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January 22, 2019

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ABSTRACT

Global household electricity consumption of appliances is anticipated to double by 2030, with most of the growth expected to occur in developing countries. The rising electricity consumption is triggered by population growth, economic development, change in lifestyle and increasing domestic appliance ownership. In Ghana, population is projected to be 40 million by 2030, with an average annual growth rate of 2.5%. Presently, urban centres account for 55% of the population and 70% of the residential electricity consumption. With the government’s efforts of decreasing rural to urban migration through its district industrialization agenda, the evolution of electricity demand becomes uncertain due to the uncertainty of how “urbanisation” or “ruralisation” influences residential electricity consumption. Consequently, the main objective of this study is to estimate the future demand for electricity in urban and rural contexts (2015-2050) under different migration scenarios (High, Medium, Low). In this study, 21 household appliances and 4 lighting technologies are categorised under 8 different end-uses and modelled. A hybrid approach is used, combining a bottom-up approach to estimate electricity consumption with top-down data from population, income and appliance ownership. The results of the 3 scenarios show that by 2050 the rural consumption may be 19%, 67% and 134% of the urban consumption for the High, Medium and Low scenarios, respectively.

KEYWORDS

Appliance ownership, Population, Bottom-up approach, Top-down approach, electricity demand, Electricity intensity, Ghana

INTRODUCTION

The significance of energy use in the development of every economy cannot be overemphasized and access to modern energy services is crucial for sustainable socioeconomic development [1]. Electricity is used in nearly all kinds of human activities, ranging from industrial production, residential purposes, agriculture, transportation, lighting and heating [2]. Global household electricity consumption of appliances is anticipated to double by 2030, with most of the growth expected to occur in developing countries [3]. The rising electricity consumption is fuelled by population growth, economic development, electrification rate, change in lifestyle and increasing domestic appliance ownership [4]. In the case of Ghana, population is projected to be 40 million by 2030, with an average annual growth rate of 2.5% [5]. The annual gross domestic product (GDP) in recent times has witnessed a consistent growth, with the country experiencing an all-time record of 14% GDP growth in 2011 [6]. The national electricity access rate is estimated to be 81%, with urban access of 99% and rural access of 49% [7,8]. This is relatively high, compared with the Economic Community of West African States (ECOWAS) target of 100% for urban and 36% for rural households by 2015 [8]. Currently, urban centres account for 55% of the population and 70% of the residential electricity consumption [9]. With the government's efforts of decreasing rural-urban migration through its district industrialization agenda, the evolution of electricity demand becomes uncertain due to the uncertainty of how "urbanisation" or "ruralisation", defined as the shares of a geographical area's population living in urban or rural areas, influence residential electricity consumption.

In a context where electricity use characterization and end-use projection estimates for residential households is a discussion of interest for many stakeholders (e.g. utilities, consumers and policy makers), the specific objectives of this study are two-fold. The first objective is to characterize and disaggregate urban and rural household electricity demand. The second is to estimate the future demand for electricity (2015-2050) in urban and rural households under different migration scenarios based on household appliance evolution. In this study, the electricity demand of 21 household appliances and 4 lighting technologies is categorised under 8 different end-uses and its evolution is modelled over time. The 8 end-use services considered include: refrigeration, air conditioning, lighting, cooking/small kitchen appliance, entertainment, laundry, house cleaning and hot water heating. The four lighting technologies are Incandescent lamp, Fluorescent lamp, CFL and LED.

A bottom-up approach is adopted to estimate electricity consumption. A bottom-up model approach uses high disaggregation data to describe energy end-uses and technological options in detail, focusing on the energy sector exclusively. This approach enables a high degree of technological detail, which can be used to assess future energy demand and supply as compared to the top-down approach [10]. For instance, Bedir *et al.* 2013 [11] evaluated the extent to which lighting and appliance use influence the total electricity consumption by using a dataset of 304 Dutch dwellings. The evaluation variables used were household characteristics, individual characteristics, economic characteristics, occupancy (number of people and duration of occupation in each room), dwelling characteristics, appliance use and lighting devices. Based on 3 developed models, the results showed that the duration of appliance use and dwelling and household characteristics are important predictors in models of electricity consumption.

Alternatively, a top-down model approach is mostly used to estimate the total residential sector energy consumption based on indicators such as GDP, employment rates, price indices, climatic conditions, housing construction/demolition rates, appliances ownership estimations and number of units. This approach does not separate energy consumption into different end-uses. The strengths are its data availability and simplicity [12]. For example, Blázquez *et al.* 2013 [13] undertook an empirical analysis of residential electricity demand in 47 Spanish provinces for the period 2000 to 2008. The study established the characteristics affecting Spanish residential electricity use, specifically, electricity price, income, and weather conditions. The results showed that weather variables have a significant impact on electricity demand while demand is price inelastic but income elastic.

As a result, this study combines the properties of both bottom-up and top-down approaches in the estimation of the residential electricity consumption considering the characteristics of the acquired dataset. The hybrid nature of this model compensates for the inherent weaknesses of using separate approaches.

METHODS AND DATA

This section presents the classification of the various end-uses, modelling methodologies for appliances and lighting, data assumptions and scenarios.

Classification of appliances and end-uses

In all, 21 appliances and 4 lighting technologies are analysed in this study, as shown in Table 1. The appliances are categorized into eight different end uses, namely: refrigeration, air conditioning, lighting, cooking/small kitchen appliances, entertainment, laundry, house cleaning and hot water heating.

Table 1. Appliances and end-uses taxonomy

End-Use	Appliances
Refrigeration	Refrigerator; Freezer
Air conditioning	Air conditioner; Fan
Entertainment	Camera; Laptop; Desktop computer; Television; CD player; Printer; Mobile phone; DVD/VCD/MP3/MP4 player
Laundry	Washing machine; Electric iron
Lighting	Incandescent lamp; Fluorescent lamp; CFL; LED
Cooking/kitchen appliances	Microwave; Rice cooker; Blender; Toaster; Electric kettle
House cleaning	Vacuum cleaner
Hot water heating	Water heater

Appliances model

The sales of an appliance in a specific year, as presented in Eq. (1), is defined as the stock of an appliance type in the predicting year minus the stock in the previous year plus the stock of appliances retired in the current year.

$$S_i^a = stock_i^a - stock_{i-1}^a + AR_i^a \tag{1}$$

where $stock_i^a$ is the number of units of appliance *a* operating in year *i*; $stock_{i-1}^a$ is the number of units of appliance *a* in operation in year *i-1*; and AR_i^a is the stock of appliance *a* retired in year *i*.

The appliance stock, as expressed in Eq. (2), is a function of the appliance ownership and the number of households.

$$Stock_i^a = HH_i \times \gamma_i^a \tag{2}$$

where HH_i is the number of households in year *i;* and γ_t^a is the ownership of appliance *a* at time *t* (unit/HH).

The total number of appliances retired in each year, as presented in Eq. (3), is the sum of the retired appliances that entered the system in previous years.

$$AR_i^a = S_i^a \times (1-\varphi_a(0)) + \sum_{j=i-k}^{i-1} S_j^a \times (\varphi_a(\mathrm{i-j+1}) - \varphi_a(\mathrm{i-j})) \tag{3}$$

where S_j^a is the number of sales of appliance *a* in year *j*; *k*: maximum age of an appliance and $\varphi_a(\mathrm{i-j+1})$, $\varphi_a(\mathrm{i-j})$ is the probability of survival of appliance *a* with age *i-j+1* and *i-j* respectively.

The appliance ownership evolution is modelled as a sigmoid function of time using logistic function that captures consumer choice (see Eq. (4&5)). The appliance ownership is a function of appliance household penetration and saturation. Penetration is defined as the proportion of households in which one or more appliance type is present (irrespective of the number of units of that appliance in the household) while Saturation refers to the average number of appliances per household for those households with one or more of the appliance. The logistic function, by formulation, has a maximum value of one, at which point saturation is reached. In this model, the maximum value could be more than one because of the propensity of households to own more than one appliance (e.g. TVs or fridges). The function is scaled by the saturation level parameter.

$$\gamma_t^a = \frac{\delta^a}{1+e^{\log_e(\delta^a/\beta^a - 1) - bt}} \quad ; \quad \begin{array}{l} \delta = \alpha \times \rho; where\{^{\alpha \geq 1}_{\rho \leq 1} \\ \beta = \alpha \times \rho; where\{^{\alpha = 1}_{\rho \leq 1} \end{array} \tag{4}$$

$$\text{And } b = \frac{\log_e(\delta^a/\beta^a - 1)}{\vartheta(t)} \tag{5}$$

where δ^a is the theoretical maximum (future) ownership of appliance *a* at t=60; β^a is the initial ownership of appliance *a* at t=0; *b* is the scale parameter; *t* is the time in years (e.g. 0 for 1990); ϑ(t) is the abscissa inflection point; ρ is the appliance penetration and α is the saturation level.

The appliance survival rate, as presented in Eq.(6), is modelled as a non-linear function using the modified Weibull probability distribution function as expressed in [14], where the survival rate is a function of the appliance average lifetime age.

$$\varphi^a(k) = \exp - \left[\left(\frac{k+b^a}{T^a} \right)^{b^a} \right] ; \ \varphi^a(0) \cong 1 \tag{6}$$

where *k* is the appliance age expressed in years (*k* = 0 to 30 since the maximum lifetime rarely exceeds 30 years); b^a is the failure steepness for appliance *a* ($b^a > 1$, i.e., survival rate decreases with age) and T^a is the characteristic service life for appliance *a*.

The unit annual electricity consumption of an appliance, as presented in Eq.(7), is modelled as a function of the appliance's power rating, annual operating hours and technological improvement factor. The technological factor is introduced because, even in the absence of energy efficiency standards, technological progress leads to yearly increases in the household appliance efficiency [15].

$$UEC_i^a = \frac{P_{i-1}^a \times (1-\eta_{t-improv}^a) \times t_i^a}{1000} \tag{7}$$

where P_{i-1}^a is the power rating of appliance *a* in year *i-1*; $\eta_{t-improv}^a$ is the technology improvement factor in appliance *a* and t_i^a is the operating hours of appliance *a* in year *i*.

The unit electricity consumption of the air conditioner, as depicted in Eq.(8), is the product of the cooling capacity and the annual operation hours divided by the energy efficiency ratio. In estimating the annual operating hours, the cooling degree-days methodology can be used and fixed for countries without much variation, such as Ghana.

$$AC(UEC)_i = \frac{CC_i \times t_i}{EER_i} \tag{8}$$

where $AC(UEC)_I$ is the unit electricity consumption of air conditioner in year *i*; t_i is the operating hours of A.C in year *i*; CC_i is the average cooling capacity of A.C in year *i* and EER_i is the Energy Efficiency Ratio of A.C in year *i*.

The electricity consumption of an appliance is modelled as a function of appliance sales, survival rate and the unit electricity consumption of the appliance as expressed in Eq. (9).

$$AEC_i^a = \sum_{j=i-k}^{i} S_j^a \times \varphi_a(\text{i}-\text{j}) \times UEC_j^a \tag{9}$$

where AEC_i^a is the electricity consumption of appliance *a* in year *i* and UEC_j^a is the unit electricity consumption of appliance *a* in the starting or sales year *j*.

Lighting model

The lighting consumption, as expressed in Eq.(10), is modelled as a key function of household energy drivers such as floorspace, household income, household size and population as defined and expressed in [16,17].

$$LEC_i = \frac{FS_i \times \sum_{l=1,2...}^{n} \left(\frac{S_{l,i}}{\eta_{l,i}} \right) \times Q_i \times t_i * HH_i}{1000} \tag{10}$$

And $FS = f(\text{Income}/HH)$

where LEC_i is the lighting electricity consumption in year *i* (kWh); FS_i is the floor space per household in year *i* (m^2/hh), which changes as a function of household income per capita; $S_{l,i}$ is the share of lighting technology *l* in year *i* (%); $\eta_{l,I}$ is the efficiency or efficacy of lighting technology *l* in year, *i* (lm/W); Q_i is the useful lighting needs (lm/m^2); t_i is the average lighting time duration for a household in year *i* (hrs) and *n* is the total number of lighting technologies.

Data and assumption

Comprehensive and reliable data on urban and rural household electricity consumption is quite scanty, which is usually the case for most developing countries. To obtain the appliance ownership data, this study relied on the living standard survey reports (GLSS) by the Ghana Statistical Service (GSS) [18–21]. To assume the future point (2050) of appliance ownership for both urban and rural under each scenario, the average household income levels for urban households were considered to be 1.8, 1.5 and 1.2 times the rural households for the High, Middle and Low scenarios, respectively. These income levels were assumed based on the averaged statistical data from the Ghana Statistical Service [18–21] while electrification rate at the various geographical regions is assumed to be 100% [22]. The estimated evolution of the appliance ownership for urban and rural is as shown in Figure 1.

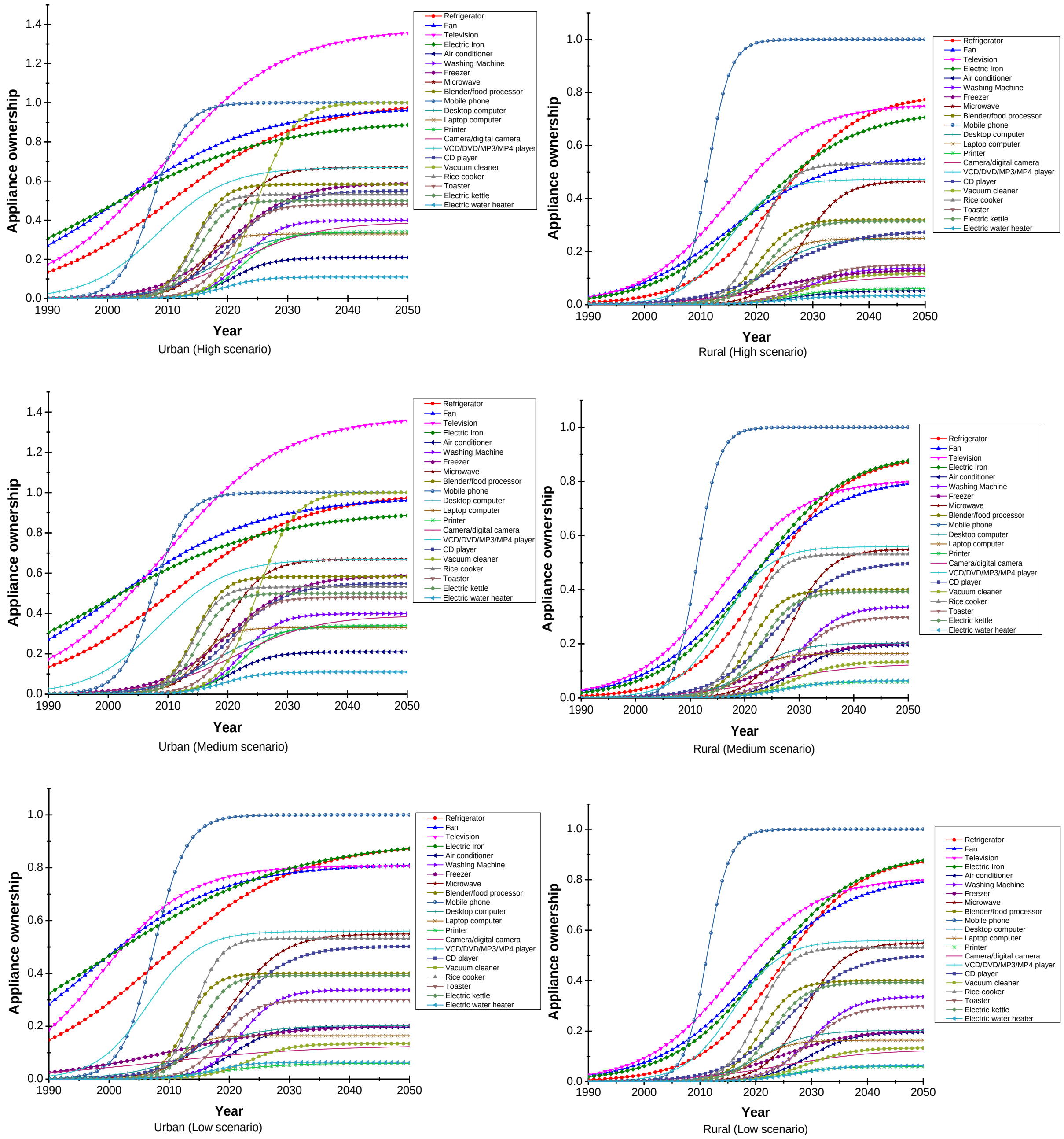

Figure 1. Appliance ownership evolution for urban and rural under scenarios (High-Medium-Low) from 1990-2050

Population, household income and household size data were sourced from GSS (1995,2000,2008,2014)[18–21] and World Bank (2017)[6]. For the estimation of the unit electricity consumption of appliances, power rating and time of use data is sourced from various household survey reports and literature [23–29]. The technology improvement factor assumed for each appliance is dependent on the technological advancement, type and nature of appliance sold on the Ghanaian market. For the air conditioner, the cooling capacity requirement, hours of operation and energy efficiency ratio (EER) data were sourced from Constantine *et al*. (1999) and Koizumi (2007) [30,31]. Figure 2 shows the estimated evolution of each appliance's unit electricity consumption.

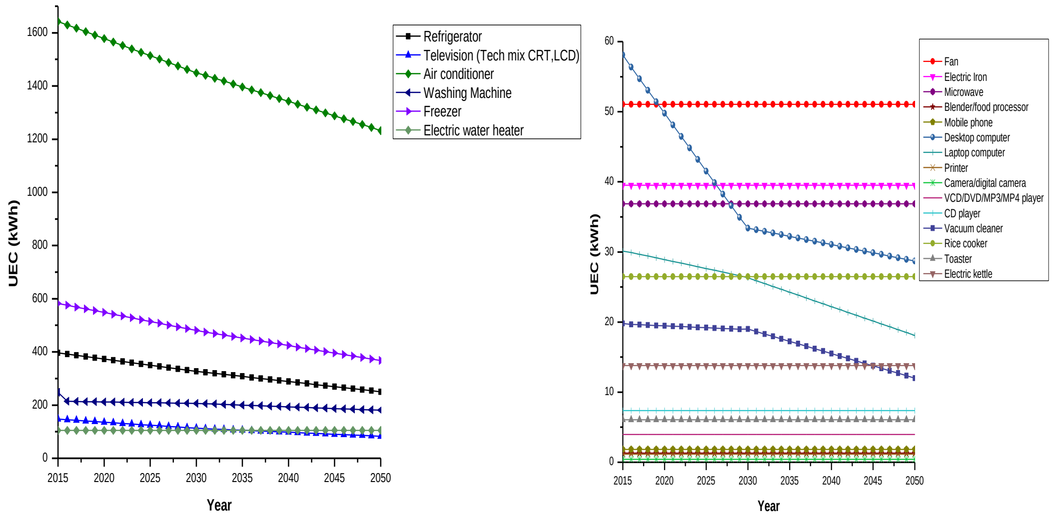

Figure 2. Evolution of unit electricity consumption of appliances from 2015-2050

For lighting, the evolution of the floor area is estimated using Eq.(11), which is based on scatter and regression analysis using global data sourced from Dol *et al*. (2010); United Nations (2001) and Kozhenova (2010) [32–34].

$$y_{fs}=0.6057x^{0.4034},\ R^2=0.84 \qquad (11)$$

where y_{fs} is the floorspace area (m^2/cap) and x is the income per capita (US$).

The required light intensity, daily duration of light use and lighting efficacy for each technology is adapted from Shen (2006); Souza (2011) and Lee (2016)[16,17,35]. The assumed technological share of lighting fixtures is indicated in Table 2.

Table 2. Baseline for lighting technology shares between 2015 and 2050

Lighting technology	2015	2020	2030	2040	2050
Incandescent lamp (IL)	1%	0%	0%	0%	0%
Fluorescent lamp (FL)	17%	15%	13%	11%	9%
Compact fluorescent lamp (CFL)	82%	84%	83%	82%	81%
Light emitting diode (LED)	0%	1%	4%	7%	10%

Scenario formulation

In this study, 3 migration scenarios were created (High, Medium and Low), as described in Table 3. The High scenario is based on United Nations projections [36], while the Medium and Low scenario are assumed based on historical antecedent when economic activities were dominant at the rural areas (Agrarian age)[6].

Table 3. Scenario definitions

Scenario	Label	Description
High	• Urban_70-30% • Rural_70-30%	The **high scenario** considers urbanization and ruralisation to follow the existing projections. In this scenario, the urban share of population by 2050 is 70% while the rural share is 30%. The urbanisation rate between 2015 and 2050 is 0.76% while the ruralisation rate is -1.26%.
Medium	• Urban_50-50% • Rural_50-50%	In the **medium scenario**, the urban share of population by 2050 is 50% and rural is 50%. The urbanisation rate between 2015 and 2050 is -0.22% and the ruralisation rate is 0.24%.
Low	• Urban_40-60% • Rural_40-60%	In the **low scenario**, the urban share of population by 2050 is 40% while rural is 60%. The urbanisation rate between 2015 and 2050 is -0.86% and the ruralisation rate is 0.76%.

RESULTS

Model Validation

The model is validated using actual historical and assumed input data, and the model results are compared with the real residential electricity demand data at the national level for the years between 2000 and 2014, due to the lack of historical annual urban and rural residential demand statistical data. The relative percentage difference between the modelled and real data is estimated at an average of -16%. This result is reasonably accurate since the difference could account for the other connected loads and appliances used in households but not accounted for in this study.

Projected electricity consumption (2015-2050)

The results for the estimated demand for the urban and rural under the different scenarios are presented next.

High scenario analysis: In this scenario, as depicted in Figure 3, electricity consumption by urban households in 2015 was 2862 GWh and would be 11747 GWh in 2050 while rural household consumption was 711 GWh and would be 2219 GWh in the respective years. Rural consumption corresponds to 25% and 19% of the urban consumption in 2015 and 2050, respectively.

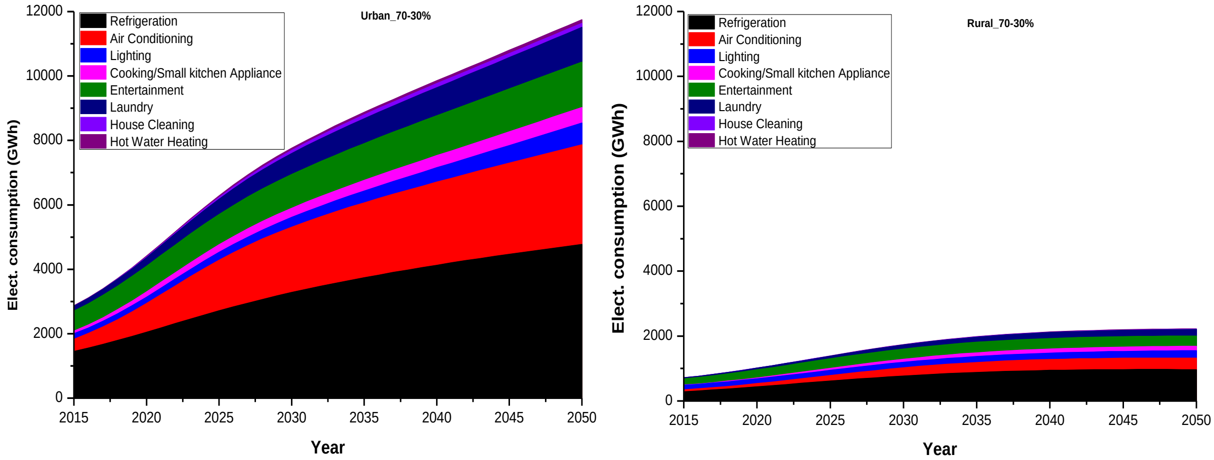

Figure 3. Electricity consumption for urban (Left) and rural (Right) under High scenario

Medium scenario analysis: In this scenario, as shown in Figure 4, urban household electricity consumption in 2015 was 2862 GWh and would be 8405 GWh in 2050, while the rural was 736 GWh and would be 5627 GWh in the respective years. This indicates that rural electricity consumption is about 26% and 67% of urban in 2015 and 2050 respectively.

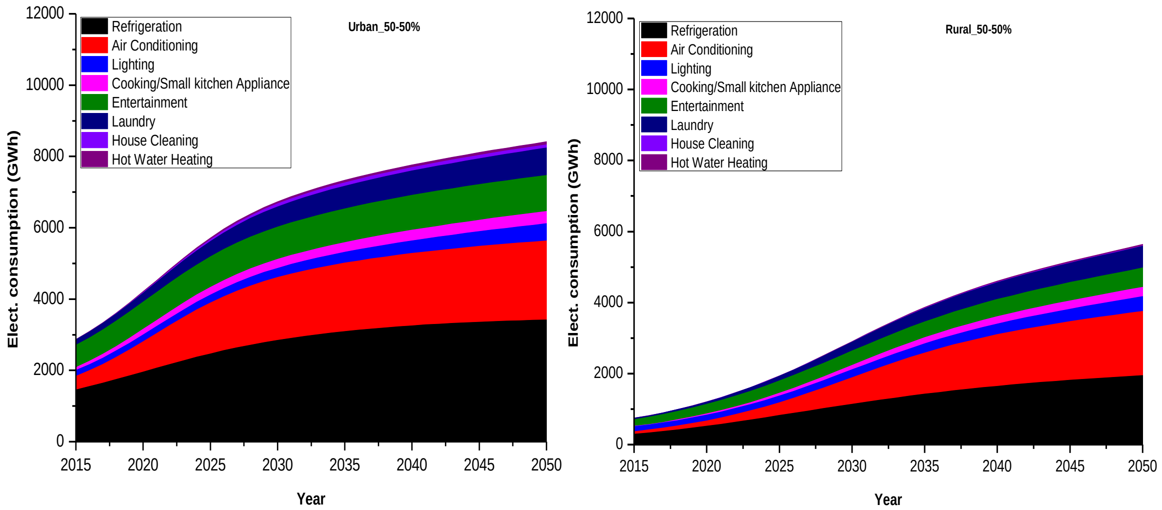

Figure 4. Electricity consumption for urban (Left) and rural (Right) under Medium scenario

Low scenario analysis: In this scenario, displayed in Figure 5, urban household electricity consumption was 2590 GWh in 2015 and would be 5076 GWh in 2050 while rural consumption was 736 GWh and would be 6780 GWh in the respective years. Rural consumption by 2050 is 34% higher than the urban.

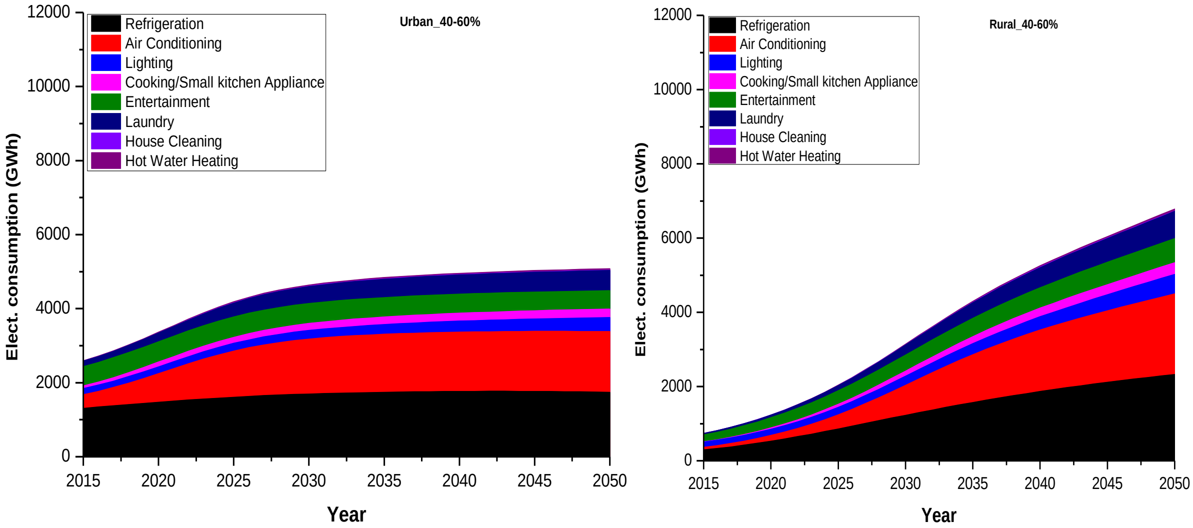

Figure 5. Electricity consumption for urban (Left) and rural (Right) under Low scenario

Figure 6 compares the urban and rural electricity consumption for all the scenarios. Further analysis indicates that in 2015, the average electricity consumption per household ranges between (629-695) kWh for urban and (252-261) kWh for rural households. Similarly, per capita consumption varies between (175-193) kWh for urban population and (56-58) kWh for rural population. By 2050 per household and per capita of the average electricity consumption ranges between (905-1196) kWh and (253-335) kWh for urban, respectively, and (591-903) kWh and (145-226) kWh for rural, respectively. This reveals that, by 2050, the average electricity consumption per household in urban areas will grow less than 100% compared to 2015 while in rural areas it will grow more than 300%. Even though the per capita consumption in rural areas increases around 4-folds over time, it will still be lower in comparison to urban areas. There is substantial increase in the electricity usage per capita though less than the current global average of 2674 kWh [37]. The summary outcome of the scenarios shows that the concept of urbanisation or ruralisation have very significant impact on the regional and geographical electricity intensity.

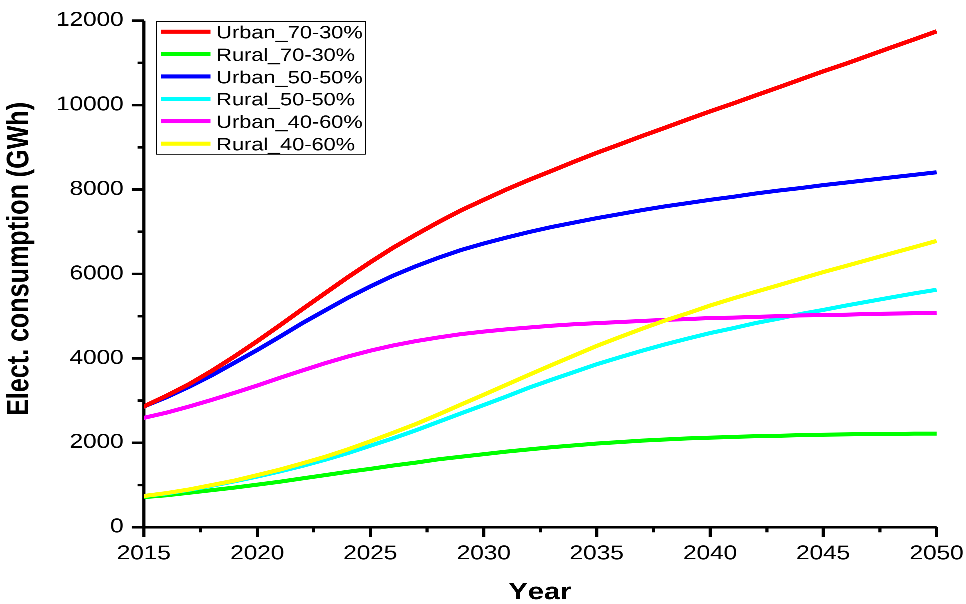

Figure 6. Electricity consumption evolution under all scenario between 2015-2050

End-use analysis (2015-2050)

The sectorial end-use analysis also revealed important aspects as shown in Figure 7 and Figure 8. In urban households, for all scenarios, the refrigeration end-use service was the largest consuming sector. In the year 2015, the share of refrigeration was about 50%, followed by entertainment with 20%. Air conditioning was the third largest sector with a share of 14%, followed by lighting with 7%, laundry with 6% and cooking with 3%. The combined consumption of house cleaning and hot water heating had a share near 0%. By 2050, the weight in share of the refrigerator had reduced to a range between (34-41%) with air conditioning increasing its share to (26%-32%) and assuming the second largest consuming sector. Entertainment reduced its weight share to (10%-12%) while laundry increased its share to (9%-11%). Lighting had a share of between (6%-7%) while cooking increased to (4%-5%). The combined consumption of house cleaning and hot water heating had a share of about (1%-2%).

Similarly, in rural households by 2015, refrigeration share of the consumption was about 39%, followed by entertainment with 26%. Lighting was the third largest consuming service with a share of 20%, followed by air conditioning with 9%, laundry with 5% and cooking with 1%. The combined consumption of house cleaning and hot water heating had a share of virtually 0%. By 2050, the weight in share of the refrigerator ranged between (34-43%) with air conditioning increasing its share to (16%-32%), securing the second largest consuming sector. Entertainment reduced its weight share to (10%-14%) while laundry increased its share to (9%-11%). Lighting had a share of between (7%-10%) while cooking increased to (5%-6%). The combined consumption of house cleaning and hot water heating had a share of about 1%.

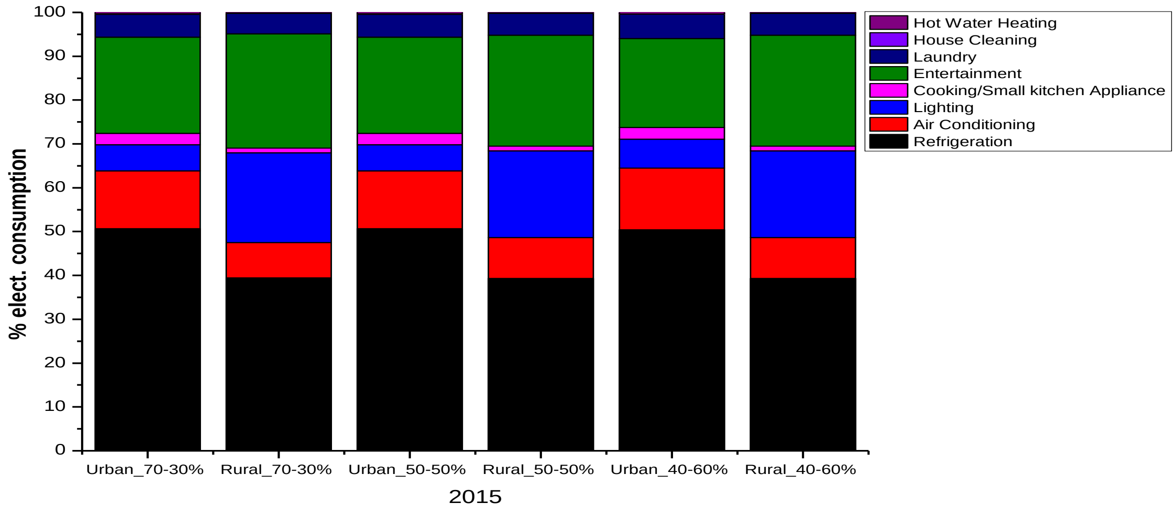

Figure 7. Percentage share of end-uses in 2015 under all scenarios

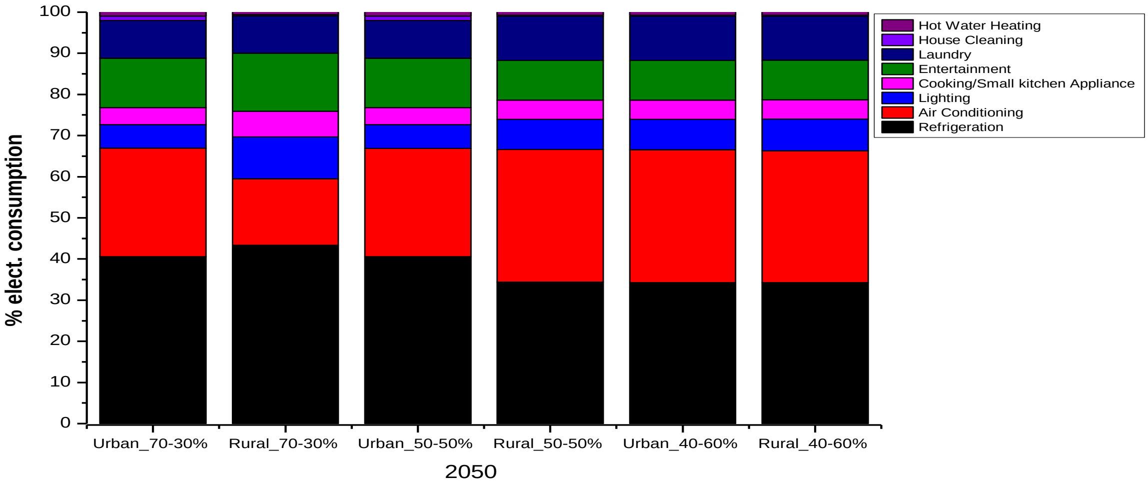

Figure 8. Percentage share of end-uses in 2050 under all scenarios

Generally, the changes in the weight share were due to the increasing ownership of some appliances over time. The increase in air conditioning for example is expected due to cooling requirements, because of the tropical climatic nature of Ghana, and economic development. The cooling capacity need is high especially for air conditioners making the unit electricity consumption high even though there is periodic improvement in the energy efficiency ratio (EER). Seven appliances and one lighting technology consisting of refrigerator, air conditioner, television, freezer, fan, electric iron, washing machine and CFL constituted about 93% of urban and rural electricity consumption share in 2015 and a range of between (88%-91%) by 2050 in all scenarios.

CONCLUSIONS

In this work, 21 household appliances and 4 lighting technologies are categorised under 8 different end-uses and its evolution over time is modelled for both urban and rural settlements in Ghana. A hybrid approach is used, combining a bottom-up approach to estimate electricity consumption with top-down data from population, income and appliance ownership. The summary results of the 3 scenarios show that by 2050 the rural consumption is expected to be 19%, 67% and 134% of the urban consumption for the High, Medium and Low scenarios respectively. In the end-use shares, by 2050, refrigeration was found to be the largest energy service, followed by air conditioning, entertainment, laundry, lighting, cooking, hot water heating and house cleaning. Consistently, most of the energy related policies have favoured the structural influence of urbanisation. This study has indicated that, with government's initiative on reducing rural-urban migration through its audacious district industrialization agenda, electricity evolution dynamics could change. It is certain that the concept of "urbanisation" or "ruralisation" has an impact on regional and geographical electricity intensity. Again, with government's policy of achieving 100% universal electricity access by 2020, appliance ownership will significantly increase due to associated change in lifestyle especially in the case of "ruralisation". Policies to promote investments in energy structures are necessary. For example, to improve the current electrical distribution network capacity and reliability for the rural sector in particular. Energy efficiency improvement strategies are also required to reduce demand especially for appliances linked with end-use services such as refrigeration, air conditioning, entertainment and laundry.

ACKNOWLEDGEMENTS

This work has been conducted within the MIT Portugal program supported financially by the Portuguese Science and Technology Foundation (FCT) through the FCT scholarship PD/BD/113719/2015. Thanks are due to the Fundação para a Ciência e Tecnologia through support from the IN+ Strategic Project UID/EEA/50009/2013 and the scholarship SFRH/BPD/96459/2013.

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