estimates by the Global Alliance for Buildings and Construction show that the global building floor area will double by 2060. According to these estimates, most of the floor area to be added to the present dwelling stock will be in Africa, as an estimated 70% of the African building stock in 2040 is still yet to be built. The United Nations Environment Programme (UNEP) opines that Africa stands a chance at sustainable construction given the established correlation of urban growth with material use and emissions. This thought is due to the abundance of low-carbon local construction techniques and materials such as timber and sand (UNEP 2022). Currently, in Africa, only South Africa, Ghana, Nigeria, Tunisia, Morocco and Egypt have mandatory or voluntary building codes, with seven other countries in the process of developing the same (UNEP 2021). Even for these countries with building codes, the level of compliance is lower than what is required to make significant changes. Some African countries have started making deliberate efforts to change this using the bottom-up and other building modelling approaches at subregional and regional levels (Attia *et al.* 2012; Deru *et al.* 2011; Geissler *et al.* 2018). However, the authors found no recent national residential building stock models for African countries.

While it is a developing method in Africa, the use of bottom-up modelling is not new as several studies have used similar approaches to represent building stocks in Canada (Farahbakhsh *et al.* 1998), Finland (Snäkin 2000), the United States (Huang & Brodrick 2000), Belgium (Hens *et al.* 2001) and the UK (Shorrock & Dunster 1997). The bottom-up modelling approach has its flaws related to the sparsity of relevant detailed input and output model data, which leads to the use of domain-heavy assumptions, making reproducibility difficult (Kavgic *et al.* 2010). However, compared with other approaches to building modelling such as the top-down (econometric and technological) or hybrid approach, this method's strength lies in its ability to obtain estimated results at a disaggregated level (Ugwoke *et al.* 2024). Such a method is very useful for policymakers and construction managers to identify improvement hotspots at (or closer to) the source and propose tailored solutions.

### 1.2 NIGERIAN CONTEXT

Nigeria is a Sub-Saharan African country located close to the equator with an estimated population in 2020 of over 200 million (UN DESA 2024). Although Nigeria is fully within the tropical zone, there are significant climatic variations because of two principal wind currents, resulting in four climate zones. Nigeria boasts of having one of the strongest and largest economies in Africa, largely dependent on crude oil and natural gas exports (Federal Ministry of Environment 2021b). This fact, in turn, means that it is economically vulnerable to efforts to reduce emissions (Federal Ministry of Environment 2021b) as 80% of grid electricity generation capacity is gas based and the remainder is hydropower (Geissler *et al.* 2018). Because of grid instability, Nigeria imports back-up generators, with 80% diesel generator ownership in 2014 (Elinwa *et al.* 2021; Geissler *et al.* 2018).

The 2017 climate change vulnerability index (CCVI) classifies Nigeria as a high-risk region, being among the top 10 most vulnerable countries globally (Federal Ministry of Environment 2021b). In 2017, Nigeria signed the Paris Agreement, committing to cut its carbon emissions and reach net zero by 2060 with a five-year emission budget. The country through its nationally determined contributions (NDCs), pledges an unconditional 20% reduction in business-as-usual emissions by

2030 (Federal Ministry of Environment 2021b). The National Renewable Energy Master Plan of 2014 projects that over 26% of the country's energy use by 2025 will be from renewable sources (Federal Ministry of Environment 2021b) to cut emissions by 38%. The Building Energy Efficiency Code signed in August 2017 is a first step to implementing its NDCs and the Nigerian government projected energy savings of up to 40% by 2030 compared with the baseline (Federal Ministry of Power, Works, and Housing 2017). This target is particularly relevant considering that residential buildings consume over 80% of energy in Nigeria (IEA 2017), a higher share than in other countries, with the world average at 30% (IEA 2023). However, to make tailored interventions rather than one-size-fits-all policies, modelling the Nigerian residential stock is critical.

### 1.3 EXISTING RESEARCH ON NIGERIAN RESIDENTIAL BUILDINGS

In exploring sustainable energy transitions, Dioha & Kumar (2020) showed that integrated assessment models (IAMs), which have formed the major aspect of quantitative top-down modelling in Nigeria, do not describe the diversity of energy use sufficiently. The researchers developed a TIMES-Nigeria-Residential model that provides the least-cost energy system based on technological and non-technological scenarios at a disaggregated level. Their results reveal the value of affordable and clean energy in reducing building final energy demand. However, the model places a high premium on cost as the main indicator and the CO<sub>2</sub> calculations appear not to follow standardised methodology.

Oluwole *et al.* (2020) developed a bottom-up weather-sensitive residential demand model to estimate uninterrupted electricity demand in Nigeria using socio-economic data and household surveys. Their results show a monthly consumption of 63 kWh. However, as they are limited to households connected to the grid, the results must be read with caution considering the low on-grid access in Nigeria (World Bank 2023).

Ochedi & Taki (2019, 2022) conducted bottom-up building models for Lokoja, Nigeria, to estimate thermal comfort and energy use. They developed a multicriteria framework for energy-efficient residential buildings in Lokoja. However, the results are specific to Lokoja only, and the study does not consider material use in reaching energy efficiency.

Ugwoke *et al.* (2024) employed the bottom-up modelling approach using reference building models for Nigerian buildings in different geopolitical and climate zones to analyse the energy performance of low-cost buildings. They identified and created reference buildings using the characteristics of real buildings based on statistical data coupled with international/national standards. The study found the average energy use in residential dwellings to be 113 kWh/m<sup>2</sup>/yr (cooking excluded) and proposed energy efficiency measures. The results are hardly generalisable beyond the specific real buildings analysed, signifying the need for more comprehensive models.

Investigating the energy use and CO<sub>2</sub> emissions of Lagos State public houses, Ezema & Okorigba (2022) found that over the building life-cycle, operational energy use was three times higher than the energy used to produce building materials. The same trend was observed for CO<sub>2</sub>. The authors found that for every 1 m<sup>2</sup> of housing added to the existing stock, over 117 kWh/yr of energy would be needed for the operation phase alone (cooking included). Hence, they caution that due to the reliance on non-renewable energy, an increase in energy use would negatively impact resource sustainability and climate change. The study only focuses on public housing in one of Nigeria's 36 states and assumes a grid electricity supply of 25%. Like other researchers, they equally recommend future research on alternative envelope materials such as timber and clay for their adaptive, energy-serving thermal properties, their low cost and their availability (Ezema & Okorigba 2022; Nwalusi *et al.* 2019; Onyenokporo & Ochedi 2018).

### 1.4 RESEARCH GAP, AIM AND OBJECTIVES

The dwelling stock in Nigeria is classified differently from that of European dwellings, and from statistics of different years, the classification keeps changing. This change makes it quite challenging to develop building typologies without first understanding the differences and similarities. The high number of new buildings expected to be created within the next 40 years compared with what exists means stakeholders must avoid past mistakes by using robust models that are realistic in the

Nigerian context. The authors find that there is a gap in research offering a consistent whole-scale comparison of typologies for the entire stock across the different climate zones in the country.

To bridge this gap, this study develops bottom-up archetype models of different residential building typologies in Nigeria to estimate the energy and material use of residential buildings in 2020. It presents five distinct archetypes: apartments, bungalows, compounds, mud houses and improvised settlements, along with their resource use and associated GHG emissions. The study is attentive to the different climate, architectural and economic characteristics, contributing to a holistic understanding of the diverse built environment in Nigeria.

The study's objectives are to provide an overview of residential dwellings in Nigeria, assess how the different archetypes differ in terms of energy and material use and emissions, and propose scenarios for sustainable residential buildings. It begins by identifying the main residential building typologies. Thereafter it calculates the baseline energy and material use in Nigerian residential buildings and translates these results to carbon emissions. The implications of different policy scenarios on sustainable housing given the huge emission impact and existing informal settlements' environmental burdens are further discussed.

## 2. METHODS

The study formulates a bottom-up model with model drivers focusing on the characteristics that best describe energy use in the 2020 building stock (Figure 1). This work adopts the methodological framework for archetype development as described by Ali *et al.* (2019) and refined by Akin *et al.* (2023) due to similarity in research objectives. The developed archetypes are further investigated in scenario analysis and life-cycle assessment (LCA). Further details of each stage and descriptions of the archetypes are given in the supplemental data online.

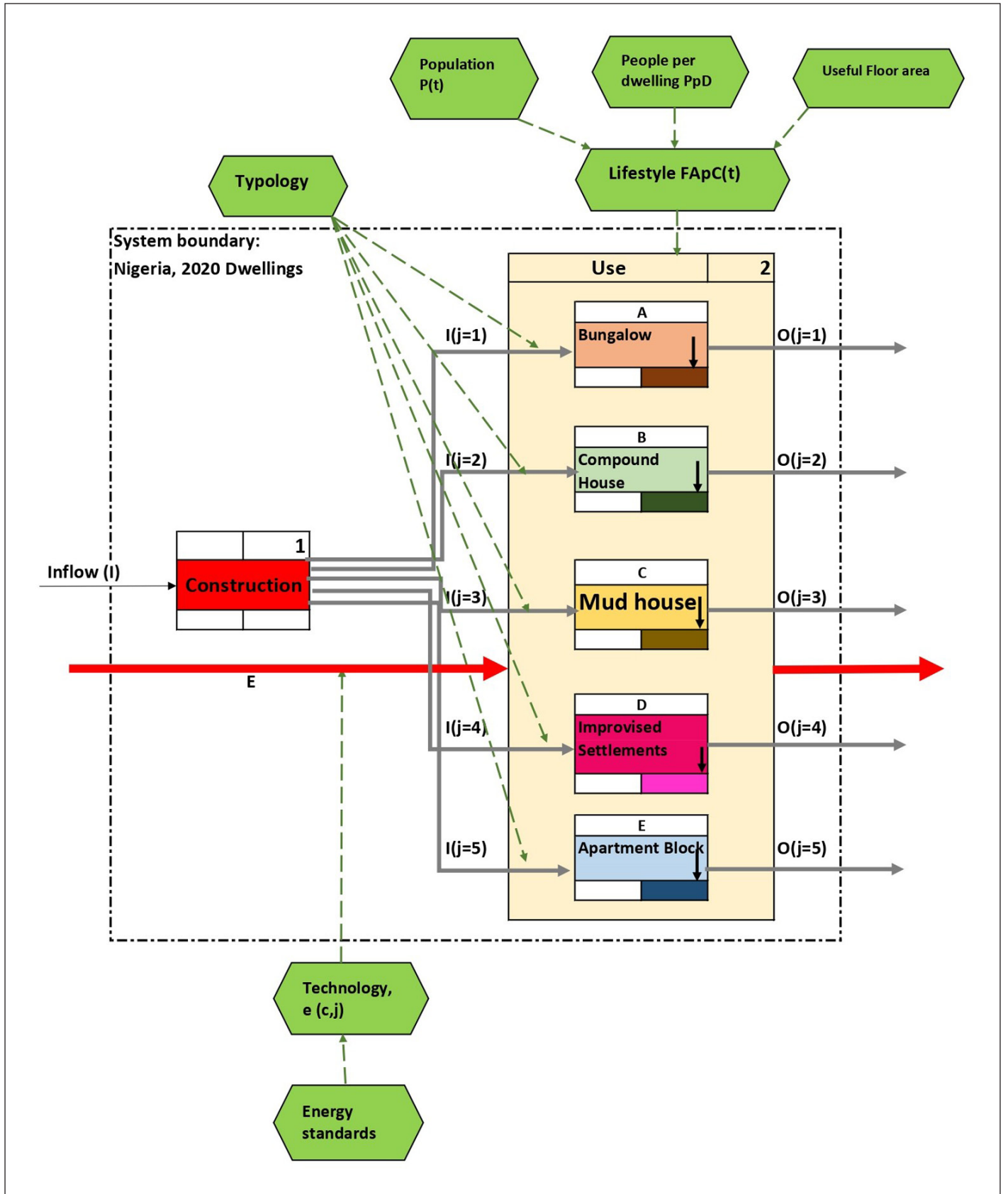
### 2.1 DATA COLLECTION

As a result of the paucity of data, the comprehensive dwelling stock data used in this study are a product of data collection and aggregation from multiple sources and using relevant ratios from statistics and literature (Table 1). One of the authors employed a local perspective in addition to three-month-long fieldwork conducted in Nigeria to gather relevant on-site knowledge and data from local architects and households. Data on the different model parameters influencing energy use such as set points, airtightness, shading, lighting density, equipment load, metabolic rate and oven energy were obtained from different literature sources and statistics as provided in the extended datasets (Nwagwu *et al.* 2024). The study identified five residential building typologies: apartments, bungalows, compounds, mud houses and improvised settlements.

Apartments, bungalows and compound houses are typically surrounded by a fence made of sandcrete blocks and joined with a gate at the front (thatch for mud houses and none for improvised settlements). Walls are mostly constructed from uninsulated hollow sandcrete blocks (clay for mud houses and wood for improvised settlements). Roofs are often uninsulated, pitched with corrugated metal sheets and wooden/asbestos ceilings (straws or tree branches for mud houses). Windows are single-glazed glass with an aluminium frame and a window-to-wall ratio of 25% (10% is assumed for mud houses and improvised settlements based on available building drawings). Floors are reinforced concrete slabs of 150 mm thickness (none/clay for mud houses and wood for improvised settlements). Interior doors are wooden, while exterior doors may be aluminium, steel or wood depending on wealth and personal preference (always wood for mud houses). Shading effects from fences and burglary-proof steel beams are considered in this study (overhangs and fences for mud houses and none for improvised settlements). The materials used for fences are not considered in this study.

### 2.2 BUILDING MODEL AND ENERGY MODEL DEVELOPMENT

The study created a single representative geometry per typology across the climate zones, and the resulting archetype geometries and their shares in the building stock are presented in Figure 2. The study used DesignBuilder software, integrated with EnergyPlus v.9.2.0 for geometry creation and



**Figure 1:** Model definition and flowchart of the study.

Source: Adapted from a lecture slide in Müller (2022).

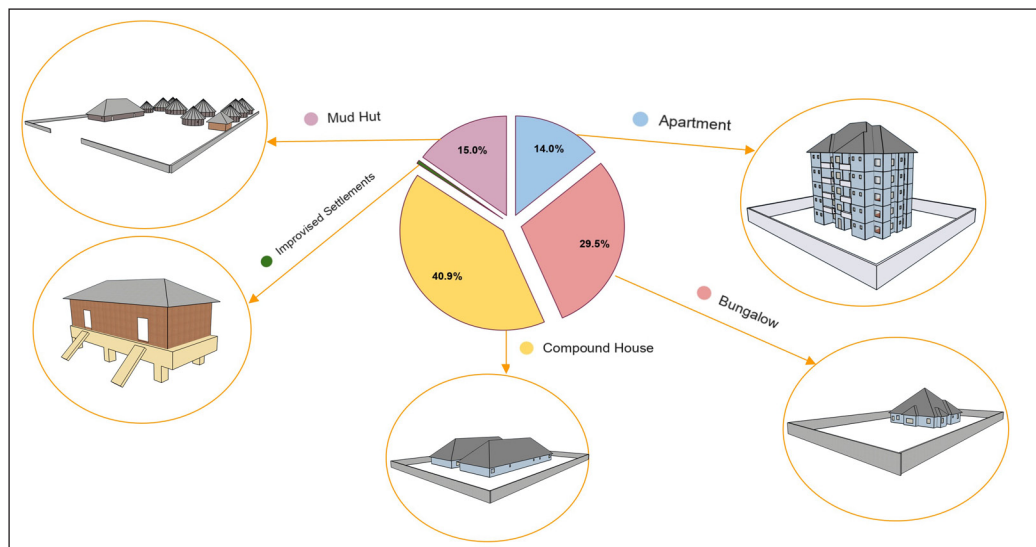
energy modelling (DesignBuilder Software 2022). Household energy was modelled based on the lighting, cooling and equipment needs in this study. Energy use related to cooking is not within the study's scope. This study relies on ideal loads as the main heating, ventilation and air-conditioning system with mixed-mode ventilation settings activated. To estimate the cooling needs of the building, weather files generated via Meteororm (AG, Meteotest 2023) were used for each climate zone. The study exported the files from DesignBuilder as input data files (IDFs) to the EnergyPlus-supported BuildME Python model (Heeren 2019) and computed the material and energy use of the different archetype energy models.

Due to some limitations in the structural framework of the building archetypes using DesignBuilder, additional surrogate elements such as beams, columns and shear walls were specified in line with Akin *et al.*'s (2023) approach. Although these elements have little impact on energy use, they are important for material use. Energy demand (kWh/m<sup>2</sup>/yr) was scaled up to the country's total residential building floor area to obtain the total energy use of Nigeria's residential building stock. The results, representing 2020, were validated using the data on the use of oil products, electricity and biomass by Nigerian households obtained from the United Nations 2020 Energy Balances (UN 2023). It should be emphasised that this study did not consider vacancy rates but rather assumed that all dwellings were fully occupied all year round.

**Table 1:** Key parameters for the representation of the Nigerian building stock.

Note: NLSS = National Living Standards Survey; Single-family house (SFH) = bungalow, mud, improvised; multi-family house (MFH) = apartment, compound.

PARAMETER	NOTES AND DESCRIPTION	SOURCES
Dwellings	41 million 75% built before 2017 and 25% built 2017–20 79% informal and 21% formal	Estimated based on household size in the NLSS of 2018/19 (National Bureau of Statistics 2020)
Typology	Apartment: flat/apartment, living quarters, boy's quarters, duplex, single-room apartment, storied building Bungalow: separate house, semi-detached, two rooms Compound: compound (colloquially called 'Face Me I Face You' or 'Face Me I Slap You' for row dwellings that face each other) Mud house: hut, mud, thatch Improvised settlement: timber houses (obtained from mass balance since most statistics have it as 'others')	National Bureau of Statistics (2011) and NLSS of 2018/19 (National Bureau of Statistics 2020)
Climate zones	Tropical monsoon (zone 1), tropical wet savannah (zone 2), hot semi-arid (zone 3) and hot deserts (zone 4)	British Geological Survey (MediaWiki 2019)
Settlement type	Rural and urban	Based on the Exposure database (Paul <i>et al.</i> 2022) using the same ratio for 2016 and 2020
Cohort type	Pre-2017 (buildings completed before 2017) Post-2017 (buildings completed 2017–20)	Based on the Exposure database (Paul <i>et al.</i> 2022) and applying simple computation using the other parameters
Electricity access	On-grid only: rural: 25%; urban: 84% Off-grid inclusive: rural: 35%; urban: 92%	World Bank Global Electrification Database (World Bank 2020) and NLSS (National Bureau of Statistics 2020)
Population	2016: 194 million 2020: 208 million	2016 (National Bureau of Statistics 2016) 2020 (UN 2022)
People per dwelling	Zone 1: SFH (6), MFH (5) Zone 2: SFH (5.7), MFH (4.5) Zone 3: SFH (7.2), MFH (6) Zone 4: SFH (7.5), MFH (6)	Estimated based on data from 2015 statistics (National Bureau of Statistics 2016)
Useful floor area (UFA; m <sup>2</sup> ) per dwelling	Apartment: formal, 122; informal, 89 Bungalow: formal, 300; informal, 183 Compound: formal, 177; informal, 110 Mud house: 75 Improvised settlement: 91	Exposure database; floor plans from local experts and the existing literature available in Zenodo (Nwagwu <i>et al.</i> 2024)



**Figure 2:** Nigerian residential building typologies in this study.  
 Source: Authors.

## 2.3 LIFE-CYCLE ASSESSMENT (LCA) METHODOLOGY

The study used calculated national energy and material use results for the LCA, following ISO 14040 and 14044 (ISO 2006; Standard Norge 2006). It also followed the European Standard (EN 15978) guidelines for the environmental performance of buildings using the LCA methodology (CEN 2012).

### 2.3.1 Goal and scope

The goal of the LCA is to estimate the climate change impacts of the Nigerian residential dwelling stock in 2020 using global warming potential (GWP) for a time horizon of 100 years, denoted as GWP100, as given by the Intergovernmental Panel on Climate Change (IPCC) in 2021. The scope covers only the material-related and operational emissions, and the end-of-life (EOL) indirectly through the cut-off method as given in the Ecoinvent database. A simplified flowchart presented in Figure 1 shows the system design, flows and boundaries. The two main foreground systems are the construction and operation/use phases. From European Standard (EN 15978), this work investigates stage A (product stage plus transport to site) and stage B6 (operational energy use). Modules B1 (use), B2 (maintenance), B3 (repair), B5 (refurbishment) and B7 (operational water use) were excluded because they generally have low environmental impacts (Frischknecht *et al.* 2019; Huang 2018; Krych *et al.* 2021). Module A5 (construction and installation) is excluded due to a lack of quality data on the installation and assembly of residential buildings, while module B4 (replacement) is excluded due to a lack of quality data on repair frequency or patterns by households. As in many other studies, stages C and D, related to reuse, recycling and energy recovery, are outside the system boundary because there are very limited demolition data for Nigeria. The functional unit is one dwelling unit of a residential building within one year of operation. The results are also given per m<sup>2</sup> of usable floor area to aid comparison across typologies. The assumed lifetime of a typical Nigerian building is 50 years, in line with the Nigerian Institute of Building (Oghifo 2021).

### 2.3.2 Inventory analysis

Data collection and inventory modelling for the LCA uses data collected and processed as described above and detailed in the supplemental data online. The energy and material use of the operational and material-related phases from BuildME are matched with Ecoinvent v.3.9 to calculate the life-cycle impact of each archetype. Considering the substantial utilisation of direct fuel for standby generators, as previously mentioned, this study examines the proportion of residences employing such generators and the duration of their operation per annum. The ratios and fuel use metrics are presented in the supplemental data online.

Computations involving direct fuel use were performed in line with relevant international energy and emissions protocols to estimate energy use at the operational and construction-related phases. Given the volume of petrol imported from the Netherlands, this work uses data on Dutch petrol from the Ecoinvent database. Subsequently, the life-cycle inventory results of the respective typologies are computed.

## 2.4 SCENARIO DEVELOPMENT

### 2.4.1 Target and scenarios

In line with Nigeria’s NDCs, the baseline for the targets is 2015. In 2015, Nigeria recorded about 1134 TWh of residential energy use (UN 2017), which increased by 10% to 1239 TWh in 2020 (UN 2023) according to the UN Energy Balances. Direct operational emissions from residential dwellings were about 36 MtCO<sub>2</sub>-eq in 2015 according to a government report (Federal Ministry of Environment 2021a). Four different scenarios are proposed in comparison with the baseline in terms of energy use and carbon emissions with 2020 as the target year and the operational emissions reduction target in all scenarios as 33 MtCO<sub>2</sub>-eq/yr based on the country’s yearly reduction target of 1.5%. No targets have been set for material emissions due to unavailable references. The study does not account for new constructions in the scenarios but applies stated assumptions to the national stock representation as in the baseline. These different measures are tested individually and as a combination for the dwelling stock in 2020 (Table 2) (for a more detailed explanation of the scenarios, see the supplemental data online).

- Scenario 1 (WIRE): assumes the swift implementation of various energy efficiency measures. Key focus areas include lighting energy loads with the replacement of incandescent bulbs with compact fluorescent lamps (CFLs).
- Scenario 2 (UHURU): as the name implies in Swahili, it assumes total freedom and is used to describe a scenario where everything is as good as possible (high gross domestic product (GDP) per capita and electricity access). This scenario does not assume that power blackouts are eliminated, but that every household has access to back-up generators.
- Scenario 3 (SLIM): given the huge share of total emissions from materials production, this SLIM scenario is one in which residential building construction changes. From lightweighting to the use of thatched roofs, this scenario focuses on reducing material-related emissions.
- Scenario 4 (EXPO): explores the possibility of meeting Nigeria’s commitments to climate change mitigation while achieving rapid growth in GDP per capita up to the level of the average European country. Given Nigeria’s abundant access to similar renewable energy sources as in Sweden, the Swedish electricity grid is chosen as a reference. It does not assume behaviour pattern changes, therefore all lighting, cooling and equipment schedules remain unchanged.

**Table 2:** The four different scenarios.

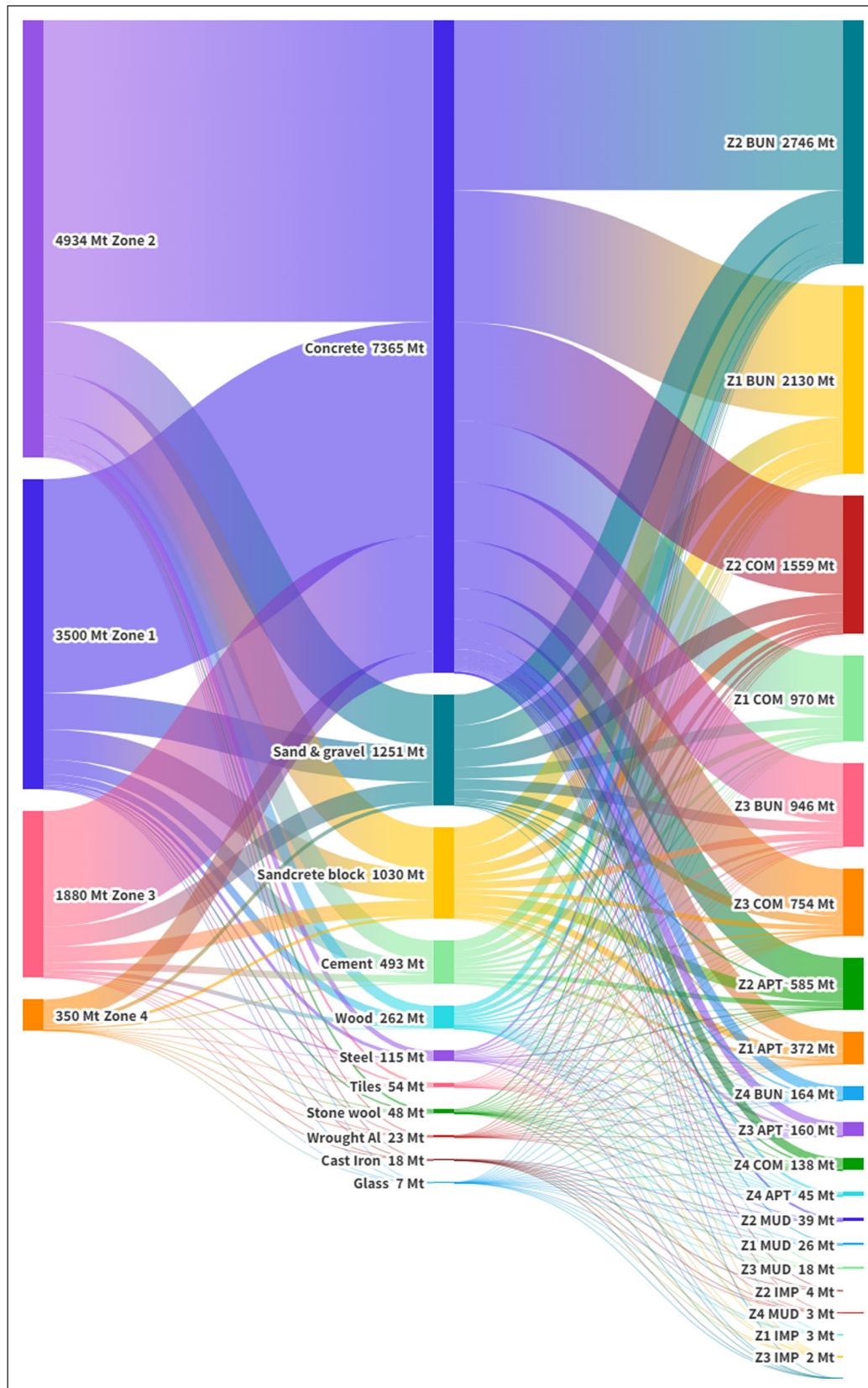
Note: CFL = compact fluorescent lamp.

SCENARIO/ INTERVENTION PATHWAYS	CFL BULBS RE- PLACE 70% OF INCANDESCENT BULBS	100% ELECTRI- CITY ACCESS (ON- AND OFF- GRID)	50% COMPLY WITH EXIST- ING REGULA- TIONS	100% ON-GRID ELECTRI- CITY	REPLACE CON- CRETE BLOCKS WITH CLAY	THATCH ROOFS	ON-GRID ELECTRICITY HAS 31% RE- NEWABLES	ON-GRID ELEC- TRICITY HAS SWEDISH-LEVEL OF RENEWABLES
WIRE-A	x							
WIRE-B	x	x						
UHURU-A			x					
UHURU-B	x		x					
UHURU-C	x	x	x					
SLIM-A	x	x			x			
SLIM-B	x	x			x	x		
EXPO-A	x			x	x	x	x	
EXPO-B	x			x	x	x		x

### 3. RESULTS

#### 3.1 ARCHETYPE ENERGY AND MATERIAL-USE ESTIMATIONS

The results from the archetype energy and material-use modelling show that the Nigerian residential dwellings hold 11 Gt of material, 0.3 kt per dwelling (Table 3). Apartments and bungalows use more material by mass than other typologies per dwelling. The findings (Figure 3)



**Figure 3:** Material-use split for Nigerian residential building types and climate zones.

Note: APT = apartment; BUN = bungalow; COM = compound; INF = informal settlements; MUD = mud houses.

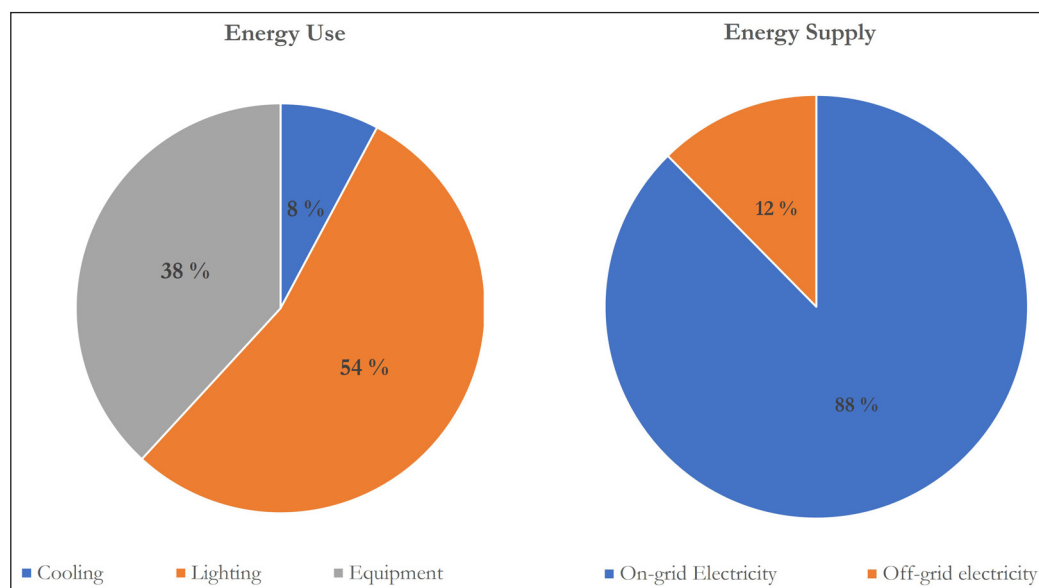
Source: Authors, using Flourish (n.d.).

prove that concrete is the primary construction material used, accompanied by supplementary or related materials such as sandcrete block, cement, sand and gravel. Concrete in this study refers solely to load-bearing materials (shears, beams, columns), thus the authors measured them mutually exclusively.

	ANNUAL EUI (kWh/m <sup>2</sup> /yr)	TOTAL ENERGY USE (TWh/yr)	ANNUAL EUI (kWh/yr per dwelling)	TOTAL MATERIAL USE (Mt)	SPECIFIC MUI (kt/unit)	SPECIFIC MUI (t/m <sup>2</sup> /50yrs)
<b>Typologies</b>						
Apartment	26	12	2,557	1,161	0.25	2.6
Bungalow	16	44	3,333	5,989	0.45	2.1
Compound	18	37	2,249	3,422	0.21	1.6
Mud house	9	4	688	254	0.04	0.6
Improvised	26	0.4	2,389	10	0.06	0.6
<b>Wealth</b>						
Formal	21	40	4,621	3,732	0.43	2.0
Informal	15	58	1,809	7,105	0.22	1.8
<b>Time cohort</b>						
Pre-2017	15	67	2,171	7,849	0.26	1.8
Post-2017	22	32	3,098	2,987	0.29	2.0
<b>Climate zone</b>						
Zone 1	18	33	2,613	3,547	0.28	1.9
Zone 2	17	46	2,400	5,013	0.26	1.8
Zone 3	15	17	2,130	1,919	0.24	1.8
Zone 4	16	3	2,158	357	0.25	1.8
<b>Settlement</b>						
Rural	9	23	1,240	4,685	0.26	1.8
Urban	23	76	3,343	6,152	0.27	1.9
National						
<b>Totals</b>	<b>17</b>	<b>98</b>	<b>2,404</b>	<b>10,836</b>	<b>0.26</b>	<b>1.9</b>

**Table 3:** Material and energy-use results at different segmentation levels.

Note: EUI = energy-use intensity; MUI = material-use intensity.



**Figure 4:** Energy uses and energy supply in the Nigerian residential building stock, 2020.

Annual energy use amounted to 98 TWh in 2020, which is 17 kWh/m<sup>2</sup>/yr of useful floor area (UFA), or 2404 kWh per dwelling. At the typology level, apartments and bungalows use more energy than other dwelling types (Table 3), while mud houses use the least energy per dwelling. Figure 4 shows that most of the energy used in Nigerian residential dwellings is for lighting. Cooling and equipment cumulatively account for only 49% of the average national energy use. The most important energy carrier is on-grid electricity (Figure 4) based on a mix of 74.5% natural gas and 25.5% hydro (Ecoinvent 2023; IEA 2024), while the off-grid electricity is diesel-based.

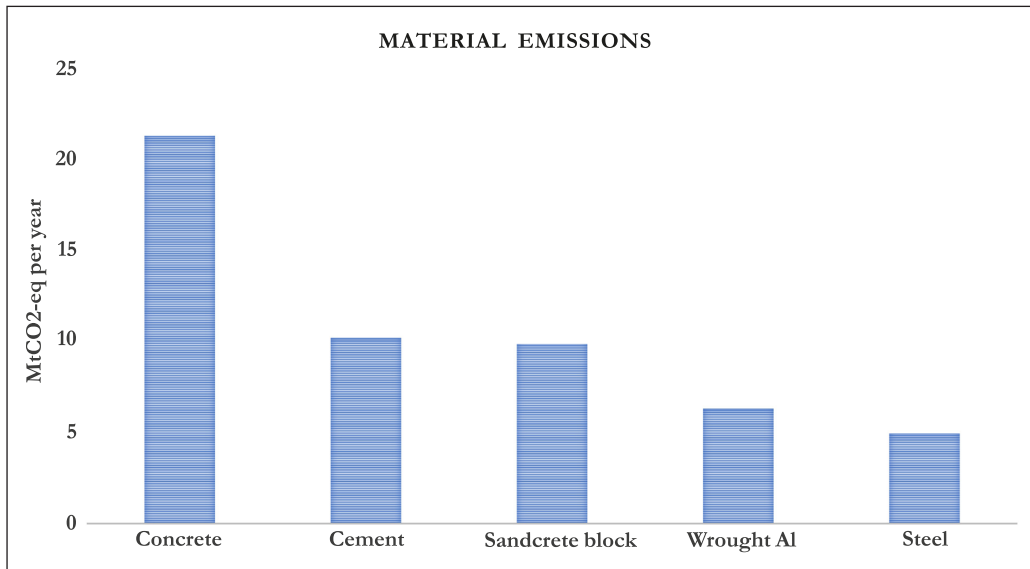
### 3.2 LIFE-CYCLE ASSESSMENT (LCA)

The LCA results show that around 6 GtCO<sub>2</sub>-eq will be emitted from Nigeria's 2020 residential dwellings stock over its entire lifetime. On average, material-related emissions are 1.4 tCO<sub>2</sub>-eq/yr per dwelling and operational emissions are 1.3 tCO<sub>2</sub>-eq/yr per dwelling.

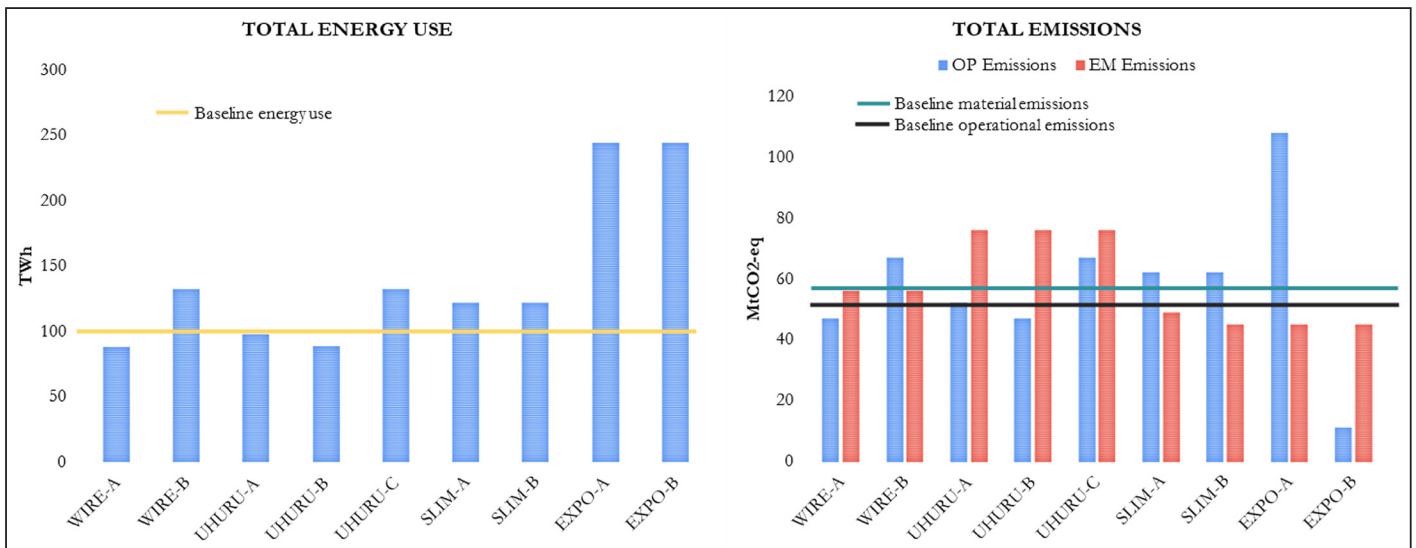
Table 4 shows that bungalows contribute most to Nigeria's residential emissions, followed by compound houses. However, per dwelling, apartments have higher emissions than compound houses because of the high material use in apartments (mostly concrete and steel for beams, shears and structural elements). The results also show that while compound houses have much higher material-related emissions than improvised dwellings, they have almost the same operational emissions. Table 4 also shows that informal dwellings contribute most to total emissions. Newly constructed dwellings have higher emissions per dwelling unit than pre-2017 dwellings, although, overall, pre-2017 dwellings contribute > 70% of residential emissions. The top five materials contributing to material-related emissions are concrete, cement, sandcrete block, aluminium and steel (Figure 5).

	TOTAL OPERATIONAL EMISSIONS (MtCO <sub>2</sub> -eq/yr)	TOTAL MATERIAL EMISSIONS (MtCO <sub>2</sub> -eq/yr)	SPECIFIC OPERATIONAL EMISSIONS (kgCO <sub>2</sub> -eq/yr per dwelling)	SPECIFIC MATERIAL EMISSIONS (kgCO <sub>2</sub> -eq/yr per dwelling)	SPECIFIC EMISSIONS (kgCO <sub>2</sub> -eq/yr per dwelling)
<b>Typologies</b>					
Apartment	6	9	1,376	1,903	3,279
Bungalow	23	30	1,763	2,237	4,000
Compound	20	16	1,185	987	2,172
Improvised	0.2	0.1	1,240	462	1,702
Mud	2	0.8	359	129	488
<b>Wealth</b>					
Formal	21	19	2,453	2,166	4,618
Informal	31	37	955	1,153	2,108
<b>Time cohort</b>					
Pre-2017	35	40	1,150	1,307	2,458
Post-2017	17	16	1,634	1,547	3,181
<b>Climate zone</b>					
Zone 1	17	18	1,382	1,478	2,860
Zone 2	24	26	1,270	1,363	2,632
Zone 3	9	10	1,127	1,220	2,347
Zone 4	2	2	1,142	1,283	2,425
<b>Settlement</b>					
Rural	10	24	552	1,319	1,872
Urban	42	32	1,852	1,406	3,258
<b>National</b>					
Totals	52	56	1,272	1,367	2,639

**Table 4:** Emissions at different segmentation levels.



**Figure 5:** Annualised greenhouse gas (GHG) emissions for the materials used in Nigeria's residential building stock, 2020.



### 3.3 SCENARIOS

The results of the four scenarios show how different intervention measures might have influenced 2020's energy use and carbon emissions. Figure 6 shows clearly that most interventions have higher energy use compared with the baseline, especially in scenarios where all dwellings have 100% access to electricity. This is despite a higher share of CFLs in use. The same trend is observed in UHURU scenarios where 50% of dwellings comply with the 2016 regulations without additional intervention measures. Energy savings of 10% from baseline are seen in WIRE-A, which is a scenario where 70% of the dwellings switch to CFL, but low electricity access and substandard housing persist. Energy savings of 9% from baseline are also seen in UHURU-B when the switch to CFLs is matched with 50% of dwellings complying with existing regulations while electricity access remains low. The SLIM-A and SLIM-B scenarios, which build on the WIRE-B scenario, but with the additional switch from sandcrete block walls and metal roofs to clay walls and thatched roofs, use 24% more energy than the baseline. The high increase in operational energy use for EXPO scenarios is because no blackouts are experienced as on-grid electricity access is assumed for 24 h all year round, unlike in other scenarios.

The results given in Figure 6 show the same trend for operational emissions across all scenarios, except for the EXPO-B scenario where on-grid electricity comes mostly from renewables. This scenario yields a reduction of 48% from the baseline (operational and material-related) emissions

**Figure 6:** Energy use and total emissions compared with the baseline for different interventions.

results for 2020 and surpasses the target of 33 MtCO<sub>2</sub>-eq/yr of operational emissions. Although the SLIM and EXPO-A scenarios led to a reduction in material-related emissions, their high operational emissions due to 100% electricity access minimised the overall impacts.

## 4. DISCUSSION

Limited attention to buildings in Nigeria and the fact that both construction and fuel provision are often part of the informal economy has affected this work due to a shortage of public statistics. This is not unique to this work but a common limitation of bottom-up models, as explained by Kavajic *et al.* (2010). Here the present paper compares the results with other literature values to check their plausibility and give some overview of the range of values.

### 4.1 MATERIAL USE

At the national level, the results show that the 41 million residential dwellings in Nigeria in 2020 used about 11 Gt of material, translating to about 0.3 kt per dwelling (or 1.9 t/m<sup>2</sup>) material use. According to Heeren & Fishman (2019), material intensity typically fluctuates around a magnitude of 1 t/m<sup>2</sup>. Another study on residential dwellings in Kuwait showed that material quantities were in the range of 0.5 and nearly 3.0 t/m<sup>2</sup> (De Wolf 2014). Krause and Hafner's work on residential dwellings in Germany put the material intensities between 0.61 and 1.96 t/m<sup>2</sup>, depending on the typology (Krause & Hafner 2022), further supporting the fact that multifamily dwellings (such as apartments and compounds in this study) use the most material by mass/m<sup>2</sup>, but that bungalows use more material by mass overall because they are often bigger. Krause and Hafner also show that wooden dwellings (such as improvised dwellings in this work) use around 0.6 t/m<sup>2</sup>. The above literature sources place the result of this study (1.9 t/m<sup>2</sup>) at the higher end of the range. UNEP (2022) also conforms with this work's results in Figure 3 as it identifies cement (used in concrete and sandcrete block) as the major material contributing to urban material use. Unlike the UNEP estimate and similar to the results of De Wolf (2014) and Akin *et al.* (2023), the use of steel is low for Nigerian residential dwellings since most of the dwellings are not made to have load-bearing properties, except for apartments.

### 4.2 ENERGY USE

The UN Energy Balance puts Nigerian residential energy use at about 200 kWh/m<sup>2</sup> in 2020 (UN 2023), while this work's model results give 17 kWh/m<sup>2</sup> in 2020. The variation in the result may be due to the study's exclusion of cooking loads, which represent nearly 97% of the UN's (2023) reported value. For operational energy use by an average residential dwelling of 120 m<sup>2</sup>, Ezema & Okorigba (2022) reported 14,379 kWh/yr with 24% on-grid supply. This work's results show around 2404 kWh/yr per dwelling. This difference is perhaps due to this study's assumption of only about 35% electricity access, 70% on-grid supply and blackouts for 12 h/day. Using consumption surveys in Khulna, the third largest city of Bangladesh, which has a relatively similar GDP to Nigeria, Rahman *et al.* (2017) found that the monthly electrical energy use in residential dwellings in 2017 was between 234 and 340 kWh depending on the number of rooms. This is equivalent to between 2808 and 4080 kWh/yr per dwelling, placing the results of this work within a plausible range.

### 4.3 ENVIRONMENTAL ASSESSMENT

The LCA by Ezema & Okorigba (2022) showed the high contribution of cement and steel in material-related energy and emissions. From Figure 5, the same trend is observed because concrete and sandcrete blocks are cement products. Steel is also a high contributor after aluminium, only because aluminium has a 10 times higher emission factor in the Ecoinvent database (from Figure 3, 18 Mt of aluminium are used in the entire stock compared with 90 Mt for steel). Unlike in Ezema & Okorigba's work, where operational emissions were three times more than the material-related emissions, operational emissions were nearly equal to the material-related emissions in this study. De Wolf (2014) equally found that, on average, residential buildings' materials typically emit between 250 and 700 kgCO<sub>2</sub>/m<sup>2</sup> for the lifetime of the building. This validates this work's

results of 477 kgCO<sub>2</sub>-eq/m<sup>2</sup> material-related emissions over the 50-year lifetime. Additionally, since post-2017 dwellings emit more than those built before the energy standards, this means that if households continue to build as they do (based on wealth and aesthetics), the emissions are bound to be much higher in future.

#### 4.4 SCENARIOS

The WIRE-A scenario, for instance, clearly shows how great an impact switching from incandescent to CFL bulbs is on energy savings and carbon emissions as it leads to 10% and 5% reductions, respectively, without the switch to renewable (on- or off-grid) power sources. All UHURU combinations (high GDP per capita and electricity access) cause higher emissions than the baseline. This shows that current low residential operational emissions in Nigeria are the result of low electricity access and energy poverty seen from high unmet energy needs. Hence, since Nigeria has a high energy use per unit of GDP compared with other countries (Kwag et al. 2019), combining the UHURU scenario of higher formal dwelling types with energy efficiency measures in lighting (UHURU-B) yields lower emissions than having a higher share of formal dwellings without these energy efficiency measures (UHURU-A).

The SLIM and EXPO scenarios, which involve replacing sandcrete walls with clay and metal roofs with thatch, perform better than the other scenarios in terms of material emissions. However, due to the increase in electricity access in these scenarios, the operational emissions are higher than the baseline. This confirms the World Bank's and UNEP's claims that Africa stands an excellent chance at sustainable construction using low-carbon local materials such as clay. Indeed, the results prove that erecting buildings using mineral materials such as concrete is the primary cause of the high material-related emissions in Nigeria. Nnimmo Bassey's theory (Bassey 1996/97, as cited in Nwalusi et al. 2019) that thatched roofs help to increase thermal comfort was inconclusive as the inclusion of thatched roofs in the SLIM scenario had very little visible effect on energy use, but more on emissions. This disparity might be because additional layers of wooden struts were added to the model's thatched roofs in keeping with recent building styles. On the other hand, the statement by Onyenokporo & Ochedi (2018) that the building's envelope design can reduce energy use was proven to be correct. This is because replacing sandcrete blocks with clay led to a reduction in energy use and operational emissions as well compared with the WIRE-B and UHURU-C scenarios which share similar interventions.

The final scenario, EXPO, being the only scenario where the country's emissions reduction targets are reached, proves that there is no single solution to the energy and emissions crises, but that combining different strategies is more effective. The difference between EXPO-A and EXPO-B further shows that although Nigeria's target of 26% on-grid renewable electricity is helpful in some ways, if all households have access to on-grid electricity without blackouts, then emissions will stay high. Therefore, given the country's abundant access to renewable energy (hydropower, solar, wind), achieving EXPO-B with about 58% renewables in the electricity grid as in Sweden (Swedish Energy Agency 2019) should be a reference guide sheet. Overall, the results show that an increase in the on-grid transmission capacity, 26% renewables share and 100% electricity access, without changing the existing energy use patterns, will worsen the emissions compared with the baseline unless significantly high amount of renewables are deployed.

#### 4.5 LIMITATIONS AND FUTURE WORK

The following uncertainties posed a limitation to this study. Due to poor or unavailable government data, the study relied upon tables, texts and graphs from literature sources. The module B2–B5 phases of the LCA were excluded from this study, but despite these omissions, the authors have high confidence in the LCA results based on the other phases included. The authors noted the limitations of assessing only one impact category on trade-offs, but continued with this to remain within the scope of the study. Future research can extend this to more impact categories and to the endpoint level of aggregation. The study excluded cooking from the operational energy calculations, which means that most of the residential energy and emissions from that activity are omitted. However, to reduce the uncertainty in the model results, the analysis proceeded without them.

Future studies can extend the WIRE scenario to see how great an impact turning off lights when not in use might have on energy emissions. The research community would also benefit from a cost-effectiveness analysis of all outlined scenarios and the baseline to test the feasibility of individual households making these switches given the current minimum wage. This is in line with previous studies that stated that the climate and energy transition would be faster at the individual household level (Emodi *et al.* 2017; Kwag *et al.* 2019).

## 5. CONCLUSIONS

Nigeria's residential dwellings stock is large, heterogeneous and growing, but many housing demands are not met considering the overall population. Comprising different typologies with features that are unique to the country, the residential stock is also mostly informal with high data sparsity and uncertainties. This influences national-scale modelling and requires the use of ratios, databases, assumptions and local context. Based on the validation using different previous studies, the models defined here correctly estimate the energy and material use of the average Nigerian residential dwelling. Considering the country's overall high energy use relative to its gross domestic product (GDP), residential energy use is low in this study because of low access to electricity and frequent blackouts. Excluding cooking in this study revealed the high impact lighting loads have on energy use in Nigeria's residential dwellings. Material use is high as cement and cement-based materials are the main contributors to material use and emissions in the stock. Energy efficiency by households and the switch to renewables were found to be very effective for energy and emissions savings.

To meet Nigeria's nationally determined contribution (NDC) of a 20% reduction in CO<sub>2</sub> emissions, it is recommended that a policy switch is made to low-carbon materials such as timber, earthen blocks, adobe bricks and clay. A huge reduction in construction-related emissions was shown in the switch from sandcrete block to clay.

The scenarios developed in this study have far-reaching benefits beyond energy and climate change as they can improve the quality of life of households in Nigeria. The potential for lock-in is also seen as newly constructed dwellings emit more than the older ones, meaning stakeholders have to act quickly and smartly as they build more to match prevailing housing needs.

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CCN, SA and EGH: conception and design. CCN: data collection, analysis and interpretation. SA: supported the analysis and interpretation. EGH: supported the results interpretation and discussion and critically revised the article.

## COMPETING INTERESTS

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

## DATA ACCESSIBILITY

Additional data can be accessed on Zenodo (Nwagwu *et al.* 2024). Data sheets for emissions calculations are not included in the supplementary data due to non-disclosure agreements around database values. However, these data sheets are available upon request.

Ethical review and approval were not required for this study following the national legislation and the institutional requirements.

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## SUPPLEMENTAL DATA

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