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An income-reflective scalable energy level transition system for low/middle income households

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ABSTRACT

In mitigating against energy poverty in Nigeria, research interest has focused mainly on electricity access and reduced electricity bills for low/medium income households. However, energy poverty in the global south is not only a problem of access but also of mobility which plays a crucial role in the economic productivity of a country. The need therefore arises for a scheme that guides low/medium income level households in increasing ownership of electrical appliances in a way that will improve their quality of life at the least-cost possible. Such a scheme is expected to address a prevailing challenge of poor satisfaction from the utilization of electrical appliances commonly observed with low/medium income households to achieve comfort, using Nigeria as a test case. This paper thus proposes a progressive system of electrical appliance ownership for low/medium income households in Nigeria for improved comfort. Furthermore, this paper advances discussions on building comfort by establishing the relationship between household comfort and economic output for Nigeria. The proposed system and the results obtained find relevance in developing countries especially in sub-Saharan Africa and developing Asia for improving household comfort, mitigating poverty and precipitating economic growth.

1. Introduction

The concept of energy poverty presents divergent views across the world. For example, in the global north (made up of the developed countries), fuel poverty is construed to imply spending more than 10% of a household's income in meeting energy needs (Katsoulakos, 2011). This narrative thus implies that fuel poverty in the global north is majorly a problem of affordability (i.e. the ability of households to afford sufficient energy for adequate heating). However, in the global south (made up of the developing countries), energy poverty presents a double divergent frontier – energy poverty due to[1] access and energy poverty due to[2] mobility (see Monyei, Jenkins, Serestina, & Adewumi, 2018). Electricity access in the European Union (EU) is about 100% and 99.92% for the Organisation for Economic Co-operation and Development (OECD) countries (as at 2014) (Baurzhan & Jenkins, 2016). On the contrary, access to clean energy sources in sub-Saharan Africa (SSA) is quite low (less than 38%) (Baurzhan & Jenkins, 2016). Furthermore, SSA as at 2014 had 62.8% of its population living in rural areas (with 15.3% having access to electricity), and 71.6% of its urban households electrified. The low electrification rate results in the high prevalence of poverty in SSA (about 41% (IEA, 2018)).

In reviewing literature on energy poverty for SSA and with focus on

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[1] By access we imply physical connection to an electricity source – grid, mini-grid, solar home systems (SHSs) etc.
[2] By mobility we mean ability of households to transit from one level of electricity consumption to another level. This could either be by increasing the duration of use of already owned electrical appliances or increasing the ownership of electrical appliances owned.

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Nigeria, attention has majorly centred on access. In highlighting the need for access to electricity, advocacy for access has spanned considerations of policy, smart systems, sustainable financing, integrated and sustainable systems, micro-grids, etc. For example, policy issues on mitigating the growth of renewable energy (RE) based electrification in Nigeria having been investigated and several suggestions recommended (Ajayi & Ajayi, 2013). Similarly, the least cost technology option for electrifying Taraba and Yobe states in Nigeria have been evaluated (Akpan, 2015). Also, indices for measuring and evaluating electrical energy poverty among micro-enterprises have been conceptualized (Ayodele, Ogunjuyigbe, & Opebiyi, 2018). A major detailed techno-economic and environmental impact assessment for a photovoltaic power system (PPS) of a small community in Bauchi State, Nigeria with a detailed assessment of its performance in terms of energy production, losses and efficiency has also been carried out (Akinyele & Rayudu, 2016). In an exhaustive work (Bertheau, Cader, & Blechinger, 2016), 47, 489 consumer clusters were identified in Nigeria; 46% of people living in these clusters were not supplied with electricity. Generally, most of the areas with low access to electricity in SSA have cottage industries that account for ~50% of the gross domestic product (GDP) in the region (Chidebell-Emordi, 2015).

Despite the prevalence of literature on energy poverty and sustainable energy development issues in Nigeria (for further reading see (Oyedepo, 2014, Ohunakin, Adaramola, Oyewola, & Fagbenle, 2014; Ozoegwu, Mgbemene, & Ozor, 2017; Oyedepo, 2012; Sanusi & Owoyele, 2016)), research on the improvement in energy efficiency especially for buildings have been limited. In the case of commercial buildings, the energy consumption in the Nigerian hotel industry have been evaluated (Oluseyi, Babatunde, & Babatunde, 2016); the authors developed a carbon footprint protocol for the hotel industry in Nigeria. For residential buildings, a load management system for off-grid houses in Nigeria utilizing solar photovoltaic (PV) system has been proposed (Ogunjuyigbe, Ayodele, & Monyei, 2015). In a subsequent related work (Ogunjuyigbe, Monyei, & Ayodele, 2015), a persuasive smart system that improved the efficiency of load allocation in low/medium income homes with grid connection was proposed. A mixed integer linear programming technique has also been deployed and used in managing residential loads for off-grid homes in Nigeria fed from solar PV systems under intermittent solar irradiation (Ogunjuyigbe, Ayodele, & Oladimeji, 2016). As an extension of these researches, the incorporation of comfort in a demand side management (DSM) scheme that improved user satisfaction per unit cost of expenditure by optimally dispatching loads to maximize satisfaction was carried out in (Ogunjuyigbe, Ayodele, & Akinola, 2017).

In all the literature reviewed, the following gaps were observed:

- None of the research works reviewed has accounted for energy mobility (strictly electricity terms) of most grid/mini-grid connected poor homes in Nigeria. While articles reviewed have argued on policy to improve access and satisfaction level, none has been able to provide a pathway for households to improve satisfaction/comfort through ownership and usage of electrical appliances in the least-cost effective way.
- Despite general acknowledgement of the primacy of electricity supply to improving GDP in Nigeria, there is lacking any literature that provides sufficient statistical framework that shows how mobility by households has direct impact on GDP and household comfort.

This paper thus advances discussion on energy poverty and its double divergent frontier by conceptualizing and modelling novel statistical indices to guide low/medium income households across Nigeria connected to grid/mini-grid systems in transitioning from one energy (electricity) level to another based on the cost of mobility and resulting comfort. In justifying the consideration for energy mobility in this research paper, the authors argue that energy mobility can ensure that electrification options for low/middle income households go beyond access and make provision for growth and obviate the need for regular upgrades and system expansion which can be capital intensive. Furthermore, the concepts proposed in this paper are majorly relevant for ensuring optimal utilization of electricity infrastructure in mini-grids or off-grid settings.

In modelling the appropriate energy transition path for various classes of households, this work also presents the relationship between energy mobility, household comfort, and GDP. Results obtained show how energy poverty can be mitigated in low/medium income households. Policy recommendations are also proposed.

1.1. A brief on Nigeria's power sector

According to World Bank reports, the per capital power consumption (kWh per capita) in Nigeria was 120.51 kW h in 2010 (Online, 2018). Previous studies have shown that only about 40% of Nigerians have access to electricity and 80% of these reside in urban areas (Kennedy-Darling, Hoyt, Murao, & Ross, 2008; Nwulua & Agboolab, 2011). Many of the rural communities in Nigeria are yet to be electrified with most of them depending on fossil for cooking, lighting and heating. The power sector in Nigeria is currently characterized by constant power shortage coupled with low power quality. Fig. 1 shows the capita electric power consumption (kWh Per Capita) in Nigeria between 2002–2010. As at December 2013, the total installed capacity

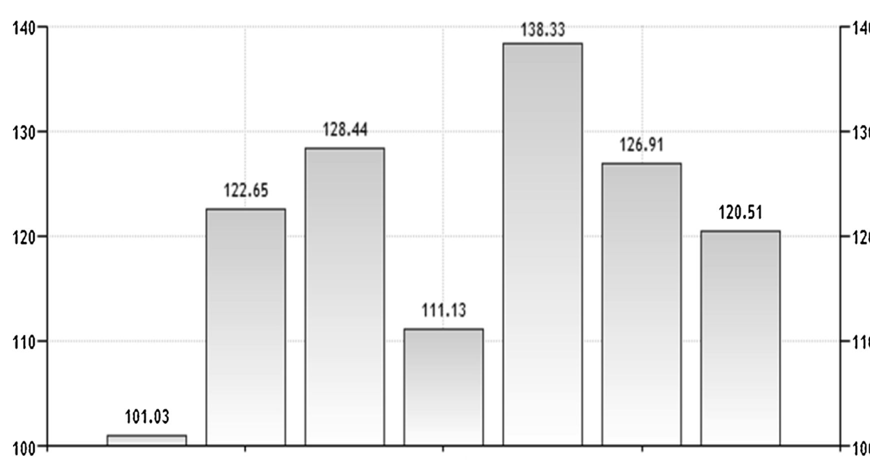


Fig. 1. Per Capital Electric Power Consumption (kWh Per Capita) in Nigeria between 2002–2010 (Ikejemba, Mpuan, Schuur, & Van Hillegersberg, 2017).

Table 1
Absolute poverty measure for selected states in Nigeria (Olabomi et al., 2017).

State	Geo-political zone	Poverty measure (%)	
		2003/2004	2009/2010
Lagos	South-west	69.4	40.3
Abia	South-east	40.9	50.2
Katsina	North-west	72.9	77.6
Edo	South-south	53.6	64.1
Kogi	North-central	91.8	67.4
Borno	North-east	59.8	60.6

(nameplate capacity) of electricity generating plants in Nigeria was 6 953 MW; available capacity was 4 598 MW; and actual average generation was 3 800 MW (PTFP, 2014). The figures improved by December 2014 to 7 445 MW, 4 949 MW and 3 900 MW for total installed capacity, available capacity, and actual average generation (PTFP, 2015). The 2014 average generation was well below the peak demand forecast of 12 800 MW for 2015 (PTFP, 2015). The situation has not changed since then (Avila, Carvallo, Shaw, & Kammen, 2017). As a result, the nation experiences consistent load shedding and blackout especially in rural communities.

A 2010 study (Olabomi, Jaafar, Musa, Sarip, & Ariffin, 2017) revealed that about 69% of Nigerians are poor, using a baseline of N55, 000 ($180.33) yearly income for the period 2009/2010. A similar analysis for an earlier period (2003/2004) used a baseline of N29, 000. Table 1 (Olabomi et al., 2017) presents the absolute poverty measure for 2003/2004 and 2009/2010 across all Nigerian states.

1.2. Associated statistics on Nigeria and motivation for research

Table 2 (NBS, 2012) presents the list of all the states in Nigeria, their geo-political zones, population and number of electrified households. Fig. 2 (Akpan, 2015) is a graphical representation of Table 2 showing the percentage of households electrified per state. It is observed from Fig. 2 that the North-east, North-west and North-central despite having the largest landmass, have the lowest electrification rates. A reason for this is due to the concentration of the major transmission lines around the major power generating stations, most of which are in the south, as shown in Fig. 3 (Akpan, 2015). The distribution of income levels for households across states is also presented in Table 3 (NBS, 2012). A deeper analysis of Table 3 shows that all the households in class C1 and most of the households in class C2 are poor based on (NBS, 2012) (which assumes a benchmark of N55 000 yearly for household income). Table 4 presents the distribution of states in Nigeria based on their electricity provider. The unbundling of the Power Holding Company of Nigeria (PHCN) after 2005 paved way for private company participation in the industry. The process resulted in the creation of eleven distribution companies (DISCOs), six generating companies (GENCOs), and one transmission company (TRANSCO) owned by the government.

Table 5 presents the monthly expenditure of households across all states in Nigeria based on classification (C1–C7) on electricity. In generating values in Table 5, cost of electricity consumption (EC in N/kWh) is the average value at which electricity is sold by the respective DISCOs to households within its coverage area, while the values under C1–C7 for each state represents the amount each class in each state spends on electricity monthly. Table 6 extends Table 5 by presenting the actual units of electricity consumed by households monthly based on their income levels.

Given $Ck^{\cos t-elect}\,(Naira)$ and $EC\,(Naira/kWh)$, then the amount of electricity consumed, $Ck^{units-elect}(kWh)$ can be evaluated as $Ck^{units-elect}(kWh) = \frac{Ck^{\cos t-elect}(Naira)}{EC\ (Naira\ /\ kWh)}$ where $Ck^{\cos t-elect}\,(Naira)$ is the amount expended by a household monthly on electricity as obtained from Table 5 and k is the index of the class i.e. $1 \le k \le 7,\ k \in Z^{+}$.

Table 2
States, geo-political zones, population and number of electrified households (NBS, 2012).

Geo-political zones	States	Population	Electrified households
North - central	Benue	4942141	1198680
	Kogi	3850369	756733
	Kwara	2748148	323549
	Nasarawa	2171906	457742
	Niger	4687610	1098726
	Plateau	3669993	829789
	FCT – Abuja	2238752	245440
North - east	Adamawa	3674992	1048161
	Bauchi	5515303	951368
	Borno	4944033	1589400
	Gombe	2775400	601375
	Taraba	2652880	910651
	Yobe	2765286	685347
North - west	Jigawa	5041491	1060396
	Kaduna	7102877	1248819
	Kano	11087814	1729744
	Katsina	6740479	1405492
	Kebbi	3802526	750452
	Sokoto	4301896	1026713
	Zamfara	3847793	907400
South - east	Imo	4609038	195075
	Abia	3256642	411623
	Enugu	3796685	770522
	Anambra	4805646	295991
	Ebonyi	2504085	637375
South - south	Edo	3700706	106335
	Delta	4825999	1145787
	Cross River	3344410	650128
	Rivers	6162063	797321
	Bayelsa	1970487	315937
	Akwa Ibom	4625119	972903
South - west	Lagos	10694915	343028
	Ekiti	2801161	325939
	Oyo	6615061	865891
	Ogun	4424069	829789
	Ondo	4020965	828557
	Osun	4009839	457604

A critical observation of Tables 3, 5 and 6 reveals that a great disparity does exist between states based on income level distribution, monthly expenditure on electricity, unit cost of electricity and consumption of electricity. For example, states like Kebbi, Zamfara and Bauchi have over 35% of households within the C1–C2 income bracket compared to states such as Lagos, Oyo, Gombe etc. with over 30% of their households in the C5 income bracket. However, despite the disparity in income levels among states, electricity tariffs are not reflective of this disparity. For example, in Table 5, states such as Benue, Bauchi, Kaduna and Zamfara have electricity tariffs that are competitive with high income paying states like Rivers, Bayelsa and Lagos. Furthermore, electricity consumption by households across states has been established to be on the decline over the years (Monyei, Adewumi, Obolo, & Sajou, 2018). The decline was further established to be related to increasing poverty (Monyei, Adewumi et al., 2018). In addition, off-grid electrification projects despite providing access to households have not guaranteed mobility in terms of energy transition for these households (which is necessary for economic growth) due to associated problems of sustainability and financing of such off-grid projects. In addition, increasing purchase of electrical goods do not seem to offer households much comfort due to underutilization of such electrical appliances (in terms of duration of usage). The need therefore arises for a concerted and progressive approach to the ownership of electrical appliances by households that can improve their comfort level (satisfaction) at a commensurate cost especially for low/medium income level households. This paper thus advances discussion beyond satisfaction based on unit cost by modelling satisfaction based on ownership of electrical appliance and duration of use.

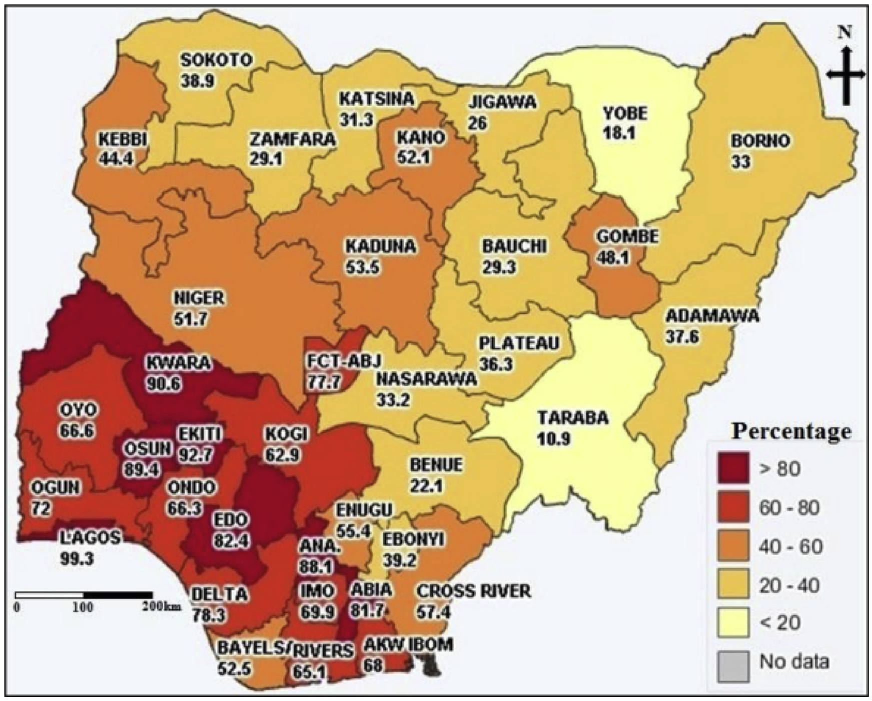


Fig. 2. Percentage of households with electricity access in the different states in Nigeria (Akpan, 2015).

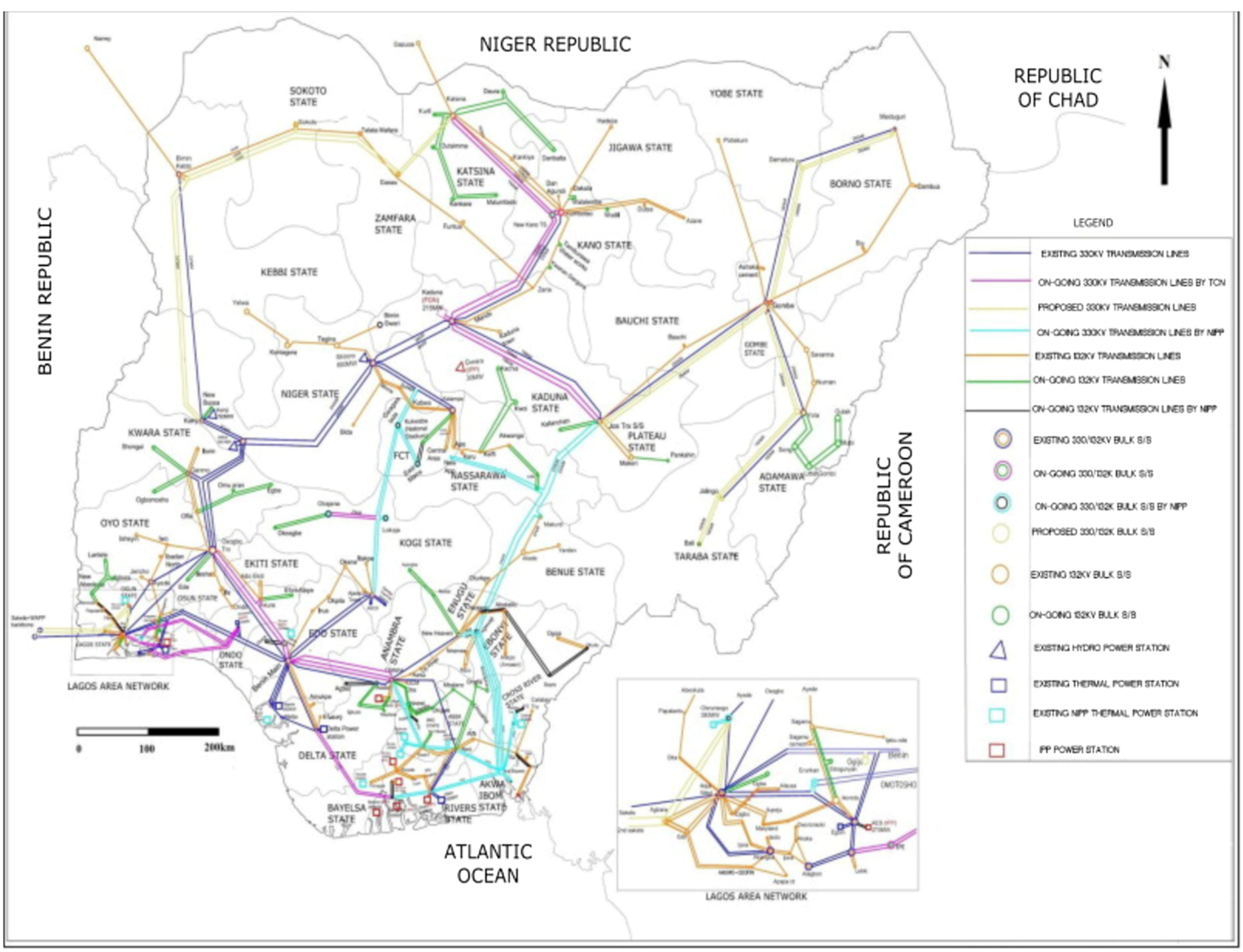


Fig. 3. Map of Nigeria showing existing, ongoing, and proposed generation and transmission (HV) projects (Akpan, 2015).

Table 3
Income distribution level per state (NBS, 2012).

State	% of households in each monthly income bracket						
	C1	C2	C3	C4	C5	C6	C7
Abia	1.2	9.1	33.8	38.3	15.1	1.9	0.5
Adamawa	2.9	13.3	22.1	33.7	26.3	1.2	0.5
Akwa Ibom	0.2	6.3	21.9	38.3	30.7	1.8	0.6
Anambra	1.5	3.1	18.6	40.9	32.7	2.4	0.9
Bauchi	14.2	25.6	23.5	30.8	4.9	0.5	0.4
Bayelsa	2	6.1	9.8	28	44.8	7.9	1.4
Benue	1.4	11.4	27.2	29.3	26.2	3.1	1.4
Borno	0.7	10	17.1	29.9	36.1	4.6	1.6
Cross River	1.7	10.3	28.8	32.9	23	2.5	0.7
Delta	0.5	3.8	13.6	36.9	38.3	6.6	0.3
Ebonyi	1.4	15.6	39.6	30.5	11.1	0.7	1.1
Edo	1.9	7.8	29.3	37.7	20.4	2	0.8
Ekiti	1.9	20.9	36	25.7	13.3	1.7	0.5
Enugu	5.9	20.3	18.5	28.7	23.6	1.2	1.8
Gombe	0.7	2.6	14.4	34.9	43.2	3.3	0.8
Imo	1.2	15	29.5	29.8	22.5	1.6	0.4
Jigawa	10.6	12.1	22.3	28.8	23	2.6	0.5
kaduna	2.9	22.9	28.9	22.7	17	2.1	3.5
Kano	3.4	17.7	22.3	29.6	24.7	2.3	0.1
Katsina	4.8	13.6	24.6	24	10.3	4.7	18
Kebbi	5.4	40.6	17.2	12.2	21.2	2.4	1
Kogi	3.4	10.2	16.7	34.6	31.9	1.7	1.4
Kwara	1.2	14.2	26.1	38	18.9	1.3	0.3
Lagos	0.2	2.5	18.9	36.6	36.1	4.8	0.8
Nassarawa	1.8	8.2	17	32.7	37.1	2.5	0.7
Niger	2.2	23.1	18.2	35	19.6	1.1	0.9
Ogun	1.3	12.8	37.8	27.9	18.9	1.1	0.3
Ondo	1.4	12.4	28	30	24.1	3.2	0.9
Osun	1	10.7	31.7	37.5	16.9	1.8	0.4
Oyo	6.1	7.1	13.7	31.6	36.6	4	0.9
Plateau	3.7	25.7	25.7	25.1	15.9	2.6	1.3
Rivers	0	2.8	15.4	32.6	37.9	7.7	3.7
Sokoto	14.1	27.9	7.2	23.2	21.7	4.3	1.7
Taraba	4	12.6	19.4	28	24.7	6.1	5.3
Yobe	4.9	24.3	23.3	30.6	15.6	0.9	0.3
Zamfara	6.5	29.6	20.5	20.3	20.5	2	0.4
FCT	4	4.8	9.5	26.2	39.1	12	4.4

C1 (N1000–N1999); C2 (N2000–N4999); C3 (N5000–N9999); C4 (N10,000–N19,999); C5 (N20,000–N49,999); C6 (N50,000–N80,000); C7 (> N80,000).

2. Methods

2.1. Derivation of mobility index

An index $CM^{s}_{k1,k2}$ is introduced to quantify the mobility of households across energy consumption classes per state. $CM^{s}_{k1,k2}$ is the difference (in kWh) between two successive classes $k1, k2 \in k$. The reason for the computation of $CM^{s}_{k1,k2}$ is to show how much is gained (in kWh) during planned transition from an energy level to another. Table 7 presents the mobility index of households per state.

The minimum, average and maximum values across the states for Table 5 are presented in Fig. 4. The values in Fig. 4 are computed to show the spread in household monthly expenditure on electricity for each class across the states. For example, the minimum expenditure for C1 households is N30.45 (Borno State), while the maximum expenditure on electricity monthly is N186.15 (FCT-Abuja). The implication of this is that a C1 household in FCT-Abuja spends as much as a C3 household in Borno State.

Similar to Figs. 4 and 5 presents the minimum, maximum and average values for electricity consumption by households across the states based on income levels while Table 8 presents the minimum, maximum and average values for Table 7.

2.2. Electrical appliances classification and weight computation

Table 9 presents the list of electrical appliances used in evaluating the comfort level of households based on ownership and income level. All the appliances in Table 9 are classified into seven main categories for this research – lighting, cooling, entertainment, kitchen, personal, general household and others. The devices under each need category are also shown. Table 9 also presents the respective abbreviation and power rating (W) for each device. It must be pointed out that the list shown in Table 9 is not exhaustive but comprehensive and encompasses most of the electrical appliances found in typical households in Nigeria (based on their ownership and income level).

To derive the weight of each need category and its associated devices, a load audit and satisfaction evaluation was carried out for a C7 household in Lagos state, Southwest Nigeria. The household contained most of the devices in Table 9, except for L4(2, 5, 8, 9), L5(1, 3), L6(3) and L7(2); however, these devices were considered in the weight computation. The reason for their inclusion is because they are owned by very up-scale houses in up-scale districts across Nigeria and are useful for providing maximum comfort in terms of ownership of electrical appliances. The nominal comfort cost for any device (n^{d}_{cc}) is such that $1 \le n^{d}_{cc} \le 4,\ \ n^{d}_{cc} \in R^{+}$. The cumulative nominal comfort cost, C^{e}_{ncc} is derived for each need category as:

$$C^{e}_{ncc} = \sum_{d=1}^{f} (n^{d}_{cc}) \tag{1}$$

Where e is the need category; d represents a device type in each category; f is the number of device types in need category. For comfort level evaluation, C^{e}_{ncc} is used to rank needs. Weights are also derived based on the usage of devices in the household. Designating the usage duration

Table 4
DISCO coverage area, number of electrified households, energy received per DISCO zone and average aggregate technical and commercial collection (ATC&C) losses.

DISCO	Coverage states[b]	Electrified Household[a]	2016 Energy received (GWh)[b]	2016 average ATC&C losses (%)[b]
Kaduna Electricity Distribution Company (KNEDC)	Sokoto, Zamfara, Kebbi, Kaduna	3,933,384	70.66	73.00
Kano Electricity Distribution Company (KEDC)	Katsina, Jigawa, Kano	4,195,632	70.66	58.67
Yola Electricity Distribution Company (YEDC)	Yobe, Adamawa, Borno, Taraba	4,233,559	30.91	61.67
Jos Electricity Distribution Company (JEDC)	Bauchi, Gombe, Plateau, Benue	3,581,212	48.58	72.75
Abuja Electricity Distribution Company (AEDC)	Niger, FCT-Abuja, Nasarawa, Kogi	2,558,641	101.57	47.75
Ikeja Electricity Distribution Company (IKEDC)	Lagos	343,028	229.63	39.38
Eko Electricity Distribution Company (EKEDC)				
Ibadan Electricity Distribution Company (IBEDC)	Kwara, Oyo, Ogun, Osun	2,162,507	114.82	50.42
Benin Electricity Distribution Company (BEDC)	Ekiti, Ondo, Edo, Delta	2,406,618	79.49	55.25
Port Harcourt Electricity Distribution Company (PHEDC)	Bayelsa, Rivers, Akwa Ibom, Cross River	2,736,289	57.41	60.42
Enugu Electricity Distribution Company (EEDC)	Anambra, Enugu, Imo, Abia, Ebonyi	2,310,586	79.49	62.17

[a] See (Ohiare, 2015).
[b] See www.nerc.gov.ng.

Table 5
Average monthly household expenditure on electricity (Naira) based on income level.

State	EC (N/kWh)	Income level class						
		C1	C2	C3	C4	C5	C6	C7
Abia	31	66.3	154.7	331.5	663	1547	2873	7293
Adamawa	26.51	39.75	92.75	198.75	397.5	927.5	1722.5	4372.5
Akwa Ibom	31.78	66.75	155.75	333.75	667.5	1557.5	2892.5	7342.5
Anambra	31	49.35	115.15	246.75	493.5	1151.5	2138.5	5428.5
Bauchi	30.93	47.1	109.9	235.5	471	1099	2041	5181
Bayelsa	31.78	38.1	88.9	190.5	381	889	1651	4191
Benue	30.93	31.95	74.55	159.75	319.5	745.5	1384.5	3514.5
Borno	26.51	30.45	71.05	152.25	304.5	710.5	1319.5	3349.5
Cross River	31.78	38.85	90.65	194.25	388.5	906.5	1683.5	4273.5
Delta	31.27	63.3	147.7	316.5	633	1477	2743	6963
Ebonyi	31	37.8	88.2	189	378	882	1638	4158
Edo	31.27	70.5	164.5	352.5	705	1645	3055	7755
Ekiti	31.27	78.45	183.05	392.25	784.5	1830.5	3399.5	8629.5
Enugu	31	38.25	89.25	191.25	382.5	892.5	1657.5	4207.5
Gombe	30.93	34.8	81.2	174	348	812	1508	3828
Imo	31	72.45	169.05	362.25	724.5	1690.5	3139.5	7969.5
Jigawa	25.46	51	119	255	510	1190	2210	5610
kaduna	28.75	82.2	191.8	411	822	1918	3562	9042
Kano	25.46	64.35	150.15	321.75	643.5	1501.5	2788.5	7078.5
Katsina	25.46	41.7	97.3	208.5	417	973	1807	4587
Kebbi	28.75	64.65	150.85	323.25	646.5	1508.5	2801.5	7111.5
Kogi	24.03	41.4	96.6	207	414	966	1794	4554
Kwara	25.71	85.2	198.8	426	852	1988	3692	9372
Lagos	25.86	88.5	206.5	442.5	885	2065	3835	9735
Nassarawa	24.03	39	91	195	390	910	1690	4290
Niger	24.03	50.55	117.95	252.75	505.5	1179.5	2190.5	5560.5
Ogun	25.71	68.1	158.9	340.5	681	1589	2951	7491
Ondo	31.27	71.55	166.95	357.75	715.5	1669.5	3100.5	7870.5
Osun	25.71	63.45	148.05	317.25	634.5	1480.5	2749.5	6979.5
Oyo	25.71	100.95	235.55	504.75	1009.5	2355.5	4374.5	11104.5
Plateau	30.93	45	105	225	450	1050	1950	4950
Rivers	31.78	73.65	171.85	368.25	736.5	1718.5	3191.5	8101.5
Sokoto	28.75	57.75	134.75	288.75	577.5	1347.5	2502.5	6352.5
Taraba	26.51	62.25	145.25	311.25	622.5	1452.5	2697.5	6847.5
Yobe	26.51	52.95	123.55	264.75	529.5	1235.5	2294.5	5824.5
Zamfara	28.75	62.85	146.65	314.25	628.5	1466.5	2723.5	6913.5
FCT	24.03	186.15	434.35	930.75	1861.5	4343.5	8066.5	20476.5

(hours) for each device type as t_d, the cumulative usage duration (C_{td}^{e} in hours) for need category e is given as:

$$C_{td}^{e} = \sum_{d=1}^{f} (t_d) \tag{2}$$

C_{td}^{e} is used to rank needs in order of usage duration. The results of the weight computation are presented in Table 10. From Table 10, the ranking of needs in order of cumulative nominal comfort cost (C_{ncc}^{e}) and cumulative usage duration (C_{td}^{e}) is depicted in Fig. 6.

2.3. Justification for weighting selection and priority arrangement

While it can be argued that a C7 household may not offer the same priority level in ranking needs when compared with a C4 household for instance, an evaluation of the ownership of electrical appliances by households in Nigeria across all classes shows that ownership of electrical appliances is in most cases ordered subsets of the C7 set. For example, the order of needs priority set for the C7 household, $NPS_{C7} = \{L4, L5, L6, L3, L2, L1, L7\}$. Random sampling of six other household yields: $NPS_{C1} = \{L5, L2, L1\}$, $NPS_{C2} = \{L5, L3, L2, L1\}$ and $NPS_{C3} = \{L4, L5, L3, L2, L1\}$ with $NPS_{C3} = NPS_{C4} = NPS_{C5} = NPS_{C6}$. The reason for the similarity between C3, C4, C5 and C6 households in terms of priority in appliance ordering is because, as households' income increases, rather than acquiring more electrical appliances, the duration of usage of already owned electrical appliances is usually extended to derive more satisfaction. Furthermore, the choice of a C7 household in evaluating the weighting to be attached to each device assumes that the values chosen by the C7 household sampled is representative of what any other household will select after transition to a C7 household level.

2.4. Scenario description

In modelling the electrical appliance ownership progression of each income level class, three cases are modelled per class as shown in Table 11. Only the cases chosen for class k = 1 are shown in Table 11. Cases j = 1, j = 2, and j = 3 are based on assumed minimum, average, and maximum values of electricity consumption respectively. Electrical appliances selected for each case are based on the universal set represented by $NPS_{C7} = \{L4, L5, L6, L3, L2, L1, L7\}$ while the duration is assumed.

The justification for the loads selected in Table 11 stems from the fact that most of the houses with this purchasing power are usually fed from mini-grids or stand-alone systems with low power capacity (ESI, 2017; Youdeowei, 2017). These low power systems are only able to power phones and one light source (compact fluorescent lamp, CFL). Furthermore, according to (NBS, 2012), access to mobile telephone in 2009 was 84.7% of the total population which resonates with the persistence of L5(4) across all cases. The addition of L3(2) for $j = 3$ is attributed to affluence since its ownership clearly distinguishes it from cases $j = 1$ and $j = 2$. It is thus seen that for the poorest households, as income increases, ownership of electrical appliances (need) increases from lighting and phone charging to basic cooling (fan) and then entertainment. Ownership of loads in L4, L6 and L7 including L2(1), L3(1, 3, 4) would be of no value to the household since they cannot be

Table 6
Monthly electricity consumption (kWh) per household based on income class.

State	Income level class						
	C1	C2	C3	C4	C5	C6	C7
Abia	2.14	4.99	10.69	21.39	49.90	92.68	235.26
Adamawa	1.50	3.50	7.50	14.99	34.99	64.98	164.94
Akwa Ibom	2.10	4.90	10.50	21.00	49.01	91.02	231.04
Anambra	1.59	3.71	7.96	15.92	37.15	68.98	175.11
Bauchi	1.52	3.55	7.61	15.23	35.53	65.99	167.51
Bayelsa	1.20	2.80	5.99	11.99	27.97	51.95	131.88
Benue	1.03	2.41	5.16	10.33	24.10	44.76	113.63
Borno	1.15	2.68	5.74	11.49	26.80	49.77	126.35
Cross River	1.22	2.85	6.11	12.22	28.52	52.97	134.47
Delta	2.02	4.72	10.12	20.24	47.23	87.72	222.67
Ebonyi	1.22	2.85	6.10	12.19	28.45	52.84	134.13
Edo	2.25	5.26	11.27	22.55	52.61	97.70	248.00
Ekiti	2.51	5.85	12.54	25.09	58.54	108.71	275.97
Enugu	1.23	2.88	6.17	12.34	28.79	53.47	135.73
Gombe	1.13	2.63	5.63	11.25	26.25	48.76	123.76
Imo	2.34	5.45	11.69	23.37	54.53	101.27	257.08
Jigawa	2.00	4.67	10.02	20.03	46.74	86.80	220.35
kaduna	2.86	6.67	14.30	28.59	66.71	123.90	314.50
Kano	2.53	5.90	12.64	25.27	58.97	109.52	278.02
Katsina	1.64	3.82	8.19	16.38	38.22	70.97	180.17
Kebbi	2.25	5.25	11.24	22.49	52.47	97.44	247.36
Kogi	1.72	4.02	8.61	17.23	40.20	74.66	189.51
Kwara	3.31	7.73	16.57	33.14	77.32	143.60	364.53
Lagos	3.42	7.99	17.11	34.22	79.85	148.30	376.45
Nassarawa	1.62	3.79	8.11	16.23	37.87	70.33	178.53
Niger	2.10	4.91	10.52	21.04	49.08	91.16	231.40
Ogun	2.65	6.18	13.24	26.49	61.80	114.78	291.37
Ondo	2.29	5.34	11.44	22.88	53.39	99.15	251.69
Osun	2.47	5.76	12.34	24.68	57.58	106.94	271.47
Oyo	3.93	9.16	19.63	39.26	91.62	170.15	431.91
Plateau	1.45	3.39	7.27	14.55	33.95	63.05	160.04
Rivers	2.32	5.41	11.59	23.17	54.07	100.42	254.92
Sokoto	2.01	4.69	10.04	20.09	46.87	87.04	220.96
Taraba	2.35	5.48	11.74	23.48	54.79	101.75	258.30
Yobe	2.00	4.66	9.99	19.97	46.61	86.55	219.71
Zamfara	2.19	5.10	10.93	21.86	51.01	94.73	240.47
FCT	7.75	18.08	38.73	77.47	180.75	335.68	852.12

Table 7
Household mobility index per state.

State	Transition classes					
	$CM^s_{1,2}$	$CM^s_{2,3}$	$CM^s_{3,4}$	$CM^s_{4,5}$	$CM^s_{5,6}$	$CM^s_{6,7}$
Abia	2.85	5.70	10.69	28.52	42.77	142.58
Adamawa	2.00	4.00	7.50	19.99	29.99	99.96
Akwa Ibom	2.80	5.60	10.50	28.01	42.01	140.03
Anambra	2.12	4.25	7.96	21.23	31.84	106.13
Bauchi	2.03	4.06	7.61	20.30	30.46	101.52
Bayelsa	1.60	3.20	5.99	15.98	23.98	79.92
Benue	1.38	2.75	5.16	13.77	20.66	68.87
Borno	1.53	3.06	5.74	15.31	22.97	76.57
Cross River	1.63	3.26	6.11	16.30	24.45	81.50
Delta	2.70	5.40	10.12	26.99	40.49	134.95
Ebonyi	1.63	3.25	6.10	16.26	24.39	81.29
Edo	3.01	6.01	11.27	30.06	45.09	150.30
Ekiti	3.35	6.69	12.54	33.45	50.18	167.25
Enugu	1.65	3.29	6.17	16.45	24.68	82.26
Gombe	1.50	3.00	5.63	15.00	22.50	75.01
Imo	3.12	6.23	11.69	31.16	46.74	155.81
Jigawa	2.67	5.34	10.02	26.71	40.06	133.54
kaduna	3.81	7.62	14.30	38.12	57.18	190.61
Kano	3.37	6.74	12.64	33.70	50.55	168.50
Katsina	2.18	4.37	8.19	21.84	32.76	109.19
Kebbi	3.00	6.00	11.24	29.98	44.97	149.91
Kogi	2.30	4.59	8.61	22.97	34.46	114.86
Kwara	4.42	8.84	16.57	44.19	66.28	220.93
Lagos	4.56	9.13	17.11	45.63	68.45	228.15
Nassarawa	2.16	4.33	8.11	21.64	32.46	108.20
Niger	2.80	5.61	10.52	28.05	42.07	140.24
Ogun	3.53	7.06	13.24	35.32	52.98	176.59
Ondo	3.05	6.10	11.44	30.51	45.76	152.54
Osun	3.29	6.58	12.34	32.91	49.36	164.53
Oyo	5.24	10.47	19.63	52.35	78.53	261.77
Plateau	1.94	3.88	7.27	19.40	29.10	96.99
Rivers	3.09	6.18	11.59	30.90	46.35	154.50
Sokoto	2.68	5.36	10.04	26.78	40.17	133.91
Taraba	3.13	6.26	11.74	31.31	46.96	156.54
Yobe	2.66	5.33	9.99	26.63	39.95	133.16
Zamfara	2.91	5.83	10.93	29.15	43.72	145.74
FCT	10.33	20.66	38.73	103.29	154.93	516.44

utilized owing to the inability of the mini-grid to dispatch them or the household to afford the cost for utilizing them via the grid. Meeting such needs such as cooking would mostly be from alternatives such as fuelwood and kerosene. This view is supported by (NBS, 2012) where it is posited that as at 2010, 72.2% of households in Nigeria utilized wood for cooking as against 0.4% who utilized electricity and 23.8% who utilized kerosene.

2.5. Mathematical modelling and evaluation of comfort

2.5.1. Comfort evaluation and modelling without productivity consideration

From Fig. 5, denoting $MC^{k,1}$, $MC^{k,2}$, $MC^{k,3}$ as the minimum, average and maximum monthly electricity consumed (kWh) respectively for class k households, $DC^{k,1}$, $DC^{k,2}$, $DC^{k,3}$ which are the minimum, average and maximum daily electricity consumed (Wh/day) respectively for class k households are computed using Eq. (3). In a similar fashion, minimum, average, and maximum electricity rates are deduced from Table 5 and presented in Table 12.

$$DC^{k,j} = \frac{MC^{k,j} \times 1000}{30}(Wh/day); \quad j = 1, 2, 3. \tag{3}$$

Three comfort variants are computed for each case j of load ownership (in each class): relative comfort ($R^{k,j}_{cft}$) - the comfort based on ownership of an electrical appliance; apparent comfort ($A^{k,j}_{cft}$) - the comfort based on duration of usage of already owned electrical appliances and real comfort ($Re^{k,j}_{cft}$) - the resultant of $R^{k,j}_{cft}$ and $A^{k,j}_{cft}$. The computation of $R^{k,j}_{cft}$, $A^{k,j}_{cft}$, and $Re^{k,j}_{cft}$ is given by Eqs. (4)–(6) respectively.

$$R^{k,j}_{cft} = \sum_{e}\sum_{d=1}^{f}\left(\frac{n^{d}_{cc}}{\sum C^{e}_{ncc}}\right) \tag{4}$$

$$A^{k,j}_{cft} = \sum_{e}\sum_{d=1}^{f}\left(\frac{t_d}{\sum C^{e}_{d}}\right) \tag{5}$$

$$Re^{k,j}_{cft} = \sqrt{(R^{k,j}_{cft})^2 + (A^{k,j}_{cft})^2} \tag{6}$$

In evaluating values for $Re^{k,j}_{cft}$ (where j is the case under consideration), the following assumptions have been made:

- Duplicity of electrical devices at the same load point does not connote more satisfaction.
- Utilization of a device d beyond its maximum duration t_d does not contribute to any increment in satisfaction/comfort level.
- Productivity (i.e. the potential of electricity consumption to

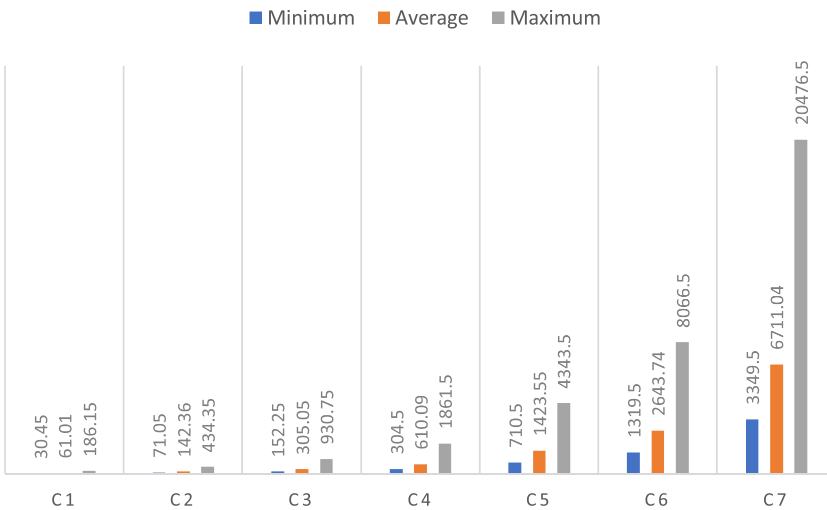


Fig. 4. Household monthly expenditure (Naira) on electricity based on income class.

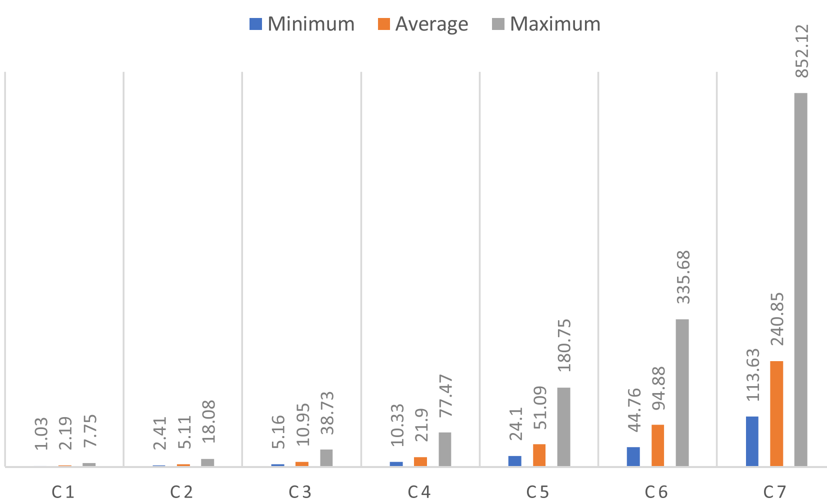


Fig. 5. Household monthly electricity consumption based on income class (kWh).

Table 8
Household electricity mobility index based on class.

Class mobility	$CM^{s}_{1,2}$	$CM^{s}_{2,3}$	$CM^{s}_{3,4}$	$CM^{s}_{4,5}$	$CM^{s}_{5,6}$	$CM^{s}_{6,7}$
Minimum	1.38	2.75	5.16	13.77	20.66	68.87
Average	2.92	5.11	10.95	29.19	43.79	145.97
Maximum	10.33	20.66	38.73	103.29	154.93	516.44

contribute to economic activities) has been neglected.

2.5.1.1. Satisfaction evaluation. To avoid repetition, the results of the cases modelled for household class C1 are highlighted below, while the general results for all the classes are presented subsequently.

- Case: $j = 1$

The evaluation of its associated values results in $DC^{1,1} = 34.33$ Wh/day, $R^{1,1}_{cft} = 0.92$, $A^{1,1}_{cft} = 0.23$ and $Re^{1,1}_{cft} = 0.95$.

- Case: $j = 2$

For this case, $DC^{1,2} = 73$ Wh/day, while $R^{1,2}_{cft}$, $A^{1,2}_{cft}$ and $Re^{1,2}_{cft}$ are evaluated to be 1.17, 0.28 and 1.20 respectively.

- Case: $j = 3$

For this case, $DC^{1,3}$, $R^{1,3}_{cft}$, $A^{1,3}_{cft}$ and $Re^{1,3}_{cft}$ are evaluated to be 258.33Wh/day, 1.42, 0.77 and 1.61.

Table 13 presents the transition value between the different cases under this class. It is observed from Table 13 that increasing the ownership of electrical appliances from $j = 1$ to $j = 2$ results in 26.3% increase in real comfort while a further increase in ownership of electrical appliances from $j = 2$ to $j = 3$ results in a 34.2% increase in real comfort. However, transiting from $j = 1$ to $j = 3$ results in a 69.5% increase in real comfort. In terms of transition within this class, the transition from $j = 1 \rightarrow 3$ is preferred than from $j = 1 \rightarrow 2 \rightarrow 3$ due to the cost/benefit ratio of the latter option ($j = 1 \rightarrow 3$) which is better than the former option ($j = 1 \rightarrow 2 \rightarrow 3$).

Fig. 7 represents the Cartesian representation of $R^{k,j}_{cft}$, $A^{k,j}_{cft}$ and $Re^{k,j}_{cft}$ including their deflection angles $\theta^{k,j}_{diff} = tan^{-1}(\frac{A^{k,j}_{cft}}{R^{k,j}_{cft}})$ and $\theta^{k,j}_{ideal} = 45 - tan^{-1}(\frac{A^{k,j}_{cft}}{R^{k,j}_{cft}})$. $\theta^{k,j}_{diff}$ represents the angle between $R^{k,j}_{cft}$ and $Re^{k,j}_{cft}$ while $\theta^{k,j}_{ideal}$ measures the deflection of $Re^{k,j}_{cft}$ from the ideal/best comfort possible (Re^{max}_{cft}) which is also shown in Fig. 1. The ideal/best values for $A^{k,j}_{cft}$ (A^{max}_{cft}) and $R^{k,j}_{cft}$ (R^{max}_{cft}) computed from Table 10 are 7 and 7 respectively which result in $Re^{max}_{cft} = 9.9$. For the satisfaction evaluation for other household classes, the selection of appliance ownership for

Table 9
Electrical needs and appliances across all households.

Need	Device	Abbreviation	Power rating (W)
Lighting	Energy bulb	L1(1)	16
	Bedside Lamp	L1(2)	10
Cooling	Air conditioner	L2(1)	1000/4000
	Fan	L2(2)	25/75
Entertainment	Television	L3(1)	150/200
	DVD player	L3(2)	25
	Speakers	L3(3)	45
	Satellite decoder	L3(4)	10
Kitchen	Electric cooker	L4(1)	1500
	Electric oven	L4(2)	2150
	Electric kettle	L4(3)	1200
	Microwave	L4(4)	1700
	Toaster	L4(5)	1000
	Fridge	L4(6)	100/150
	Freezer	L4(7)	400
	Heat extractor	L4(8)	176
	Dish washer	L4(9)	1200
Personal	Desktop computer	L5(1)	150/450
	Laptop	L5(2)	45/60
	Printer	L5(3)	25
	Phone charging	L5(4)	10
General household	Washing machine	L6(1)	500
	Cloth dryer	L6(2)	1000
	Vacuum cleaner	L6(3)	700
	Power shower	L6(4)	8500
Others	Pumping machine	L7(1)	400
	Luxury lighting	L7(2)	30/70/150

Table 10
Weight computation for need categories and devices.

Need	Abbreviation	n_{cc}^{d}	C_{ncc}^{e}	t_d	C_{td}^{e}
Lighting	L1(1)	2	3	12	16
	L1(2)	1		4	
Cooling	L2(1)	3	4	10	22
	L2(2)	1		12	
Entertainment	L3(1)	2	6	6	28
	L3(2)	1.5		8	
	L3(3)	1		8	
	L3(4)	1.5		6	
Kitchen	L4(1)	4	17	3	32.75
	L4(2)	2		1.5	
	L4(3)	1.5		0.25	
	L4(4)	1.5		0.25	
	L4(5)	1		0.25	
	L4(6)	2		12	
	L4(7)	2		12	
	L4(8)	2		2	
	L4(9)	1		1.5	
Personal	L5(1)	1.5	6	2	7.25
	L5(2)	2		4	
	L5(3)	1		0.25	
	L5(4)	1.5		1	
General household	L6(1)	1.5	6	0.75	2.5
	L6(2)	1.5		1	
	L6(3)	1		0.25	
	L6(4)	2		0.50	
Others	L7(1)	2	3	0.75	2.75
	L7(2)	1		2	

each case, under each household class is presented in Table 14. Table 15 presents the summary of the computation of $R_{cft}^{k,j}$, $A_{cft}^{k,j}$, $Re_{cft}^{k,j}$, $\theta_{ideal}^{k,j}$ and $\theta_{ideal}^{k,j}$ for all classes and their respective cases. It is observed from Table 13 the consistency in the utilization of L1(1), L2(2) and L5(4) which cut across the typical needs of most low/medium income level households. It is also observed from Table 14 that as income level increases, the household is able to increase ownership of electrical appliances and also increase duration of usage of already owned devices. The case of substitution is also observed i.e. the use of an alternative in place of another (for example L2(1)/L2(2) which have not been owned concurrently).

Furthermore, the sparse use of L4, L6 and L7 needs devices is not uncommon. This is because of the cost implication for utilizing them. Two further observations from Tables 14 and 15 are the class spill-over effect and class transition-dip effect. The class spill-over phenomenon is used to describe a situation where $Re_{cft}^{k+1,1}$ and the electrical load ownership profile of a household is similar to $Re_{cft}^{k,2}$ and the electrical load ownership profile of same household. For example, $Re_{cft}^{3,1} = Re_{cft}^{2,2} = 1.31$, with electrical load ownership similar for both cases, and their respective classes as L1(1), L2(2) and L5(4). The class transition-dip effect describes the drop in comfort during the transition from $Re_{cft}^{k,3} \rightarrow Re_{cft}^{k+1,1}$. This phenomenon is observed across all cases as shown in Table 15. Reasons for the transition-dip phenomenon are due to the segregated billing method (Table 12) and the class spill-over effect which always constrain $Re_{cft}^{k+1,1}$ such that $|Re_{cft}^{k+1,1} - Re_{cft}^{k,2}| \leq \alpha$ and $Re_{cft}^{k+1,1} < Re_{cft}^{k,3}, \forall\, k, j$. The maximum value for α from Table 15 is 0.24.

2.6. Evaluation of comfort productivity

In the evaluation of[3] productivity due to comfort, we propose a term called *'leisure time monetization'* which has been applied in (Praktiknjo, Hähnel, & Erdmann, 2011; Shivakumar et al., 2017) and define it as the economic value for the leisure hours of a household. The premise is that marginal values of leisure and labour are equal i.e. wage corresponding to one hour of labour/work equals the value of one hour of lost leisure (where the leisure hours are the hours of the week excluding work day hours). Based on the foregoing, we can assume (for simplicity) that household activities and leisure are entirely dependent on electricity. Accordingly, we can compute in monetary terms the net welfare (W_N^k) gained or lost due to households' transition across energy classes when productivity is considered. The derivation of (W_N^k) is shown subsequently in Eqs. (7)–(11).

$$HW_k = \frac{Income\,(monthly)}{(wd - h) \times dw \times 4}\,(Naira/hr) \tag{7}$$

$$HC_k = \frac{Electricity \quad consumption \quad (monthly)}{720}\,(Wh \quad per \quad hour) \tag{8}$$

$$W_{HC}^k = \frac{HW_k\,(Naira/hr)}{HC_k\,(Wh/hr)}\,(Naira/Wh)\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \tag{9}$$

$$W_T^k = W_{HC}^k \times X\,(Naira) \tag{10}$$

$$W_N^k = -(W_T^k - EC_T^k)(Naira) \tag{11}$$

Where HW_k is a household's hourly wage for a given class k, $wd - h$ is the number of productive hours per work day (9 h, 8 am – 5 pm), dw is the number of work days for a week (5 days), HC_k is the hourly energy value, W_{HC}^k is the marginal monetary value of welfare due to 1Wh of electricity consumption for leisure and household activities in a class k household, X is the energy gained/lost during any transition, W_T^k is the welfare gained/lost during a transition, W_N^k is the net welfare and EC_T^k is the added electricity cost incurred by a household in class k due to a transition. The value of 4 in Eq. (7) represents the number of weeks in a month while 720 in Eq. (8) represents the number of hours in a month. The negative sign in Eq. (11) is because for any possible progressive transition, $EC_T^k > W_T^k$ such that $EC_T^k > 0, W_T^k > 0$.

In the evaluation of W_N^k, productivity is only computed during transition which implies that productivity is a function of energy mobility (and not necessarily access). Thus, households' ability to be

[3] By productivity, we imply the economic contribution of the work day hours of a household. These work hours (typically 8 am–5 pm, 5 days a week) refer to the time (hours) of the day that income for a household is generated.

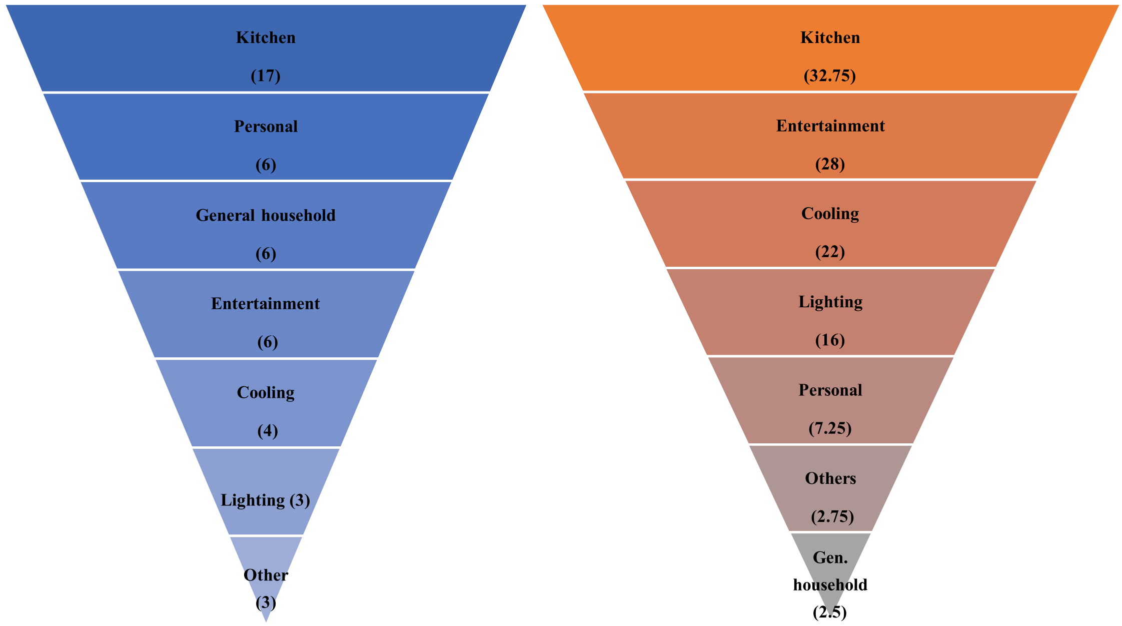


Fig. 6. Left – ranking of needs in order of cumulative nominal comfort cost (C^{e}_{ncc}); right – ranking of needs in order of cumulative usage duration (C^{e}_{td}).

Table 11
Load allocation for household class C1.

Need	Devices	Units	Rating (W)	t_d (hours)
Case: j = 1				
L1	L1(1)	1	16	1.5
L5	L5(4)	1	10	1
Case: j = 2				
L1	L1(1)	1	16	0.75
L2	L2(2)	1	25	2
L5	L5(4)	1	10	1
Case: j = 3				
L1	L1(1)	1	16	6
L2	L2(2)	1	25	4
L3	L3(2)	1	25	2
L5	L5(4)	1	10	1

Table 12
Electricity cost summary from Table 5.

Cases	EC (N/kWh)
Minimum (j = 1)	24.03
Average (j = 2)	28.46
Maximum (j = 3)	31.78

Table 13
Comfort gained by a household in transition across energy classes.

$Re^{1,1}_{cft}$ = 0.95	$Re^{1,2}_{cft}$ = 1.20	$Re^{1,3}_{cft}$ = 1.61
(0.25/37.58/150.32)		
	(0.41/183.97/448.71)	
(0.66/221.55/335.68)		

(a/b/c) – a represents the comfort gained in transition, b is the cost increment in monthly electricity bill for the household under consideration while c is the unit cost of comfort.

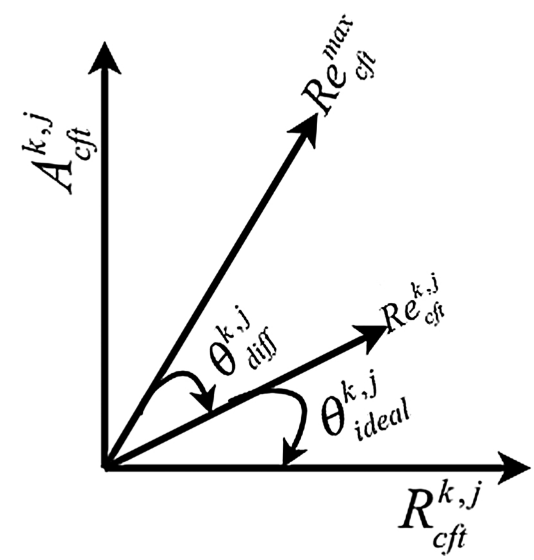


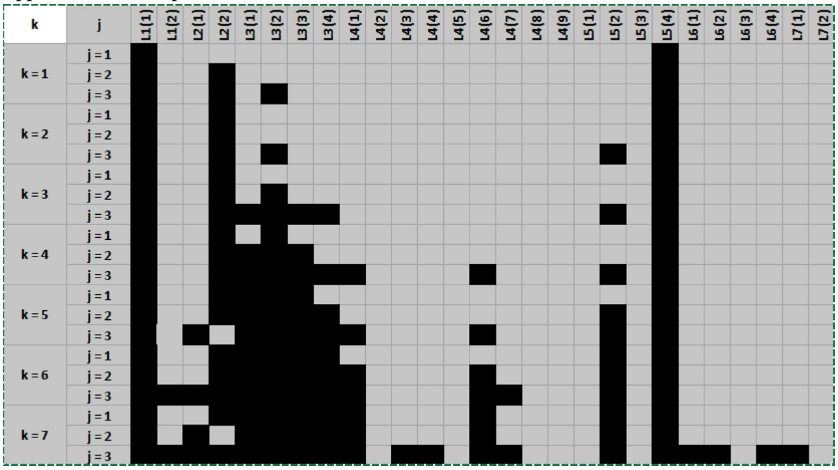
Fig. 7. Deflection of relative and real comfort from the maximum real comfort.

engaged in productive activities becomes noticeable when such households have been able to guarantee some comfort (based on initial access) with the incentive for productivity thus becoming the monetary benefit of further consumption of electricity. Table 16 presents the evaluation of HW_k, HC_k, W^k_{HC}, W^k_T, EC^k_T and W^k_N based on Eqs. (7)–(11).

2.7. Progressive transition path selection

The selection of the progressive transition path for a household based on ownership of electrical appliances for guaranteed productivity assumes that for any transition, $W^k_N(present) - W^k_N(past) > 0$. Also, it is assumed that transition should be minimized within classes to eliminate the class spill-over and class transition-dip effects. Fig. 8 presents the

Table 14
Appliance ownership for each household class in each case.



plot of $Re_{cft}^{k,j}$ and $\theta_{ideal}^{k,j}$ which is used to show the progression path for ownership of electrical equipment. In expanding Table 14, Fig. 8 provides perspective by helping to advise households on the best path in terms of electricity usage that will bring about increased comfort and productivity at the least-cost. It is observed from Fig. 8 that as the ownership level increases, the difference $\theta_{ideal}^{k,j}$ approaches zero which is the ideal difference between $Re_{cft}^{k,j}$ and Re_{cft}^{max}. The progression path as seen from Fig. 6 from an initial point $j = 1; k = 1$ is traced from $Re_{cft}^{1,1} \to Re_{cft}^{1,3} \to Re_{cft}^{2,3} \to Re_{cft}^{3,3} \to Re_{cft}^{4,3} \to Re_{cft}^{5,3} \to Re_{cft}^{6,3} \to Re_{cft}^{7,3}$. The implication of this is that transition between classes does not offer much improvements (cost/benefit wise) while intermediate inter-class transitions (for example $Re_{cft}^{1,2} \to Re_{cft}^{2,1}$) might lead to reduced comfort as shown by the class spill-over and class transition-dip effects. Algorithm 1 presents the ownership progression path incorporating productivity.

2.8. Economic implications

In estimating the economic implications of the computation of $Re_{cft}^{k,j}$ and W_N^k, we seek to establish the relationship between $Re_{cft}^{k,j}$, W_N^k and GDP. From (NBS, 2012), GDP for 2011 is estimated to be N834 000.83 million while electricity generated for 2011 was 21 480 066.26 MW h. If we assume that 10% of the electricity generated was lost during transmission and distribution (T&D losses) while 30% of the generated electricity was also lost as aggregate technical and commercial collection (ATC&C) losses, then about 60% of the generated electricity for 2011 is about 12 888 039. 76 MW h. If we also assume that GDP for 2011 was due primarily to the useful electricity previously computed, then GDP/Wh (N/Wh) is estimated to be about 0.065. Table 17 presents the corresponding values for $R_{cft}^{k,j}$, $A_{cft}^{k,j}$, $Re_{cft}^{k,j}$, W_N^k and GDP_N^k (Naira).

Algorithm 1: Ownership progression based on productivity

Input: $DC^{k,1}, DC^{k,2}, DC^{k,3}$
Output: Ownership progression matrix
For each case j in each class k
  evaluate $R_{cft}^{k,j}$, $A_{cft}^{k,j}$, and $Re_{cft}^{k,j}$
Endfor
Initialize transition start point at $k = 1; j = 1$
For each case $j \to j+1$ transition
  If $(Re_{cft}^{k,j+1} > Re_{cft}^{k,j}$ *and* $Re_{cft}^{k,j+2} > Re_{cft}^{k,j+1})$ ***then***
    $Re_{cft}^{k,j+2}$ is selected to avoid class spill-over effect
  Endif
Endfor
For each class $k \to k+1$ transition
  If $(Re_{cft}^{k+1,j} \geq Re_{cft}^{k,j+2})$ ***then***
    Transition is beyond $Re_{cft}^{k,j+2}$ to avoid the class transition-dip effect
  Endif
Endfor
Incorporating productivity
For each class k and case $j \to j+1$ transition
Compute W_N^k for a household in case j
Transition only possible *iff* $W_N^k(present) - W_N^k(past) > 0$
Endfor

Table 15
Results of satisfaction evaluation of other household classes.

k	j	$R_{cft}^{k,j}$	$A_{cft}^{k,j}$	$Re_{cft}^{k,j}$	$\theta_{ideal}^{k,j}$	$\theta_{diff}^{k,j}$
$k = 1$	$j = 1$	0.92	0.23	0.95	14.04	30.96
	$j = 2$	1.17	0.28	1.20	13.46	31.54
	$j = 3$	1.42	0.77	1.61	28.47	16.53
$k = 2$	$j = 1$	1.17	0.31	1.21	14.84	30.16
	$j = 2$	1.17	0.59	1.31	26.76	18.24
	$j = 3$	1.75	1.60	2.37	42.44	2.56
$k = 3$	$j = 1$	1.17	0.60	1.31	27.15	17.85
	$j = 2$	1.42	1.02	1.75	35.69	9.31
	$j = 3$	2.50	2.20	3.33	41.35	3.65
$k = 4$	$j = 1$	1.42	0.95	1.71	33.78	11.22
	$j = 2$	1.92	0.96	2.15	26.57	18.43
	$j = 3$	2.85	2.27	3.64	38.54	6.46
$k = 5$	$j = 1$	1.92	1.10	2.21	29.81	15.19
	$j = 2$	2.50	2.44	3.49	44.30	0.70
	$j = 3$	3.35	2.32	4.08	34.70	10.30
$k = 6$	$j = 1$	2.50	2.37	3.44	43.47	1.53
	$j = 2$	2.85	2.46	3.77	40.80	4.20
	$j = 3$	4.05	3.39	5.28	39.93	5.07
$k = 7$	$j = 1$	2.85	2.82	4.01	44.70	0.30
	$j = 2$	3.35	2.61	4.24	37.92	7.08
	$j = 3$	5.73	5.53	7.96	43.98	1.02

Table 16
Associated productivity inputs and their values for each class.

k	j	HW_k	HC_k	W_{HC}^k	W_T^k	EC_T^k	W_N^k
$k = 1$	$j = 1$	5.56	1.43	3.89	–	–	–
	$j = 2$	8.33	3.04	2.74	3.18	30.56	27.38
	$j = 3$	11.11	10.76	1.03	5.73	125.14	119.41
$k = 2$	$j = 1$	11.11	3.35	3.32	−17.73	−115.10	−97.37
	$j = 2$	19.44	7.10	0.20	0.54	71.31	70.77
	$j = 3$	27.77	25.11	1.11	14.40	291.99	277.59
$k = 3$	$j = 1$	27.78	7.17	3.87	−50.00	−282.10	−232.10
	$j = 2$	41.67	15.21	2.74	15.86	152.80	136.94
	$j = 3$	55.55	53.79	1.03	28.61	625.70	597.09
$k = 4$	$j = 1$	55.56	14.35	3.87	−109.91	−626.25	−516.34
	$j = 2$	83.33	30.42	2.74	31.70	305.59	273.89
	$j = 3$	111.11	107.60	1.03	57.24	1251.41	1194.17
$k = 5$	$j = 1$	111.11	33.47	3.32	−177.19	−1151.00	−973.81
	$j = 2$	194.44	70.96	2.74	73.95	713.05	639.10
	$j = 3$	277.77	251.04	1.11	143.92	2919.95	2776.03
$k = 6$	$j = 1$	277.78	62.17	4.47	−607.88	−3024.00	−2416.12
	$j = 2$	361.11	131.78	2.74	137.33	1324.24	1186.91
	$j = 3$	444.44	466.22	0.95	228.76	5422.76	5194.00
$k = 7$	$j = 1$	444.44	157.82	2.82	−626.18	−4717.00	−4090.82
	$j = 2$	555.56	334.51	1.66	211.19	3361.54	3150.35
	$j = 3$	666.67	1183.50	0.56	342.31	13765.46	13423.15

Statistical analysis is applied to Table 18 to estimate the relationship between $Re_{cft}^{k,j}$ and W_N^k as inputs and GDP_N^k as output. The statistical tests are carried out to evaluate the most significant of the inputs in terms of contribution to GDP_N^k. In generating Table 18, base values $W_{N,base}^k$ and GDP_{base} are taken to be N987.63 and N6 168.81. The base values are the averaged values for $\sum_{k=1}^{21} W_N^k$ and $\sum GDP$ that are used in normalizing W_N^k and GDP_N^k such that $W_{N,norm}^k = \frac{W_N^k}{W_{N,base}^k}$ and $GDP_{Norm} = \frac{GDP_N^k}{GDP_{N,base}^k}$.

3. Discussion of statistical results

A multiple linear regression was calculated to predict GDP_N^k based on $Re_{cft}^{k,j}$, W_N^k and $Re_{cft}^{k,j} \times W_N^k$. A significant regression equation was found ($F(3, 17) = 222.191$, $p < 0.000$), with an R^2 of 0.975. Participants' predicted GDP_N^k is equal to $-0.626 + 0.091(Re_{cft}^{k,j} \times W_N^k) - 0.265(W_N^k) + 0.430(Re_{cft}^{k,j})$. Participants' GDP_N^k increased by 0.430 and 0.091 for each unit increment of $Re_{cft}^{k,j}$ and $Re_{cft}^{k,j} \times W_N^k$ respectively compared to W_N^k. From the statistical analysis, $Re_{cft}^{k,j}$, $Re_{cft}^{k,j} \times W_N^k$ and W_N^k were significant predictors of GDP_N^k. However, it was observed that both $Re_{cft}^{k,j}$ and $Re_{cft}^{k,j} \times W_N^k$ affect GDP_N^k positively, while W_N^k affects GDP_N^k negatively. The results obtained justify our earlier positions on energy poverty being a function of both access and mobility and the fact that $NPS_{C3} = NPS_{C4} = NPS_{C5} = NPS_{C6}$. The implication of this result thus shows that low/medium income households would prefer to extend the consumption of electricity to derive extra satisfaction than trade off their leisure time for more productivity. A reason for this might be attributed to the limited economic activity/productivity that can be achieved for such trade-off due to their low energy levels (also evidenced from the negative contribution of W_N^k to GDP_N^k).

4. Policy discussions

In this section, we explore the policy implications of ease of access to electricity and mobility of households from one energy (electricity) level to another and its impact on the wider society beyond the household. This is necessary to provide recommendations that will assist the government in formulating policies that will guarantee sufficient electricity for households and that is capable of boosting national productivity.

4.1. Policy discussion on electricity pricing

As earlier established, the disparity in social status across states in Nigeria based on income level has not translated into flexible pricing schemes. An example is observed for states such as Kebbi, Zamfara and Bauchi having over 35% of their households within the C1 – C2 income bracket compared to states such as Lagos, Oyo, Gombe with over 30% of their households in the C5 income bracket. Despite this growing disparity in income levels, electricity tariffs in such states as Benue, Bauchi, Kaduna and Zamfara compare favourably with tariffs from high income paying states like Rivers, Bayelsa and Lagos. In South Africa, the Free Basic Electrification (FBE) policy provides 50 kW h/monthly to poor and vulnerable households at no cost (GNESD, 2018). The implication of this is that irrespective of the unit cost of electricity, households have a minimum level of electricity access that is immune to price variations. In Nigeria, while a flat rate (N4/kWh) is adopted for low electricity consuming households, it becomes difficult proving to the utility what pricing tariff should be used for households due to unavailable energy auditing of households. A pricing policy that ensures the proper labelling of household's *ab initio* for easy dispense of monthly electricity vouchers is thus advocated to guarantee a minimum level of electricity access to vulnerable households that is immune to electricity price fluctuation. Furthermore, while it is important for DISCOs to recoup their investments through appropriate billing, a more flexible billing strategy (incline block tariff, IBT) is advocated. This is to encourage electricity usage from the vulnerable households by appropriately billing households based on their volume of electricity usage. Consider Table 19 which shows on average what the typical energy costs for C1, C4 and C7 households are. It is observed from Table 19 that as the income level of households increases, the energy burden (i.e. the fraction of their monthly income spent on meeting energy needs) reduces. This phenomenon also observed in (CURES, 2009) thus justifies the need for a more appropriate billing method as shown in Fig. 9.

4.2. Policy discussion on poverty mitigation

Considering the dual relationship between energy and poverty (Monyei, Adewumi et al., 2018), and the potential for electricity access to mitigate poverty, it becomes necessary for government policies to address the prevalent case as observed from Table 19. Since it is observed from Table 19 that impoverished households spend a greater

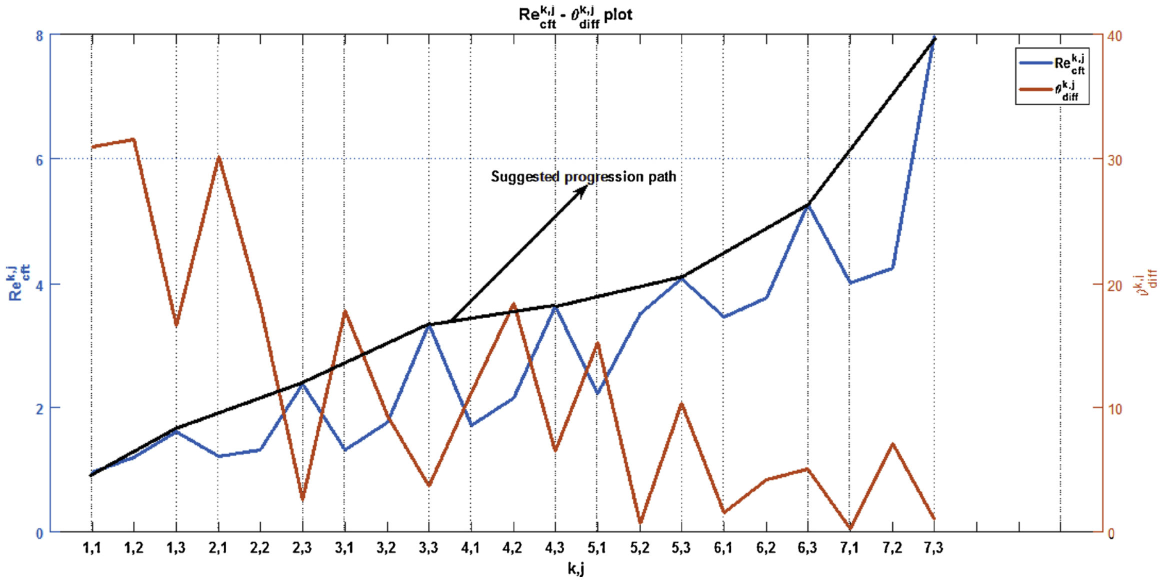


Fig. 8. Progression path for ownership of electrical equipment.

Table 17
Proposed inputs to GDP.

$R_{cft}^{k,j}$	$A_{cft}^{k,j}$	$Re_{cft}^{k,j}$	W_N^k (N)	GDP (N)
0.92	0.23	0.95	–	66.95
1.17	0.28	1.20	27.38	142.35
1.42	0.77	1.61	119.41	503.75
1.17	0.31	1.21	−97.37	156.65
1.17	0.59	1.31	70.77	332.15
1.75	1.60	2.37	277.59	1 175.20
1.17	0.60	1.31	−232.10	335.40
1.42	1.02	1.75	136.94	711.75
2.50	2.20	3.33	597.09	2 517.45
1.42	0.95	1.71	−516.34	671.45
1.92	0.96	2.15	273.89	1 423.50
2.85	2.27	3.64	1194.17	5 035.55
1.92	1.10	2.21	−973.81	1 566.50
2.50	2.44	3.49	639.10	3 320.85
3.35	2.32	4.08	2776.03	11 748.75
2.50	2.37	3.44	−2416.12	2 909.40
2.85	2.46	3.77	1186.91	6 167.20
4.05	3.39	5.28	5194.00	21 819.20
2.85	2.82	4.01	−4090.82	7 385.95
3.35	2.61	4.24	3150.35	6 167.20
5.73	5.53	7.96	13423.15	55 387.80

Table 18
Normalized Table 17.

$Re_{cft}^{k,j}$	$W_{N,Norm}^k$	$Re_{cft}^{k,j} \times W_{N,Norm}^k$	GDP_{Norm}^k
0.95	–	0.00	0.01
1.20	0.03	0.04	0.02
1.61	0.12	0.19	0.08
1.21	−0.10	−0.12	0.03
1.31	0.07	0.09	0.05
2.37	0.28	0.66	0.19
1.31	−0.24	−0.31	0.05
1.75	0.14	0.25	0.12
3.33	0.60	2.00	0.41
1.71	−0.52	−0.89	0.11
2.15	0.28	0.60	0.23
3.64	1.21	4.40	0.82
2.21	−0.99	−2.19	0.25
3.49	0.65	2.27	0.54
4.08	2.81	11.46	1.90
3.44	−2.45	−8.43	0.47
3.77	1.20	4.52	1.00
5.28	5.26	27.77	3.54
4.01	−4.14	−16.60	1.20
4.24	3.19	13.53	1.00
7.96	13.59	108.18	8.98

portion of their income in meeting their energy needs, government policies must thus confront this by ensuring that vulnerable households have access to alternative energy sources (in the absence of electricity connections) at very reduced or highly subsidized prices. For example, the Free Basic Alternative Energy (FBAE) policy in South Africa provides poor off-grid rural households with limited quantities of alternative energy sources (fuels) to meet their basic energy needs (DME, 2007). A direct consequence of this is that households would thus be able to deploy income saved (due to reduced energy burden) to other economic activities that contribute significantly to improving their quality of life (QoL). Furthermore, for households connected to off-grid schemes, adopted billing strategies must identify vulnerable households and provide support for them (through direct government financing in the form of subsidy) to encourage them in consuming electricity. According to (Azimoh, Klintenberg, Mbohwa, & Wallin, 2017), while it is posited that electrification cannot solve the entirety of the developmental problems plaguing rural households, households cannot access development assistance opportunities without having access to electricity.

4.3. Policy discussion on productivity

The results from the statistical analysis presented in Table 18 show that $Re_{cft}^{k,j}$ has the highest impact on GDP_{Norm}^k. The implication of the obtained result means that beyond owning an electrical appliance, the duration of its usage contributes significantly to the QoL of the household occupants. With highly satisfied household occupants, there is more motivation to be productive to sustain an income level that will guarantee at the minimum, the level of comfort currently being enjoyed. Furthermore, our research has shown that increasing electrical appliance ownership as a result of increasing income does not necessarily translate to increase in comfort derived from those owned electrical appliances. An increasing optimum comfort is thus only derived from a concerted ownership of electrical appliances that follows the progression path shown in Fig. 8. This research thus serves as a policy framework on two fronts – first, it provides the households and

Table 19
Households' energy use pattern and associated energy burden.

End use	C7 (k = 7, j = 3)		C4 (k = 4, j = 2)		C1 (k = 1, j = 1)	
	Source	Cost	Source	Cost	Source	Cost
Lighting	kWh		kWh		kWh	
Cooking	kWh		Kerosene/wood		Wood/kerosene	
Space-cooling	kWh		kWh			
Refrigeration	kWh					
Water heating	kWh		Kerosene/wood		Wood/kerosene	
Television	kWh		kWh			
Radio	kWh		kWh			
Cell phone charge	kWh		kWh		kWh	
Electricity cost (N)		6,711.04		610.09		61.01
Other cost (N)		0.00		4,430.00		651.00
Total energy costs (N)		6,711.04		4,950.09		712.01
Average monthly income (N)		120,000		15,000		1,500
Energy burden (%)		5.59		33.00		47.47

kWh – implies mains electricity as source; kerosene/wood – implies that kerosene is the primary source for this class; wood/kerosene – implies that wood is the primary source for this class; wood/kerosene and kerosene/wood costs have been computed using kerosene cost equivalent of N434/l (utilized January 2017 price from (NBS, 2017)) with monthly equivalents of 10 l and 1.5 l for the C4 and C1 household classes.

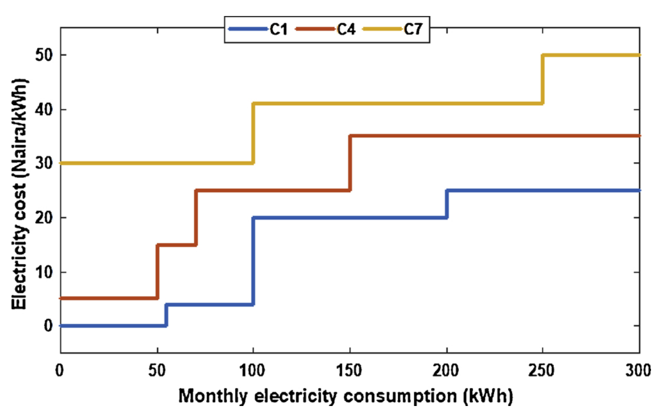


Fig. 9. A proposed sample incline block tariff (IBT).

government with evidence to show that the progression path in Fig. 8 offers households maximum comfort and, secondly, it enables the government target policies that will ease the acquisition and ownership of critical electrical appliances that will contribute significantly to improvement in comfort and ultimately productivity.

4.4. Policy discussion on electrification

Beyond providing households with electricity access, this research has shown the impact of mobility on QoL. It thus becomes important that electrification exercises especially off-grid must offer households beyond access, mobility up to a certain level. According to (Valer, Manito, Ribeiro, Zilles, & Pinho, 2017), there is the possibility of energy growth for off-grid poor rural homes owing to the mutual influence between demand and supply that exists when communities are electrified due to the purchase of new appliances. Off-grid electrification projects must thus adopt measures that guarantee availability, security of supply and adequacy of supply which form part of the energy justice framework presented in (Sovacool & Dworkin, 2015). Furthermore, considering the potential impact for weather variations to adversely affect the electricity production of renewable energy projects, alternative sources like diesel/petrol generators should be provided to guarantee supply security while optimization schemes could be employed to ensure that appropriate slots are created for households to utilize higher energy consuming appliances – electric cookers/stoves, water heater etc. This is to ensure that households have daily guaranteed supply and can derive optimum comfort from owned electrical appliances.

5. Conclusion and policy implications

This research work has investigated the impact of ownership of electrical appliances and duration of use on comfort level of building occupants. The findings from this work reveal the following. First, increasing ownership of electrical appliances does not necessarily translate to increasing comfort. Based on the progression path for ownership of electrical appliances shown in Fig. 8, it is seen that higher income levels do not automatically lead to increase in comfort levels based on the class spill-over effect and class transition-dip effect. Second, this research has shown that beyond energy access, households must be able to migrate from one energy (electricity) level to a higher one without the hindrance of energy usage limitation for improved productivity. Based on the statistical analysis carried out to determine the effect of the inputs – $Re_{cft}^{k,j}$, W_N^k and $Re_{cft}^{k,j} \times W_N^k$ on GDP_N^k, our research has shown that there are statistically significant differences in which the three inputs affect GDP_N^k. For example, our work shows that both $Re_{cft}^{k,j}$ and $Re_{cft}^{k,j} \times W_N^k$ affect GDP_N^k positively, while W_N^k affects GDP_N^k negatively with $Re_{cft}^{k,j}$ having the greatest positive significant contribution to GDP_N^k. Third, this research advocates the need for an appropriate billing system that does not discourage electricity consumption especially from the low/middle income households. This is necessary to avoid the cases of declining electricity consumption observed in (Monyei & Adewumi, 2017; Monyei, Adewumi et al., 2018). Fourth, our research presents policy discussions that target improving electrification projects, electricity pricing, poverty mitigation and productivity, by providing government and households with a guide to owning electrical appliances with increasing income (Fig. 8) for increasing comfort (QoL) and productivity. Furthermore, this research work has shown that energy burden increases significantly for low/medium level households (Table 19) with increasing needs. We thus offer based on our findings that a more co-ordinated approach to electrification that guarantees mobility and productivity including an appropriate billing method can help address the issue of energy poverty. This is because, households will be able to plan their ownership of electrical appliances to: derive optimum utility, precipitate economic growth and further utilise the available electricity supply capacity at the cheapest cost. An argument for the implementation of the proposed model in this research work in SSA (for example Nigeria) is based on the current awareness and increasing penetration of pre-paid meters. We offer that pre-paid meters and the existing infrastructure can allow the utility company the ability to *ab initio* apply a flexible billing method on initial purchases of electricity units from households based on their energy demand levels (MYTO II). This work finds general application across sub-Saharan Africa (SSA) and developing Asia due to the similarity in electrification access problems and the need for a concerted ownership of electrical appliances that guarantee households value for investments in electrical appliances.

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