

SUPPLEMENTAL DATA

1.1 Model Development

The typology, referring to the types of dwellings concerning geometry and function is a key driver of the model because every other driver is dependent on it. The study obtained information about the typology from the National Bureau of Statistics in its 2011 annual abstract (National Bureau of Statistics, 2011) and the Living Standards Survey of 2018/19 (National Bureau of Statistics, 2020). However, based on available information from multiple literature sources and the Living Standards Survey, the buildings are re-categorized as presented in the system diagram below. This decision is in line with the fact that the Living Standard Survey and literature sources relied upon are more recent and show current trends of building categorization confirmed upon discussion with local experts consulted.

Lifestyle (FApC) is obtained based on information on Population (P), People per Dwelling (PpD), Number of Dwellings, and Usable Floor Area per Dwelling (UFAPD). Technology refers to how different forms of energy are used in the dwellings for appliances, lighting, cooling, cooking, and other energy-consuming activities, and the intensity related to these energy uses. Experts believe that energy standards brought by policymakers equally influence technology use in formal dwellings. Only one energy standard was found to be in existence in Nigeria, and this is the Building Energy Efficiency Code (BEEC) introduced in 2016 (Federal Ministry of Power, Works, and Housing, 2017).

1.2 Model Input and Data Collection

1.2.1 Climate Zones

Since most Nigeria-related statistics are done based on geopolitical zones, it was necessary to regroup the different states according to the climate zone mapping as presented by a British Geological Survey conducted in 2019 (MediaWiki, 2019) as shown in Figure S1. To do the reclassification of the states, the map of Nigeria showing the states and geopolitical zones presented below was overlaid on the climate zone map.

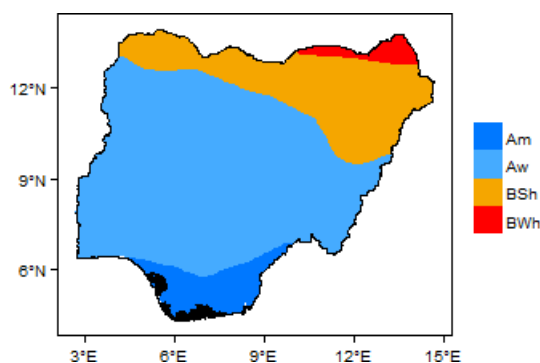


Figure S1: Climate Zone map (MediaWiki, 2019)

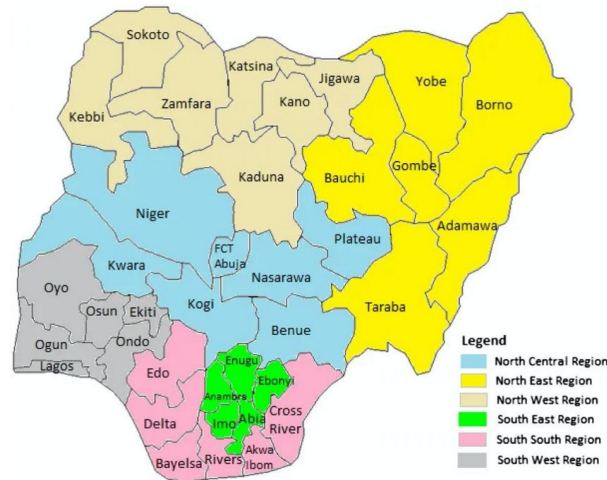


Figure S2: Nigerian States by Geopolitical Zones (Nigeria maps, 2022)

1.2.2 People per Dwelling (PpD)

Due to the uneven distribution of the population and differences in cultures, the number of people per dwelling (PpD) differs for the different geo-political zones. The 2016 data on the PpD was unavailable, so the 2015 data from statistics (National Bureau of Statistics, 2016) was used. Since the other data used for this work are not categorized according to geopolitical zones, but climate zones, the PpD was reclassified for the different typologies and climate zones.

1.2.3 Usable Floor Area

The usable floor area (UFA) in this work refers to the total floor area of the living space in the dwelling. Data from Exposure Database and floor plans from local experts were used as a reference to avoid overstating or understating the real values. The UFA per dwelling (UFAPD) is obtained from verified scientific literature and real estate/property websites for validation.

1.2.4 Dwelling Stock

The study used stock data for 2016 and 2020 alone, each obtained using different methods.

2016 Stock Data:

To obtain the 2016 dwelling stock total, the population of each state in Nigeria in 2016 from statistics (National Bureau of Statistics, 2019), and the 2015 PpD of each state (after adjusting for an estimated increase in the Southern states) (National Bureau of Statistics, 2016) were used.

$$2016 \text{ Stock} = \frac{2016 \text{ Population}}{2015 \text{ PpD}}$$

2020 Stock Data:

For 2020, household size data or dwelling stock data from statistics was not found. Therefore, available 2020 Geographical Information System (GIS) map data from the Exposure Database (Paul et al., 2022) was utilized instead. These maps were originally designed to assess earthquake risks for different countries, including Nigeria. Data from Exposure Database was, however, not presented in the form required for this study. While the database presented the building stock data in a table and pre-segmented into rural and urban agglomerations, it did not clearly define the building type. To solve this, data on the floor area and the number of storeys which was available were used to classify buildings into Traditional, Bungalow, and Apartments in the following order:

$< 75m^2$ and single-storey = Traditional houses

$75 - 89m^2$ and multiple storey = Apartments

$> 89m^2$ and single-storey = Bungalows

After this classification, the study obtained the number of dwellings for each state categorized into the dwelling types mentioned and rural/urban settlements. To fully understand the categorization, the study proceeded to understand the dwelling types as a share of the total. With this, it was easy to see that the

fraction of dwellings in each state were bungalows, apartments, or traditional houses. It was also easy to validate these results with available average numbers of the shares of different buildings in Nigeria reported by the NBS in 2019 through the Living Standards Survey (LSS) (National Bureau of Statistics, 2020).

The fractions from the Exposure Database and LSS were found to match for traditional dwellings, but the fractions for apartments and bungalows were quite different. Also, after speaking with local experts on the two fractions obtained, it was concluded that the LSS fractions represent the reality and that perhaps Exposure Database fractions understate the fraction of apartments and overstate the number of bungalows. This discovery may not be unconnected with the fact that some apartments are larger than $89m^2$, contrary to the earlier assumption. To solve this issue, the shares of apartments in the different states were increased to achieve the average share in the LSS report. The share of bungalows was reduced in the same manner. The traditional houses were then divided into mud houses and compound houses based on further categorization from the LSS report. The fraction of informal dwellings was obtained from mass balance after upscaling apartments and downscaling bungalows to the LSS data.

Afterward, the Exposure Database rural/urban fractions on the new dwelling shares were used to split the total dwelling stock of different states and obtained the actual number of rural/urban apartments, mud houses, bungalows, compound houses, and improvised settlements for 2020.

1.2.5 Cohort Split

The term cohort in this study refers to the period of construction of dwellings. As described in the model definition, the cohorts are based on the available standards in Nigeria. In this case, only one energy efficiency code approved in 2016 is known and used in the country (Federal Ministry of Power, Works, and Housing, 2017) as seen in Figure S3. This information means that the dwelling stock has two time cohorts: Pre-2017 and Post-2017. Pre-2017 dwellings are those constructed before the approval of the energy code, while Post-2017 are those constructed afterwards. To determine the number of dwellings in the Post-2017 time cohorts, the number of dwellings in 2016 is subtracted from the total number of dwellings in 2020. This approach is premised on the assumption that the difference represents the number of new dwellings in the stated period from 2016 to 2020. Unfortunately, this assumption fails to account for demolition and other stock removals or additions, but a different approach was not feasible due to a lack of demolition data.

In summary, for all states and settlement categories:

Pre-2017 cohort = Total stock in 2016

Post-2017 cohort = Total stock in 2020 – Total stock in 2016

NATIONAL BUILDING ENERGY EFFICIENCY CODE

Table 1 Star rating for energy efficiency label

Rating	Intervention	Minimum Specification
1 star	Window to Wall Ratio or shading	20% maximum and/or shading as per BEEC Calculator
2 star	Window to Wall Ratio or shading	20% maximum and/or shading as per BEEC Calculator
	Lighting - Residential	Maximum lighting power density 6 W/m ²
3 star	Lighting - Office	Maximum lighting power density 8 W/m ²
	Window to Wall Ratio or shading	20% maximum and/or shading as per BEEC Calculator
	Lighting – Residential	Maximum lighting power density 6 W/m ²
	Lighting - Office	Maximum lighting power density 8 W/m ²
4 star	Roof insulation	Minimum R-value 1.25 m ² K/W
	Window to Wall Ratio or shading	20% maximum and/or shading as per BEEC Calculator
	Lighting - Residential	Maximum lighting power density 6 W/m ²
	Lighting - Office	Maximum lighting power density 8 W/m ²
	Roof insulation	Minimum R-value 1.25 m ² K/W
	Air-conditioning minimum performance ¹⁾	Minimum EER/COP 2.8 and Inverter Compressor
5 star	On application only. This allows for taking into account renewable energy systems (Photovoltaic, Solar water heating) which are currently outside BEEC.	

¹⁾ Only if air-conditioning is necessary.

Figure S3: 2016 Building Energy Regulation (Federal Ministry of Power, Works, and Housing, 2017)

1.2.6 Type split

Bungalow: These are dwellings with a single storey, typically built with concrete blocks. They have different forms of architecture, but most times, they require a large land area because they extend outwards and, in some cases, have some open spaces for leisure and outdoor relaxation. In many parts of Nigeria, these buildings are owner-occupied single-family dwellings fenced around for security. (Adaji et al., 2017; Ibem et al., 2015; E. T. Ochedi & Taki, 2022; E. Ochedi & Taki, 2019)



Figure S4: (a) Fenced Bungalow (Ibem et al., 2015) (b) Unfenced Bungalow (E. T. Ochedi & Taki, 2022)

Apartment Blocks: Apartment blocks are multi-family housing types with two storeys or more and many different living units assigned for domestic use-function. This type is typically not owner-occupied, but a single family or household rents rooms within the apartment. It has common areas like outdoor space and a garage. In many informal apartments, a group of flats may share bathrooms and toilets. It requires less land area to build

since it extends vertically, and the floor area is less than bungalows in many cases. Due to urbanization and erosion, these house types have gained popularity in the real estate market. Like the bungalows, they may be fenced or unfenced, depending on the owner’s preference and costs. (Ezema et al., 2016; D. M. Nwalusi et al., 2022; Olusegun et al., 2020)



Figure S5: (a) Fenced Apartment (D. M. Nwalusi et al., 2022) (b) Unfenced Apartment (Olusegun et al., 2020)

Mud House: Mud houses are traditional Nigerian houses built using natural materials like laterite mud, straw, stones, wood, palm fronds, grasses, and other materials in the respective regions. As a result, it is considered the cheapest housing unit due to the availability and cost of these materials. It is typically owner-occupied and can be single-family or multi-family dwellings built beside each other like detached bungalows. In these houses, the kitchen, bathroom, storage, and toilet are excluded and built as separate buildings within the area demarcated for the family, usually marked using palm fronds (as a fence). Most of these building types are considered informal and are more present in rural areas today. In rural areas, modern forms of these buildings have been introduced, using zinc roofing sheets. (D. Nwalusi et al., 2019; Oladigbolu et al., n.d.; Orumu & Yabefa, 2018)



Figure S6: (a) Mud house (D. Nwalusi et al., 2019) (b) Mud house (Oladigbolu et al., n.d.)

Compound House: The term “face me I face you” or “face me I slap you” is often used to refer to these dwellings in local parlance. However, according to global building designs, these are similar to row houses in that a single-family dwelling shares at least a wall with another single-family dwelling. The term “face me I face you” is used as a direct reference to the fact that the entrance of one residence usually faces that of another, with a passageway separating them and leading to the main entrance. In theory, this has similar features to an apartment as described above except that, unlike apartments, these are usually a single storey and use more land area. The toilets, bathrooms, and kitchens are mostly shared and dedicated to single zones along the row.

They can also be at the end of the passageway connecting the different rows. It can be that the rows have a single roof or each with a separate roof, depending on the homeowner's preference. This type of dwelling is found in very dense areas and is mostly informal. Formal types are often called self-contained compound houses because the kitchen, toilet, and bathrooms are set within each single-family unit.



Figure S7: (a) Typical Compound House with Single Roof (Nairaland Photos, 2021) (b) Typical Compound House with Separate Roofs (Badejoko, 2020)

Improved Settlements: Different types of improved settlements are springing up in many parts of Nigeria. This change is due to poverty, urbanization, and poor housing programs by the government. One of these is the timber houses, very synonymous with shanties in the coastal areas. These houses are elevated on wooden stilts supported at the base by stones or clay and zinc roofing sheets for the top cover. Most timber dwellings being just a single storey, are typically for single-family occupation and may be owner or tenant occupied.



Figure S8: Typical Improved House with Timber (Etomi, 2012)

1.2.7 Settlement Categorization

This study categorizes the dwelling stock first into the climate zones based on the respective states. Then it further categorizes the stock based on settlement type - rural or urban. In Nigeria, a rural settlement is a settlement with less than 20,000 inhabitants, according to the 1991 census. Having no other definition from an official source, this work adopts the definition of the 1991 census.

1.2.8 Wealth Categorization

To further categorize the dwelling stock, the study uses informal/formal categorization as an added layer of detail to the time cohorts. This step accounts for the actual number of dwellings built following the set standard. According to a 2018 assessment of compliance with building regulations in Ogun state, Nigeria, only about 26% of the buildings complied with basic building regulations regarding town planning (SODIYA & OKUBENA, 2018). Also, according to the 2020 household survey report of Lagos State, while 66% of households claimed to have their building plans approved by the government, only about 40% of these households actually built according to the approved plans (Lagos Bureau of Statistics, 2020). This finding means that only 26% of the households

were built according to approved building standards.

With this information, the following definitions for the different time cohorts are provided:

Pre-2017 cohort:

- Formal: These refer to buildings that are built in compliance with extant town planning regulations relating to distance from drainage, distance from the main road, setback from the wall fence, building coverage, ventilation, and plot size (SODIYA & OKUBENA, 2018).
- Informal: These refer to buildings not meeting the above criteria by town planning law.

Post-2017 cohort:

- Formal: These refer to buildings that are built in compliance with extant town planning regulations relating to distance from drainage, distance from the main road, setback from the wall fence, building coverage, ventilation, and plot size (SODIYA & OKUBENA, 2018). In addition, these buildings meet the 2016 energy efficiency requirements relating to roof insulation, lighting density, and shading (Federal Ministry of Power, Works, and Housing, 2017).
- Informal: These refer to buildings not meeting the above criteria by town planning law and/or energy efficiency body.

1.2.9 Access to Electricity

In the baseline model, the data on access to electricity from the Nigeria Living Standards Survey (LSS) of 2018-2019 (National Bureau of Statistics, 2020) are used together with data from World Bank Global Electrification Database (World Bank, 2020).

Urban:

91.6% of 90.6% total electricity access in 2018 = 82.99% on-grid access in 2018 (LSS)

83.9% on-grid access in 2020 (World Bank) = $83.9 / 91.6\% = 91.6\%$ total electricity access in 2020

Rural:

70% of 46% total electricity access in 2018 = 32.2% on-grid access in 2018 (LSS)

24.6% on-grid access in 2020 (World Bank) = $24.6 / 70\% = 35.14\%$ total electricity access in 2020

It should be noted that total access to electricity in this report includes on-grid, mini-grid, generators, solar systems, inverters, and all other sources as indicated in the LSS report. For lack of more recent ratios, the share of on-grid electricity in the total electricity use is the same in 2018 and 2020.

1.3 Supplementary Material Regarding Life Cycle Assessment

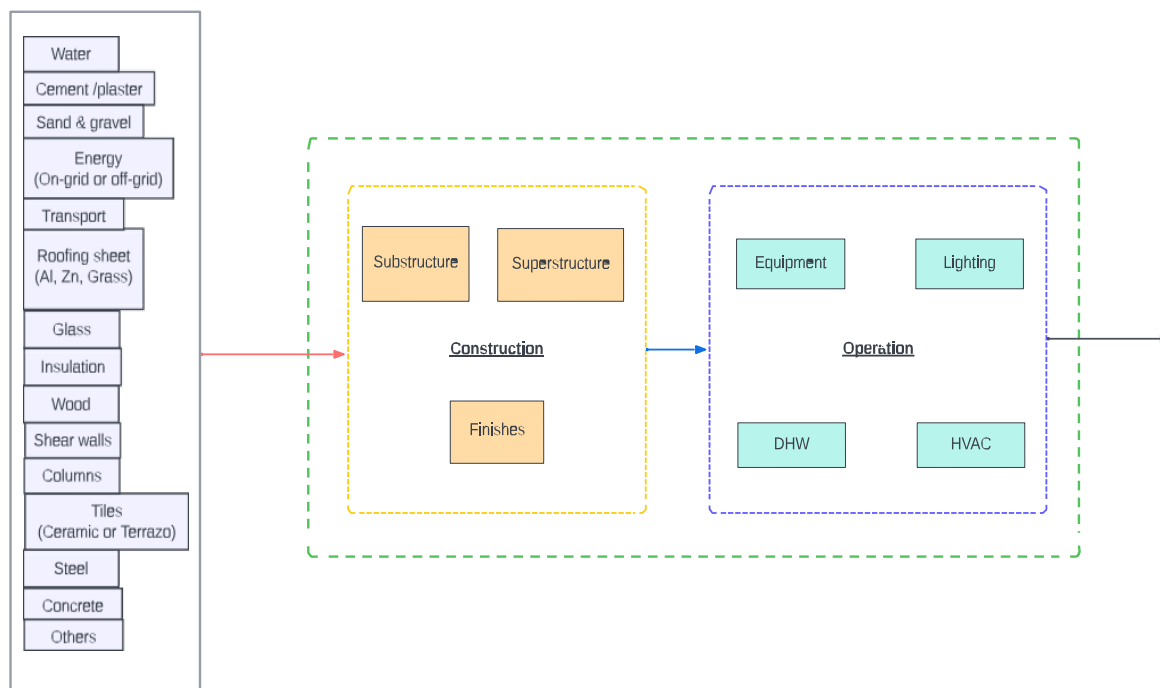


Figure S9: Simplified Life Cycle Assessment Flowchart

1.3.1 Operational Energy Use Inventory

Electricity generated, however, depends on the heat content of the fuel and the efficiency or heat rate of the generator. Using the US Energy Information Administration (EIA) energy conversion factors (1 L is equivalent to 34 MJ; 3.6 MJ is equivalent to 1 kWh) (Olaniyan et al., 2018)

Table S1: Parameters used for energy use calculations

Parameter	Source
Share of Generator Used	(National Bureau of Statistics, 2020)
Energy Conversion (MJ to kWh)	(U.S. Energy Information Administration, 2023)
Generator Type	(Ezema et al., 2016)
Generator Efficiency	(China, 2023)
Generator Fuel Consumption rate	(China, 2023)
Density of Gasoline	(Onyinye & Nkechi, 2015)
Days in a year	Standard leap year

1.3.2 Supplementary Information on Energy-related Emissions Calculations

Table S2: Energy-related emissions calculations

Parameter	Formula	Eqn No.
kWh on-grid electricity	% on-grid access * kWh electricity	(i)
Emissions from on-grid electricity	(i) * ecoinvent emission factor for Nigeria electricity mix	(ii)

kWh off-grid electricity	(1 - % on-grid access) * kWh electricity	(iii)
Number of hours of running gasoline generating set	(iii) / 2.4	(iv)
Number of hours per day	(iv) / 366	(v)
Litres of gasoline needed	(v) * 1.38	(vi)
Kg of gasoline needed	(vi) * 0.7436	(vii)
Emissions from off-grid electricity	(vii) * ecoinvent emission factor for gasoline	(viii)

where: 2.4 in (iv) is 2.4kW based on 80% efficiency of a 3 kVA generator which is the most used type in the country; 1.38 in (vi) is the fuel consumption rate of a 3 kVA generator; and 0.7436 in (vii) is the density of gasoline.

1.3.3 Material Life Cycle Inventory

Table S3: List of sources for material use conversion to carbon emissions

Name in project	Ecoinvent search name	Ecoinvent unit	GWP100 Value in kgCO ₂ /unit	Source
Cement	market for cement, Portland - ZA - cement, Portland	kg	Confidential	(Muigai & Pradhan, 2017)
Sandcrete block	market for lightweight concrete block, expanded clay, RoW	kg	Confidential	(Bourgault, 2011a)
Wood	market for slab and siding, hardwood, wet, measured as dry mass, RoW	kg	Confidential	(Bauer, 2007)
Glass	market for flat glass, uncoated - RoW - flat glass, uncoated	kg	Confidential	(Bourgault, 2011a)
Concrete	market for concrete, 30MPa - ZA - concrete, 30MPa	m ³	Confidential	(Muigai & Pradhan, 2017)
Stone wool	market for stone wool - GLO - stone wool	kg	Confidential	(Bourgault, 2011b)
Sand	market for sand - RoW - sand	kg	Confidential	(Undefined, 2011f)
Wrought Al	market for aluminium, wrought alloy - GLO - aluminium, wrought alloy	kg	Confidential	(Bourgault, 2011c)
Stone	market for natural stone plate, cut - GLO - natural stone plate, cut	kg	Confidential	(Undefined, 2011g)
Clay	market for clay, RoW	kg	Confidential	(Undefined, 2011c)
Cast Iron	market for cast iron - GLO - cast iron	kg	Confidential	(Undefined, 2011a)
Grass	market for straw - RoW - straw	kg	Confidential	(Undefined, 2011i)
Tiles	market for ceramic tile - GLO - ceramic tile	kg	Confidential	(Undefined, 2011b)
Steel	market for reinforcing steel - GLO - reinforcing steel	kg	Confidential	(Undefined, 2011h)
Gravel	market for gravel, crushed - RoW - gravel, crushed	kg	Confidential	(Undefined, 2011d)
Electricity (NG)	market for electricity, low voltage - NG - electricity, low voltage	kWh	Confidential	(Itten & Frischknecht, 2012b)
Electricity (HR)	market for electricity, low voltage - HR - electricity, low voltage	kWh	Confidential	(Itten & Frischknecht, 2012a)
Petrol	market for petrol, low-sulphur - RoW - petrol, low-sulphur	kg	Confidential	(Undefined, 2011e)

NOTE: Concrete was given in m³ but using the density (based on dry mass) of concrete as 2285kg, it was converted to kg. This is because the model results for concrete were available in kg

1.4 Supplementary Material Regarding Scenario Development

1.4.1 Scenario 1: WIRE

A - CFL bulbs replace 70% of the incandescent bulbs: Here, the ban on incandescent bulbs in Nigeria was assumed to be supported by awareness and incentives and could lead to up to 70% switching to compact fluorescent lamps from incandescent bulbs. This is in line with a proposed scenario and statistics from existing literature (Emodi et al., 2017; Hussaini, 2013).

B - 100% electricity access: Different projections support the claim that electricity access will likely increase and reach 100% for urban and rural areas by 2030-2040 (Dioha & Kumar, 2020). The government in its Vision 2020 program also planned to reach an overall electrification rate of 75% (Kwag et al., 2019). Here, the effect of 100% electricity access in 2020 on the results is tested. As a result, the study assumes that the urbanization rate remains the same in this scenario since rural areas have equal opportunities for growth. The share of on-grid and off-grid electricity is retained to keep this assumption within a modest range. This is in addition to WIRE-A above.

1.4.2 Scenario 2: UHURU

A - 50% compliance to existing regulations: In this scenario of a near Utopian Nigeria with high GDP per capita, compliance to existing regulations is believed to rise from about 25% to 50% since households have more disposable income to meet them. This means that there are more formal types in terms of energy use but not in terms of floor area or geometry.

B – Increased lighting efficiency accompanies compliance: A blend of WIRE-A and UHURU-A above.

C - 100% electricity access: This adopts the same logic as WIRE-B and is merged with interventions in WIRE-A and UHURU-A.

1.4.3 Scenario 3: SLIM

A - Replace concrete blocks with clay: Concrete and sandcrete block use are suspected as being the main contributors to the construction-related emissions. In this measure, the single-storey residential dwelling types like compounds and bungalows which are material intensive are instead built using clay. Here, the assumption that given the established benefits of traditional dwellings, perhaps Nigeria never abandoned the use of clay as the primary material is adopted. In this measure, the roofs are assumed to be metal sheets, in keeping with the fashion as the only borrowed design technique. This is in addition to WIRE-B above.

B - Thatched roofs: Nnimmo Bassey as referenced by Nwalusi and colleagues discovered that Igbo traditional dwellings “breathe through their roofs which are porous to air and impervious to water”, providing easy airflow. With this, they proved the value of a continuous gentle breeze in achieving indoor thermal comfort because the difference between comfort and discomfort is often only 3°C (D. M. Nwalusi et al., 2022). Drawing from Nnimmo Bassey’s postulation that traditional dwellings breathe through the roofs, the study wishes to test how a switch of the roof type for compounds and bungalows to thatch roof impacts operational and construction-related emissions. This is in addition to SLIM-A above.

1.4.4 Scenario 4: EXPO

A - 100% on-grid electrification rate: Currently, 4.7% of dwellings use solar power as a backup while others use between 1-10ltrs a week on kerosene and/or 6-30ltrs for petrol (Hussaini, 2013). In this scenario, there is no need for a backup power supply since electricity from the grid is available for 24 hours each day. The justification for this is similar to what is stated in WIRE-B above and also supported by the fact that that is the case in Europe (World Bank, 2020) which is to be considered as a benchmark. Nigeria projects having renewables contributing about 26.7% to its on-grid electricity mix by 2025. The energy forecast for Africa postulates a 17% increase in solar energy capacity by 2040 in line with the stated policies scenario. Nigeria is expected to achieve 49% electricity generation by solar-powered technology by the year 2030 (Elinwa et al.,

2021). This vision is close to the share of renewables in the European electricity mix in 2015 (30%). Therefore, the study adopts Croatia which has 31% of its on-grid electricity from renewables (International Renewable Energy Agency, 2023) in this scenario.

B- On-grid electricity has more renewables: This is similar to EXPO-A above but with far more renewables in the energy mix up to the level in Sweden with about 58% renewables in electricity grid (Swedish Energy Agency, 2019).

1.5 Supplementary Material Regarding Archetype Development

1.5.1 Apartment Block

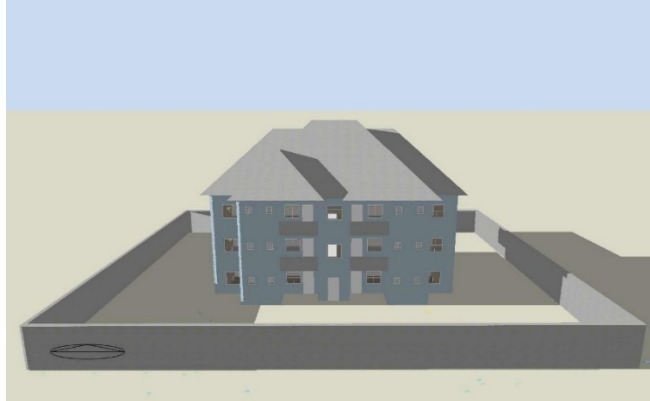


Figure S10: Typical Apartment Block (Axonometric View from Entrance)



Figure S11: Typical Apartment Block

As shown in Figure S10, the typical Nigerian apartment building has two floors of 3m height (Akande et al., 2015; Kwag et al., 2019), excluding the ground floor of the same height. Each floor has at least two flats, making a total of 6 flats in an apartment (Ezema et al., 2016). Depending on the wealth of the occupants, the size of a flat may be around 79 to 140 m^2 (Geissler et al., 2018; Onyenokporo & Ochedi, 2018).

1.5.2 Bungalow

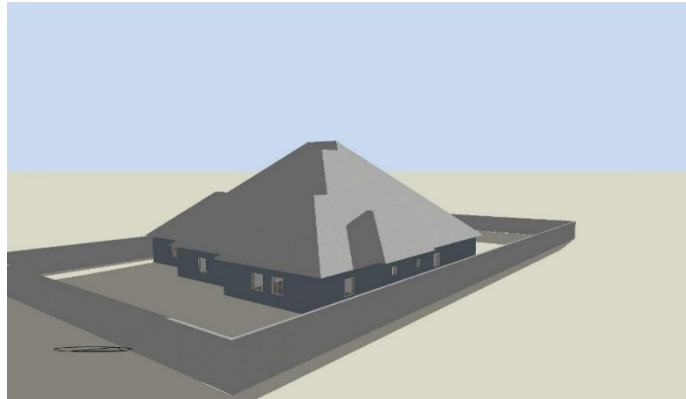


Figure S12: Typical Bungalow (Axonometric View from Side)

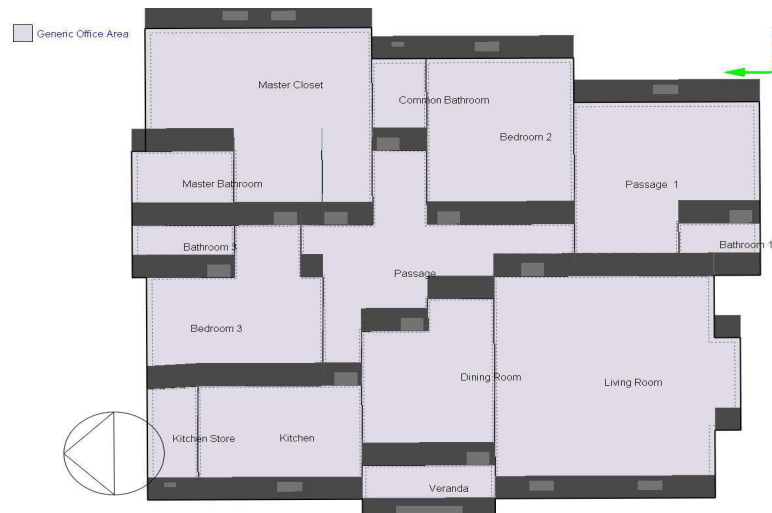


Figure S13: Typical Bungalow

As shown in Figure S12, the typical Nigerian bungalow is a single-floor dwelling of 3m in height. Unlike the apartment type, these buildings are often built with the focus on maximising the available land, hence, they are stretched with large areas.

1.5.3 Compound House

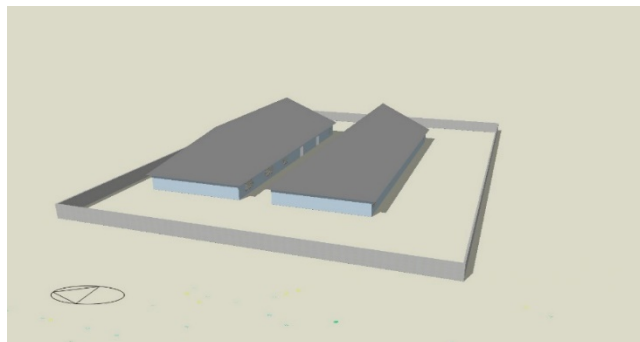


Figure S14: Typical Compound House (Axonometric View from Side)

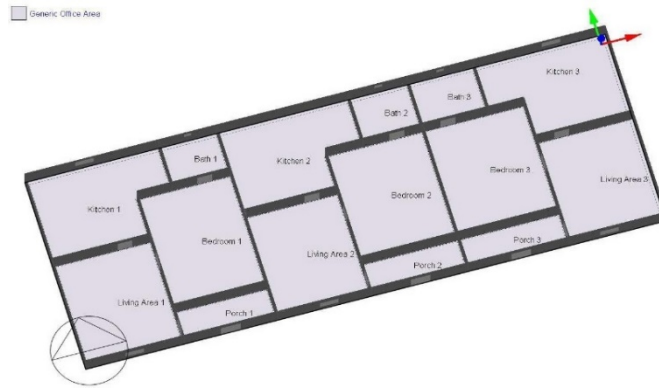


Figure S15: Typical Compound House

As shown in Figure S14, the typical Nigerian compound house has multiple buildings each with one floor of 3m in height. Each building within a compound has at least three flats. Depending on the wealth of the occupants, the size of a flat may be around 110 to 177 m^2 .

1.5.4 Improved Settlement

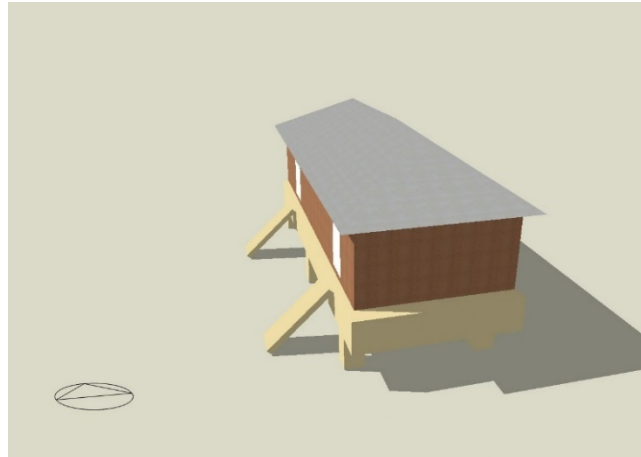


Figure S16: Typical Improved Settlement in Riverine Areas

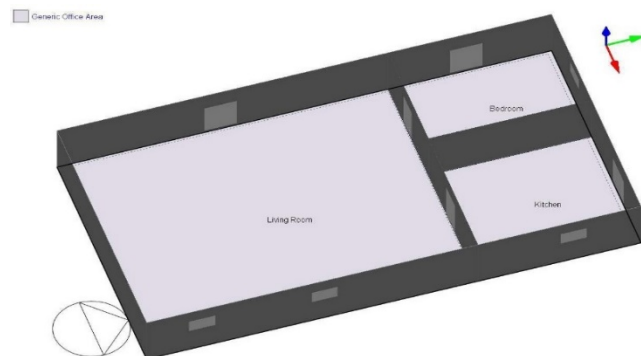


Figure S17: Typical Improved Settlement

As shown in Figure S16, the typical building in the riverine areas is built to stay afloat on the river and has one floor of 3m height. Each building of around 91 m^2 houses just one family.

1.5.5 Mud House (Hut)

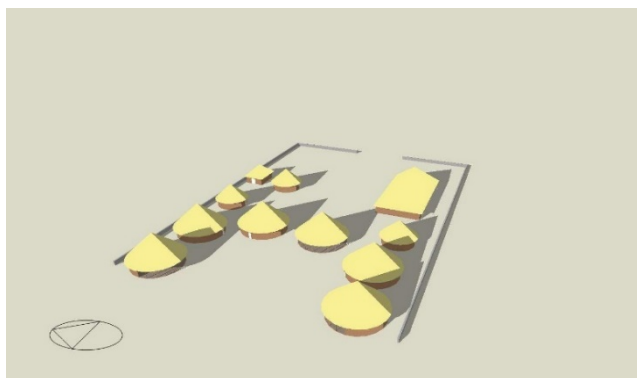


Figure S18: Typical Mud House

Figure S18 shows the typical traditional Nigerian house which is built with each room of about 75 m² area having a separate building within the compound. The bathroom, kitchen, storage, and toilet is equally built separately.

References

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