TÉCNICO LISBOA

Modeling Microgrid Energy Services in the Urban Residential Sector for Developing African Countries

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Abstract

As the human population continues to rise, especially in developing countries, it is necessary to plan for the rise in population that occurs in the urban areas of developing countries due to migration. There are methods of linking human development indices and econometric indices with models for electricity consumption. Models that link the human development index to rural electricity planning as well as general models that link the GDP of a country to the electricity savings potential from policies on efficiency in developed countries currently exist. Till now, there is no study linking economic indices to the electricity consumption on developing African countries or in the urban areas of these countries. This thesis intends to contribute to the field of energy planning by observing and utilizing the link between the per capita income and the electricity demand of households. A case study was run for AsaDuru a Swedish housing company, which intends to build their pilot project in Accra, Ghana. The electricity profile was found. It had peaks that correspond to the times residential customers wake up to begin their day and when they return home. It was also found that 6 household appliances contribute 80-98% of the household electricity load, depending on the income of the household. Diffusion curves based on these 6 appliances showed that in a few years most countries will have their average household electricity demand increase by 15% on average. The case study ran on behalf of Asaduru found that at the current tariff of 17 US cents per kilowatt hour, the maximum fraction of electricity from renewable sources in the microgrid could be 0.34. However, factoring in the load shedding schedule in Accra this fraction rises to 0.43. A large determinant for this penetration of renewables is thought to be the low price of diesel to run household diesel generators in Ghana.

Keywords: energy, developing countries, africa, urban development

Resumo

O aumento da população do planeta a aumentar continuamente, em particular nos países em desenvolvimento, é necessário planear o acesso da população a serviços de energia. Existem diversos métodos que ligam os índices de desenvolvimento humano e índices de desenvolvimento económico a modelos de estimação do consumo de electricidade. Em particular, existem métodos que ligam os índices de desenvolvimento humano ao planeamento da electrificação rural, assim como modelos gerais que ligam o produto Interno bruto ao desenvolvimento de políticas de eficiência energética para países desenvolvidos. Contudo, não existem estudos que liguem os indicadores económicos ao consumo de electricidade em países em desenvolvimento em África, em particular para a zonas urbanas.

Esta tese contribui para a área científica do planeamento energético ao propor um modelo que liga o rendimento per capita ao consumo de electricidade no sector residencial. O modelo foi baseado no caso de estudo da empresa sueca AsaDuru, que pretende desenvolver um projecto piloto de construção em Acra, no Gana Com base no modelo desenvolvido, foi calculado um perfil residencial, em que o pico corresponde ao acordar dos clientes domésticos e ao chegar a casa após um dia de trabalho. Foi descoberto que o uso de apenas 6 electrodomésticos pode contribuir para 80 a 98% do consumo de toda a habitação, dependendo do rendimento disponível. Diferentes curvas de difusão das tecnologias mostram que para diversos países, os consumos podem aumentar em 15% no sector residencial. O modelo mostra ainda que considerando a tarifa corrente de 0,17 USD por kWh, a máxima fracção de renováveis é de 34%. Contudo, se consideramos os actuais cortes de electricidade em Acra, a fracção pode aumentar para 43%, porque o preço do diesel no gana é relativamente baixo.

Palavras-chave: energia, paises en desenvolvimento, africa, desenvolvimento urbano

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1. Introduction

1.1. Motivation

Population growth is highest in developing countries. As the population grows, it leads to a growth in urban migration as in many developing countries, as the centers of industry and by extension opportunity are located in urban areas. This causes rural urban migration as citizens seek betterment for themselves or their families. This migration eventually leads to an increased usage and demand on urban electricity provision, which has to be fulfilled to power economic growth.

This thesis focuses on the residential sector in urban areas of developing countries and specifically on household electricity consumption. We focus on household electricity consumption as according to (Mcneil, Letschert, & De, 2012) in low-income countries consumption largely driven by increases in connection to electricity grids, and in increased consumption due to ownership of household appliances. The latter is in turn driven by increases in household income (McNeil, 2012).

1.1.1. **Sustainable Buildings and Rammed Earth Buildings**.

AsaDuru is a Swedish startup which desired an energy estimation for a pilot project in Accra, Ghana. The company specializes in constructing rammed earth green buildings as a way of reducing the construction sector's dependency on concrete and cement on buildings. This thesis project begun as an effort to design a suitable energy system for Asaduru's first project planned in Ghana. It then evolved into an inquiry into energy planning in urban areas of African countries.

The use of rammed earth instead of concrete reduces the carbon footprint involved in the construction of a building, hence making a building more sustainable. The term "sustainable buildings" is generally used to refer to buildings which have been equipped to minimize energy consumption over their operational life cycle. While emissions released during the life time of a building have a great impact in the overall GHG emission in the life cycle of a building, emissions in the construction phase are also significant. The design of green buildings should therefore start with selection sustainable materials. The energy required to manufacture 1 m^3 of earth (soil) bricks is about 36 MJ (10 kW h), compared to about 3000 MJ (833 kW h) that is needed to manufacture the same quantity of concrete. (Oyelami & Rooy, 2016)

Earthen construction dates back at least 5000 years. It is one of the oldest and most globally widespread construction methods. (Picuno, 2016) Up to an estimated 50% of the world's population lives in earthen structures. These structures are largely located in developing countries in Africa, Asia and Latin America. Such structures usually have thick walls made of local soil and they are often susceptible to earth- quake damage because of their heavy weight, low strength and brittle behavior and frequently need to be retouched to maintain their structural integrity. Traditional rammed earth buildings usually have walls with large thicknesses (from 50 cm to 1 m approximately). This thickness allows the material to provide good thermal and acoustic properties. However, construction systems used today tend to reduce thickness and mass of walls and rammed earth cannot provide a proper thermal behavior when thin walls are used. Hence, in modern construction rammed earth buildings are made thinner but with insulation materials such as wood, straw and other engineered building materials in order to work just as well as contemporary building materials.(Cabeza et al., 2013)

In Africa, laterite soils are commonly used in making low cost buildings from compressed earth bricks. Laterite soils are generally brownish or reddish in color. This is because they are readily available and cheap. They are composed of both cohesion and cohesionless soils. The cohesionless portion consist of gravel, sand and silts while the cohesive portion includes fine particles usually in silt and clay sizes.

Other types of soil may be used but will need more added stabilizer or mixing. The strength and durability of a compressed earth building depends on the parent rock material, which determines the mineralogy, grading characteristics and type of soil derived. According to Oyelami, "these parameters will also determine the amount and type of stabilizer, compaction pressure in moulding of bricks, method and duration of curing."

The final product and whether only stabilization or additional firing of earth materials are needed will depend on the geology of the soil, including the mineralogy, weathering mode and stage as well as the climatic region. (Oyelami & Rooy, 2016)

With regard to thermal control, compressed earth buildings possess efficient thermal properties in both cold and tropical climates. They are also fire resistant and stronger in terms of compressive strength. (Oyelami & Rooy, 2016)

1.2. Growth in developing countries

Urbanization rates in developing countries are much higher than in any other part of the world. In addition to that, the rise of the African middle class, as a percentage of the population, has been steady – in 1980, 111 million or 26% of the continent's population fell in this category rising to 151.4 million or 27% of the population in 1990 with a further surge to 196 million in 2000 and a dramatic increase to 313 million in 2010, equating to 34.3% of the population. The rise in absolute numbers, compared to the percentage rise, has been more dramatic and this is best observed in the increase in population, with Africa hitting 1 billion population in 2010 (KPMG, 2014). The figure below, from the World bank, shows the rise in urban population of low and lower middle income countries compared to that of the World, OECD countries and EU countries over the last 50 years.

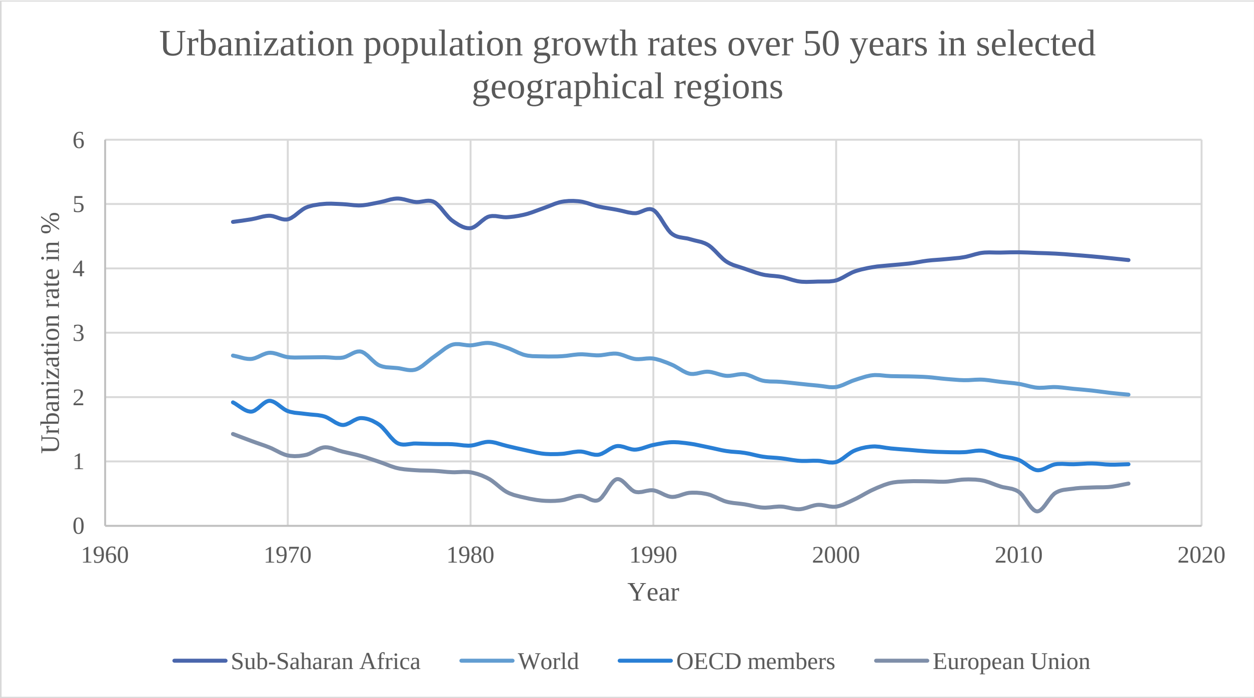


Figure 1: Urban population growth rates

In 2010, Africa had 51 cities with more than a million inhabitants, and only one city – Cairo – with more than 10 million. By 2040, it is expected to have more than 100 cities of more than one million inhabitants and 7 cities of more than 10 million. The largest city is projected to be Kinshasa, where the population is expected to reach 24 million by 2040. In a bid to cope with this rising urbanisation, entire new cities are already being developed such as Tatu City in Kenya, the City of Light in Accra and King City in Takoradi, Ghana. In Nigeria, there is the Greater Port Harcourt City and the modern Eko Atlantic City being built on reclaimed sea.(KPMG, 2014) In fact the UN DESA population growth estimates fpr 2050, estimate that 2.5 billion out of the 9.8 billion people estimated to be alive in 2050 will be African. This means that 1 in 4 people in the would will be African, a rise from the current 16% of the global population.

With growth in the urban areas of developing countries comes the need to supply electricity to the residents. Currently, many African countries suffer from load shedding. This inability for governments to provide electricity required, especially in fast growing urban areas leads to large loads (usually urban areas) being switched off in order to prevent damage to the system and meet other demands.

In Ghana, the growth of its three largest cities, Accra, Tema, and Kumasi, has led to the inability of electricity supply to meet the demand. In fact, these three cities have been the key drivers in increased national urban electricity usage. In 2009, the total peak electricity demand for these cities rose from 48%

in 2000 to 52% and there was a corresponding steady growth of electricity consumption at just over 50%. The most significant growth was in observed in Tema, where peak demand grew more than 106% over the 10 year period and energy consumption grew more than 159% (Essah, 2011). Unfortunately over the same period, energy supply grew by 20% (International Energy Agency). This, generally, affects the economic growth and development of countries as significant commercial activities that drive production are sited in urban areas. Without energy they cannot efficiently grow and contribute to the revenue generation system of a country. According to Welsch et al., 2013, the estimated economic value of power outages in Africa amounts to as much as 2% of GDP, and 6–16% in lost turnover for enterprises. (Welsch et al., 2013)

1.3. Contribution of this work

There is a large body of work centered on energy access in Africa, particularly in rural areas. With regard to energy planning in African urban regions, there is a much limited focus. This thesis aims to contribute to that sector of research because most cities in developing Africa have their unique set of characteristics with regard to quality of energy access and the rate of growth and development. These characteristics make the design of energy systems in such environments and interesting challenge. In this thesis, macroeconomic variables are used to study past and predict future electricity demand in households in selected African cities. This work serves to explore the field of microgrid and household electricity planning, while exploring the relationship between macroeconomic growth and household electricity use. The final aim of this work is to create a tool that will aid housing companies like Asaduru to estimate the size and cost of electricity systems that they will need to plan for in their projects, especially in cases where demographic data is not readily available.

1.4. Objectives

This thesis uses national, economic indicators to create bottom up electricity estimates. To counter the effect of using aggregated data, the economic indicators are broken up appropriately and in some cases, stratified by income level in order to get more reliable estimates of electricity demand. A case study is run on behalf of ASADURU, a Swedish housing company, with more detailed information, but with the same methodology in order to get the daily electricity load for their proposed pilot project. This load demand curve is put into HOMER to obtain the economic feasibility of the project in Accra, Ghana.

1.5. Structure of Thesis

The thesis is broadly organized as follows:

- Literature review
- Methodology
- Results and Discussion
- Conclusion

2. Literature Review

The chapter below expands on advances on literature with respect to microgrid and hybrid renewable energy systems in cities in urban areas of developing countries based on macroeconomic variables.

2.1. **Hybrids Renewable Energy Systems**

One possible way to address this problem of meeting electricity demand is the outfitting of residential loads with Hybrid renewable energy systems. This solution reduces the load on the electric grid and frees up more electricity that can be used to power commercial/ industrial customers. Hybrid Renewable Energy Systems (HRESs) are combination of renewable, traditional energy resources, and energy storages to meet the load locally in both grid connected and standalone modes. (Bahramara, Moghaddam, & Haghifam, 2016)

Advantages of HRES include:

- increasing penetration of renewable energy resources
- decreasing Cost of Energy (CoE)
- reduction of greenhouse gas emission,
- providing access to electricity for people in remote and rural areas.

Hybrid renewable energy systems (HRES) are considered more reliable and economical compared to single source renewable energy system with 26–40% saving as compared to only photovoltaic (PV) systems (Zafar & Dincer, 2014). Hybrid system configurations generally perform better than diesel only systems and display better performance in fields of electrical, fuel consumption and CO_2 reduction. (Olatomiwa, Mekhilef, Huda, & Ohunakin, 2015) In addition to this, there is reason to believe that hybrid renewable energy systems are going to uptick in developing countries as there is a lack of centralized infrastructure which leads people to seek their own solutions of obtaining power. An example of this leapfrogging effect is the spread of mobile phones and mobile banking technology in Africa. However, unlike mobile phones, mini grids and independent power are currently much higher in cost than the cost of mobile phones. Also, unlike mobile phone, for decentralized energy systems there is the possibility of no reliance on a central utility. Whereas, with mobile phones there is the need for central phone towers to support the transmission of signal hence all the customer has to buy is a sim card, a mobile phone and a credits (Welsch et al., 2013)

2.2. HOMER Software

In this thesis, HOMER is used to assess the case studies. HOMER (Hybrid Optimization Model for Electric Renewable) is a tool used to assist in the design of renewable off grid systems and HRES. HOMER software is a tool for designing and planning of HRES in order to determine optimal size of its components. HOMER performs three basic calculations: simulation, optimization, and sensitivity analysis.

(Adaramola, Agelin-chaab, & Paul, 2015) It contains resources such as wind, photovoltaic, fuel cells, small hydropower, biomass, converter, batteries, and conventional generators than can be modeled in HOMER. HOMER also considers HRES in grid- connected and stand-alone modes. HOMER requires six types of data for simulation and optimization including meteorological data, load profile, equipment characteristics, search space, economic and technical data. (Bahramara et al., 2016)

After all required data is fed into HOMER and the simulation and optimization stages are done, the results of each plan including the Net Present Cost (NPC) ($), the initial capital cost ($), the operation cost ($/yr), renewable fraction (percent), Cost of Electricity(CoE) ($/kWh), and emissions produced (kg/yr) are calculated. Although best plan is determined according to the minimum NPC by HOMER, the best plan may be selected with notice to the other criteria considering the perspective of the user. (Bahramara et al., 2016)

2.3. Projects using HOMER in Africa

According to (Welsch et al., 2013), “In 2009, around 585 million people in sub-Saharan Africa (about 70% of the population) had no access to electricity services. This figure is expected to rise significantly to about 652 million people by 2030. 85% of those without access to electricity live in rural areas. In addition to low energy access rates, the energy sector is characterized by several other significant challenges including: electricity costs as high as USD 0.50/kWh, insufficient generation capacity to meet rapidly rising demand, and poor reliability of supply. As stated earlier, the estimated economic value of power outages in Africa amounts to as much as 2% of GDP, and 6–16% in lost turnover for enterprises.”(Welsch et al., 2013) Hence there exists an opportunity to experiment with ways to supply this demand. Off grid solutions, in particular, are being sought after to combat these problems. Below is a description of a few of the projects that have used HOMER as the tool to determine the suitability of off grids in Africa as sourced by (Bahramara et al., 2016)

HOMER has been used to design a number of off-grid projects in Africa. Bahramara in 2013 reviewed 92 HOMER projects. Out of these, 25 were in rural areas and 20 were in Africa and 12 in Sub Saharan Africa. All of those studied in Sub Saharan Africa were solar stand alone systems with diesel generators although some of them had wind turbines in addition to these. The range for the African studies was from 3.8 to 236 kW at the peak. 50 percent of the projects were less that 10kW peak and an average of 55kWp (although greatly skewed by two projects that had a peak power of greater than 200 kW). The CoE’s for these projects ranged from 0.189$/kWh to 0.425$/kWh. Below is a table with the kWp, location, and the cost of electricity of the 12 Sub Saharan African projects. The LCOE is the price of electricity required for a project where revenues would equal costs, including making a return on the capital invested equal to the discount rate. An electricity price above this would yield a greater return on capital, while a price below it would yielder a lower return on capital, or even a loss.

Table 1: HOMER simulations around Sub Saharan Africa (adapted from Bahramara 2013)

Location	Peak load (kW)	LCOE($/kWh)
Cameroon	12	0.296.
Cameroon	8.3	0.352
Senegal	24	0.425
Cameroon	7.5	0.234
Somalia	211	0.197
South Africa	15	0.189
South Africa	9.4	0.707
DRC	8	0.281
Ghana	83	0.265
South Africa	3.8 and 5.6	0.348
Nigeria	236	0.288
Nigeria	25	0.324

It is an interesting prospect to study the CoE of hybrid systems in Africa, especially in urban areas due to the fact of load shedding and the pervasiveness of diesel generators affect the final cost output. These factors greatly change the economic value of off grid systems as the final CoE to the customer is not just the tariff of electricity but the cost of the lack of electricity and the fuel used to produce the shortfall of energy. This can be proven by looking at the case of Nigeria.

Nigeria has one of the highest numbers of generators in Africa due to inability of the government to supply the energy needed and the poor state of transmission and distribution networks. This trend is carries across the African continent resulting in the large-scale employment of electricity gensets, with Nigeria at the forefront of the market.

According to the African business review, only 45 percent of Nigeria's population has access to electricity, and only 30 per cent of demand is currently being met. Therefore, a total of 90 percent of industrial customers, and a considerable percentage of residential and non-residential customers, have their own means of power generation.

The corresponding unavailability of power has led to consumers turning to diesel and gas generators. In 2011, they had a market value of $450m. This figure is predicted to reach $950.7m by 2020.(African Business Review, 2012)

The genset market also continues to grow in East Africa as the current demand for electricity in Kenya, Uganda and Tanzania far outstrips supply. Currently, a large market for diesel gensets exists in these countries. Continuing economic and population growth will only increase the demand for power. Thus, companies that can supply effective diesel gensets, which can ensure stable electricity supply, will gain market share.(African Review of Business and Technology, 2015)

These paragraphs are quoted to show that this study is cogent to the current situation in African countries. Decentralized hybrid and renewable energy systems have the potential to help in the solution to some of the problems although there is the need for centralized governments to also take action in many ways to reach the targets they have set for themselves as well as the sustainable development goal of 100% energy access by 2030.

2.4. Energy systems design for developing countries

According to (Beeck, 1999), energy models can be classified into the by the following criteria.

- General and Specific Purposes of Energy Models
- The Model Structure: Internal Assumptions & External Assumptions
- The Analytical Approach: Top-Down vs. Bottom-Up
- The Underlying Methodology
- The Mathematical Approach
- Geographical Coverage: Global, Regional, National, Local, or Project
- Sectoral Coverage
- The Time Horizon: Short, Medium, and Long Term
- Data Requirements

Of interest are the top down method and the bottom up analytical methods of energy planning. The top-down approach is associated with the *economic paradigm*, while the bottom-up approach is associated with the *engineering paradigm*.

Top-down models use aggregated data to examine interactions between the energy sector and other sectors of the economy, and to examine the overall macro-economic performance of the economy. Past aggregated behavior can then be extrapolated into the future. In contrast, bottom-up models use highly disaggregated data, such as the electrical performance of machines to describe energy end-uses and technological options.

Due to their properties, top- down models are generally used for prediction purposes and are best used to predict a short distance in the future, while bottom-up models are mainly used for exploring purposes and used for studies on a smaller scale than the top down analyses, which are used for nationwide or international studies.

Most studies that look at predicting energy demand and supply in developing countries do so with a top down perspective. Whereas, bottom up methods, when used, are used to plan energy systems for projects that are smaller or that are realized around the time the study is conducted.

In Africa, most studies that look at long term energy planning approach the topic from the viewpoint of the national infrastructure that needs to be installed to reach targets. In Nigeria, (Ibitoye, 2013) estimated an amount of 25GWh, roughly double the 2013 electricity generation will need to be generated by 2020 to meet millennium development targets. This prediction was done using LEAP(Ibitoye, 2013), (Sambo, 2008). In Ghana, Gridco predicts a doubling of consumption from 2010 levels by 2020. Many of these studies end up predicting what sort of infrastructure will be needs to be built in order to reach government targets

However, considering the fact that many African governments are greatly behind in meeting infrastructural goals to meet current energy needs, we can predict that, without a humongous injection of funds, it will be difficult to meet these goals through centralized infrastructure. According to Bazilian, "Most projections from international organizations, regional entities, national governments, and power companies foresee average annual growth rates in generating capacity on the order of 6 to 8% in line with GDP forecasts and typical demand forecasting techniques. While these are dramatic increases over historical rates, and would result in installed capacities of about three-times current levels in just two decades, they are insufficient to meet even modest definitions of universal access." (Bazilian et al., 2012) In fact, according to some authors, installed capacity [in Africa] will need to grow by more than 10 percent annually just to meet Africa's suppressed demand, keep pace with projected economic growth, and provide additional capacity to support efforts to expand electrification and Panos, Densing, & Volkart) state that an annual investment of more than $55 billion dollars will be required to provide energy access to everyone on the African continent by 2050.(Panos et al., 2016)

The trend of distributed service provision which is common in sub Saharan Africa, has the potential to meet these goals in a decentralized manner but will have to be employed in a much larger manner than it currently is. Hence, it is worth exploring the option of how energy needs evolve with in smaller household units rather than the use of national aggregates. Information gathered from an interview with head of renewable energy programs, in the Ghana Energy Commission, Mr Kwabena Otoo-Danquah, led to the observation that some African countries, for example, Ghana, have a policy focus on reducing the residential load on the grid due to insufficient supply. They plan to promote renewables and independent generation in residential sector through government programs sponsoring solar panels.

Also, much of the literature on the power sector in SSA is not surprisingly focused on the Republic of South Africa (RSA). However, there has been a steady group of dedicated researchers focusing on SSA or on particular SSA countries. Still, there is a relatively small existing literature on scenarios for the power sector in sub-Saharan Africa. (Bazilian et al., 2012)

These well-understood techniques, based on aggregates such as GDP and exogenous inputs like future annual grid connections of households, are not ideally suited for situations where much of the population lacks access to electricity services. Hence the studies contained in this thesis generally studies urban areas in African where access is relatively high and will rise due to trends of urban migration in many African countries.

2.5. Predicting and forecasting energy demand using economic metrics

Most global and long-term projections of energy consumption take a top-down approach, correlating consumption growth to macroeconomic trends. The model utilized by EIA’s International Energy Outlook, called the World Energy Projection System (WEPS), for example, forecasts total energy consumption according to region-specific elasticities, which relate growth in GDP to growth in energy consumption. (Mcneil, 2012)

Most effort on energy demand forecasting seems to have concentrated on OECD countries, where detailed data is most readily available, with the possible addition of emphasis in major developing countries (Russia, China, India and Brazil).

In 2008, (Mcneil & Letschert, 2008) published a paper on an analysis system, which was later named the Bottom up energy analysis system (BUENAS) method as a tool to estimate energy the emissions and the effects of energy efficiency measures in appliance in the residential sector based on appliance diffusion. In 2010, this model integrated appliance diffusion rates in the BUENAS model with macroeconomic variables.

In 2012, the team used these studies to determine the costs of efficiency measures in 13 countries around the globe(Mcneil et al., 2012). South Africa was used as a representative country for Africa. However, in some ways the use of South Africa does not provide a valid support for a model of sub Saharan Africa as the rest of the African continent is made up of countries significantly less developed than the South African Republic. These less developed countries also mostly have a different structure of the economy, distribution of wealth, urbanization rates and electricity expenditure.

The BUENAS tool was developed as a tool to assess the effects of energy efficiency programs on greenhouse gas emissions and energy savings. This is done by plotting diffusion curves of electrical appliances within a country and multiplying this number by the number of each type of appliance to get the consumption of each appliance in the sector being looked at. The effect of efficiency measures can then be taken into account as they reduce the consumption of the appliances.(Letschert & Mcneil, 2009; Mcneil & Letschert, 2005, 2008, 2010; Mcneil et al., 2012; Mcneil, Letschert, & Wiel, n.d.)

The use of national aggregates such as urbanization, GDP and electrification to calculate the diffusion rates overcome the hurdle of a lack of information. However, in many developing countries, these aggregates may introduce an amount of error as the values (of electrification) are not uniform all around the country and electrification is generally in urban areas. There is also a great disparity between household incomes in rural and urban areas. Hence the model begins to weaken in its efficacy when it is moved from developed countries with lower GINI coefficients.

Other authors have tried to compensate for this in many ways. (Adaramola et al., 2015), makes an assumption based on national residential consumption that the household residential usage is 5kWh per day. (Essah, 2011), using a bottom up methodology, arrives at how much energy is needed to power Ghanaian households based on reasonable assumptions that compare the appliances he and a group of researchers use with the general Ghanaian population.

Both Adaramola and Essah estimate the energy consumption of a house hold at 5kWh/day. In line with national estimates of electricity use and divided by the whole population.

In 2015, Paleta (Paleta, 2015) performed a study linking the Human development index with the electrification rate. The results obtained from the study did not factor in the spike that usually occurs in rural areas once access to electricity is obtained and were based on a weak correlation, however, they were within an order of magnitude of data used to verify the model. One thing significant property of the study is that it focused on off-grid communities. Till now, no work has been done correlating these indices with urban areas of developing countries. Most studies either look at the country in general or look at rural areas. However, access to electricity does not indicate availability of it, hence autonomous systems are viable projects in urban areas as well.

2.6. GDP and expenditure of a country linked to appliance usage

With the exception of the impact of energy transitions, economic indicators are not usually used in the field of energy planning. Lorenz curves were used by Kammen et al to plot appliance and electrical inequality in different countries and there by observe the effects of inequality, characterized by the Lorentz curve on energy efficiency policies. Outside of this wealth distribution functions of the GDP have not been used in the field of residential energy planning.

2.7. Ghana energy situation

Growth of electricity demand in Ghana

There are seven public institutions involved in the power sector. These are the:

- Ministry of Power (MOP)
- Energy Commission (EC)
- Public Utility Regulatory Commission (PURC)
- Volta River Authority (VRA)
- Ghana Grid Company (GridCo)
- Electricity Company of Ghana Limited (ECG)
- Northern Electricity Department Company(NEDCo), a subsidiary of the VRA.

Other bodies include:

- Energy Foundation is a private-public sector partnership to promote energy efficiency and conservation countrywide.
- Independent Power Producers (IPPs) are also private sector players in the power sector.

Generation is the first arm of the power chain in Ghana. Volta River Authority (VRA) is the major power generation company, solely owned by the Government of Ghana and established in 1961 by an Act of Parliament. VRA combines hydro, thermal and solar plants to generate electricity for supply to the local and export markets. Due to the energy sector reform, there are also other generation companies that are privately owned known as the **Independent Power Producers**. Notable among them are Ameri, Karpower, Sunon-Asogli and Cenit. Below is a list of the generation plants in Ghana adapted from (Diawuo, FA 2013)

Table 2: Electricity Generation Sources in Ghana

Plant	Fuel Type	Capacity(MW)	
Hydropower Generation		Installed	Dependable
Akosombo	Water	1020	900
Kpong	Water	160	140
Subtotal		1180	1040
Thermal Generation			
Takoradi Power Company(TAPCO)	LCO/Diesel/Natural Gas	330	300
Takoradi International Company(TICO)	LCO/Diesel/Natural Gas	220	200
Sunon Asogli Power(Ghana) Ltd	Natural Gas	200	180
Tema Thermal 1 Power Plant(TT1PP)	LCO/Diesel/Natural Gas	110	100
Mines reserve Plant(MRP)	Diesel/Natural Gas	80	40
Tema Thermal 2 Power Plant (TT2PP)	Diesel/Natural Gas	49.5	45
Subtotal		989.5	865
Bui Hydro Power Project-BPA	Water	400	340
Takoradi 3 (T3)-VRA/GoG (Phase 1)	LCO/Diesel/Natural Gas	132	120
Kpone Thermal power Plant(KTPP)-VRA/GoG	Diesel/Natural Gas	230	200
Takoradi 2 (T2) Expansion-VRA/TAQA	Steam	110	110
VRA Solar Power Project (CSP)	Solar	2	
VRA Wind Power Project	Wind	150	
Subtotal		1024	770

Total		3194	minus(S&W) 2675
Planned Generation Projects(2015-2016)			
Osonor/TT1PP Expansion - VRA/IPP	Steam	110	100
Takoradi 3 (T3) - (Phase 2)	LCO/Diesel/Natural Gas	132	120
Domunli Thermal Project	Gas	450	440
Pwalugu Hydro Project	Water	48	45
Subtotal		740	705

Transmission is the second arm of the Power Chain in Ghana. GRIDCo owns and operates the transmission grid mainly at 161kV with a total length of about 5,100 km. The other transmission voltages are 69kV, 225kV, and 330kV. These lines carry power from various generating stations to over fifty-four (54) substations owned by GridCo. At these substations, the power is stepped down to lower voltages including 34.5 kV and 11kV for the major bulk customers which include the distribution companies namely; Electricity Company of Ghana (ECG), Northern Electricity Distribution Company (NEDCo) and Enclave Power Company (EPC).

Distribution is the last and final arm of the Power Chain in Ghana. The Electricity Company of Ghana (ECG) is the major distribution company with over 70% market share. It is responsible for distribution of power in six administrative Regions in Ghana namely Greater Accra, Western, Ashanti, Central, Volta and Eastern regions.

The **Northern Electricity Department (NEDCo)** was established under the Volta River Authority (VRA), to take the responsibility of electric power distribution in Northern part of Ghana. There is a third distribution company, Enclave Power Company, the only privately owned distribution company which is mainly responsible for the industries in the Free Zone Enclave of Ghana in Tema. The distribution companies receive power at 34.5kV from GridCo. and step it down to 11kV to industrial customers and step it further down to 440/230Volts to commercial and residential customers. [ECG website]

Residential customers are by far the largest ECG customer group. Residential customers account for the 80% of the total number of customers and represent 50% of the total energy billed(AF-MERCADOS EMI, 2014).

Challenges to electricity supply in Ghana

The following challenges affect the reliability of energy supply in Ghana:

- Inadequacy of available generation capacities to meet the projected demand under all system conditions

- Security of fuel supplies such as natural gas supply from West Africa Gas pile line (WAGP), Ghana Gas and adequate stocks of Light crude oil (LCO) and Diesel fuel Oil (DFO)
- Potential of WAGP not being able to meet contractual quantity of gas.
- Possible delay in Completion of Ghana Gas Project (GGP)

These challenges resulted in load shedding of about 4.34 TWh in 2015. The phenomenon of load shedding did not only occur in 2015 but was a gradually exacerbated problem reported by GridCo in their annual reports since 2012(GridCo, 2013; GRIDCo, 2014, 2015)

The uncertainties related to gas supply from the WAGP negatively impact the ability of the power generating companies to meet the forecasted demand. The cost of thermal generation also increases increase because of the relatively higher cost of LCO as substitute for gas.

The current inadequacies in transformer capacities lead to overloading at most major substations during normal operation conditions. This state of affairs is exacerbated during contingency conditions and normally results in load reduction. According to GridCo, most substation transformers are already overloaded and do not satisfy the N-1 security rule. Most security rules call for the system to be able to withstand the loss of any single component. When a power system satisfies this criterion, it is said to be “N-1 secure” because it could lose any one of its N components and continue operating. Similarly, in a system that is “N-2 secure”, no consumer would be disconnected even if two components were suddenly disconnected.

The transmission system has inadequate firm transfer capability to most of the major load centers (of Accra Kumasi etc) mostly at peak. This situation results in low voltages and increase in transmission system losses. A significant percentage of network loads are islanded in case of outage on single line.

Voltages at Kumasi towards the north and some mining areas in the western region are extremely low because of inadequate installed reactive power and voltage support devices to boost voltages.

Generation scheduling has significant impact on system losses. System losses are lower with maximum generation at the west compared to losses with maximum generation at the east. (GRIDCo, 2014)]

GridCo in 2010 stated “The current predicament is a result of a decade of chronic underinvestment in generation and transmission infrastructure despite robust growth in demand and energy consumption. From 2000 to 2009, the natural (i.e. uncurtailed) peak demand and energy grew growth rates were 44% and 100%, respectively, driven in large by three major factors: economic growth, urbanization, and industrial activity. In the same period, installed generation capacity grew only 7% while very few new transmission projects were completed compared to the capacity needed.” [Gridco 2010]

3. Methodology

3.1. Energy demand profile

In order to develop the energy demand profile for households the following process was used.

- The probability of home appliance ownership was obtained from the Ghana Living Standards Survey 6 (GLSS6). The data for home appliances is distributed into urban areas and rural areas, hence only data for urban areas (namely, Accra) was used.
- Under the assumption that most new residential development projects also stock new appliances the average power required for each appliance. The data for this was taken from appliance website Jumia.com where appliances were ranked by highest sales [NM1]and the leading performer was chosen and electrical details for each appliance was found
- For each appliance, the number of times a day it was switched on was assumed. This was set as the probability of an appliance being on. (Peqp)
- The duration of time the appliance was switched on was also assumed. (eqpruntime)
- A program in MATLAB was written. At each hour of the day, for each appliance, MATLAB chooses a random number between 0 and 1 with a probability fraction of it being on according to the number of times a day a machine is usually used, calculated from the BUENAS study and from Chuan (Chuan, Ukil, & Member, 2014; Mcneil et al., 2012). If the number is less than the probability of the appliance being switched on, the appliance is switched on by including the wattage of the appliance into a matrix created for that hour.
- From this appliance curve, the average power needed and the maximum power needed were calculated to be fed into the HOMER simulation.

All the figures used in the calculation are in the table that follows:

Table 3: Characteristics of Household equipment considered In study

Equipment	Wattage	Spread	Number	eqpru ntime	PeqP	Assumptions
Lights(LED)	11.5	0.931	8	1.00	1.00	
Outdoor lights (Florescent Tubes)	16	0.931	4	1.00	1.00	
Television	47	0.859	1	1.00	0.18	Used everyday for 4 hours
Radio	7	0.415	1	1.00	0.11	Used everyday for 3 hours
Refrigerator	360	0.619	1	1.00	1.00	
Fan	70	0.821	1	1.00	0.24	Cooling degree days from 20C
Air Conditioner	540	0.036	1	0.50	0.09	Cooling degree days from 25C Assuming people who use AC, are more price conscious and want to save energy
Deep Freezer	138	0.157	1	1.00	1.00	
Desktop Computer	120	0.095	1	1.00	0.26	
Laptop	45	0.148	1	1.00	0.14	Used everyday for 3.5 hours
Washing machine	1800	0.026	1	1.00	0.01	Used once a week 2 hours
DVD players	10	0.506	1	1.00	0.02	Used 2 a week, 2 hours
Water heater	4600	0.011	1	0.16	0.01	Everyday 15 minutes
Blender	450	0.326	1	0.16	0.01	Everyday 10 minutes
Microwave	1200	0.135	1	0.08	0.01	Everyday 10 minutes
Electric cook stove	2500	0.018	1	0.50	0.17	
Vacuum cleaner	750	0.013	1	0.50	0.01	Used once a week 1 hour
Electric Iron	1800	0.785	1	0.08	0.01	Everyday 10 minutes
Rice cooker	300	0.277	1	0.50	0.01	Every other day

- At the end of each hour, the wattage of all appliances switched on is summed to obtain the total consumption in that hour.
- For equipment that runs for less than an hour, the average consumption during that hour was calculated, rather than setting the appliance on for the whole hour.
- This consumption for one house was multiplied by the number of houses and a matrix of the probability of equipment being in a household.
- This base program was inserted into a loop that runs it for any number of days desired. The test case in this paper was for 25 residences for 30 days.

Results of the program were compared to data from survey responses.

3.2. HOMER design

A hybrid energy system was designed to meet the energy demand modeled. Various configurations of energy supply means were used in the model. The energy demand per hour as determined by the Matlab program written above is as follows:

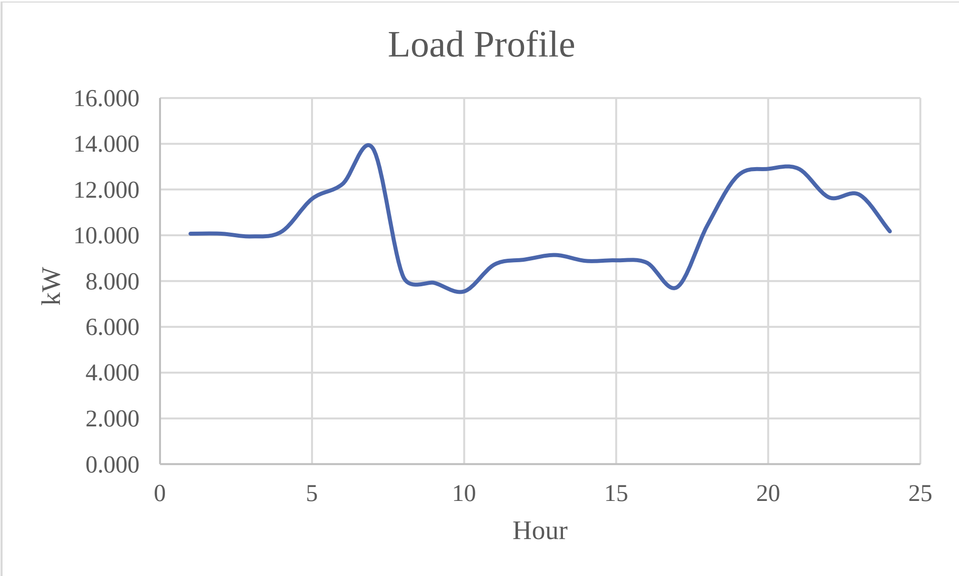


Figure 2: Load profile from Homer

This chart is similar to the descriptions of load profiles in many countries as discussed later in the results section.

For this study the electricity supply options considered were:

- Diesel generators, which are the current solution that is adopted by those who can afford them
- Solar Photovoltaic Options
- Grid extension: To make the study realistic, a simulation was also created that connected the system to the grid and the number of power outages, was simulated in addition to constant electricity supply. This was done because in Ghana, a t the time of running the study there was a load shedding program that had been going on for year where scheduled blackout would occur. The schedule varied from 12 hours with electricity and 12 without to 12 with electricity and 24 without in Accra.

Wind turbines were not considered as they are not a very economic option for small projects although they are some of the cheapest resources for generating electricity ($0.067/ kWh in 2010) on a large scale. Wind turbines achieve this cheapness though economies of scale hence, despite the high initial costs, the LCOE is low. Compared with utility-scale wind systems, small wind turbines generally have higher capital costs and achieve lower capacity factors. Although there is no official definition of what constitutes a small wind turbine, it is generally defined as a turbine with a capacity of 100 kW or less.

(IRENA, 2012). The LCOE for such small wind turbines is on average $0.12/kWh but ranges from $0.06/kWh at 100kW to $0.95/kWh (2014 dist wind market). Countries located further from the equator generally have relatively high wind energy potential compared to countries closer. Ghana has wind speeds of 4m/second to 6m/second which is considered by some investors as not being adequate for a bankable PPA(Energy, 2011). Small wind turbines share of the total global wind power market was estimated at around 0.14% in 2010 and is expected to increase to 0.48% by the year 2020.

Improved biomass to electricity technologies were also not considered, as due the siting of the project, it would be hard to predict what sort of biomass would be available and will be used.

The solar resource used in calculating the amount of available energy are shown below. HOMER obtains this data from the NASA database. The final search space for the project is shown below

Table 4:Parameters used in Homer Simulation

System Designed				
Power Sources	**Diesel Gen**	**Solar (PV)**	**Converter**	**Batteries**
	Size(kVA)	Size(kVA)	Size(kW)	Size (1kWh)
	0	0	0	0
	5	25	25	100
	10	40	40	500
	20	80	80	1200
	25	100	100	2000
Price sensitivities	**Grid price**	**Sellback**	**Diesel price**	
	$/kWh	$/kWh	$/L	
Current	**0.17**	**0.00**	**0.87**	
	0.10	0.02	0.80	
	0.15	0.05	0.90	
	0.20	0.08	1.00	
	0.30	0.10	1.10	
			1.20	
			1.30	

The criteria chosen were chosen to cover the peak load and in increments of it. The prices were also chosen in accordance with current prices on the market and estimating how the change in prices could be. The effective interest rate, as HOMER uses it was set at current national interest rates minus the inflation rate.

HOMER takes in the electricity demand and various options provided in the search space in this and calculates by feasibility and the CoE of each feasible option and ranks them by the Cost of Electricity (CoE).

The levelized cost of energy is the average cost per kWh of useful electrical energy produced by the system. It is used as the metric in this study because it is helpful to compare the electricity cost purchased from the grid to the electricity that is produced. It is an economic assessment of the cost of the energy-generating system including all the costs over its lifetime: initial investment, operations and maintenance, cost of fuel, cost of capital. A net present value calculation is performed and solved in such a way that for the value of the LCOE chosen, the project's net present value becomes zero.

This means that the LCOE is the minimum price at which energy must be sold for an energy project to break even.(National Renewable Energy Laboratory, 2013)

sLCOE = {(overnight capital cost * capital recovery factor + fixed O&M cost)/(8760 * capacity factor)} + (fuel cost * heat rate) + variable O&M cost. (National Renewable Energy Laboratory, 2013)

In a sense, it is a tool to compare the opportunity cost between buying from the grid and independent production of electricity.

3.3. Incorporating Macro Economic Variables into Household Electricity Planning

The theory behind this process is as follows: household electricity use rises with household income. This is because with more income, people have the possibility to purchase household equipment to meet their needs. It follows that by tracking the factors of electrification and of household income (represented as a function of the gross domestic product of the country).

.In light of this , diffusion curves were plotted for the following household appliances:

- Lighting
- Televisions
- Fans
- Refrigerators
- Washing Machines
- Air Conditioners

As indicated by the data from the survey, and from various national surveys, the order of purchase of appliances after electrification is Lighting -> Televisions (and/or Radios) -> Fans-> Refrigerators->Washing Machines-> Air conditioners.

With the exception of climate control equipment, specifically fans, the order of appliance purchase can be explained by the price of equipment. Climate control equipment, such as fans are purchased due to the climate of the area they are located in. The order of purchase between fans and air conditioners is dependent, like all other appliances, on cost.

The appliances listed above make up at least 80% of household electricity consumption in urban areas. Hence by estimating the numbers of such equipment in the average household, it is possible to estimate electricity demand using a similar methodology to section 3.1

Diffusion curves generally have follow the logistic function in the form:

$$\frac{k}{1 + Ce^{-rt}} \tag{1}$$

Where:

- k is a constant that represents the maximum value the function can take
- C represents is the starting quantity of the growing function
- r represents the intrinsic growth rate of the function (which in this case is thought to be a function of other variables pertaining to the country)
- t represents time

According to (Mcneil & Letschert, 2010), appliance purchase is a function of household income, electrification and urbanization and time. This is represented in the equation below:

$$Diff = \frac{k}{1 + c \times \exp\left(r_{inc}I + r_{elec}E + r_{urb}U\right)} + \varepsilon \tag{2}$$

Where:

- I represents household income, which he defines as the GDP/number of households
- E represents the electrification rate
- U represents the urbanization rate
- ε represents the error term
- r represents the rates of growth with respect to the factor it is coupled with.

However, since this project focusses on appliance distribution in households in urban areas, the factor for urbanization was taken out and assumed to be zero. Hence there is no growth with respect to urbanization in urban areas. The constants in the numerator, were assumed to be the diffusion levels of the same appliances in developed countries. In order to generate a predictive function, each of the other factors; household income and and electrification were plotted as linear functions of time for each of the countries selected for time since 2000. Making the final equation used:

$$Diff = \frac{k}{1 + c \times \exp\left((r_{inc}I + r_{elec}E)t + (r_{inc}I + r_{elec}E)\right)} + \varepsilon \tag{3}$$

Where all the terms in this equation are the same as listed above.

Country Selection

Five countries were selected, one from each geopolitical subsection of Africa (excluding North Africa) and Ghana. These countries were chosen based on their stability and GDP per Capita (PPP), as relative indicators of the infrastructural development of the country. Countries were ranked by their GDP per capita in each geopolitical section and the countries in the middle of each section that were politically stable were chosen.

The countries chosen were:

- Ghana
- Kenya (East Africa)
- Namibia (Southern Africa)
- Nigeria (West Africa)
- Republic of Congo (Congo-Brazzaville) (Central Africa)

Data for household income were obtained from statistical data from the countries. The behavior of household income with time was assumed to be the same as the behavior of gross national income per capita over the last 15 years. This behavior of the countries chosen is shown below.

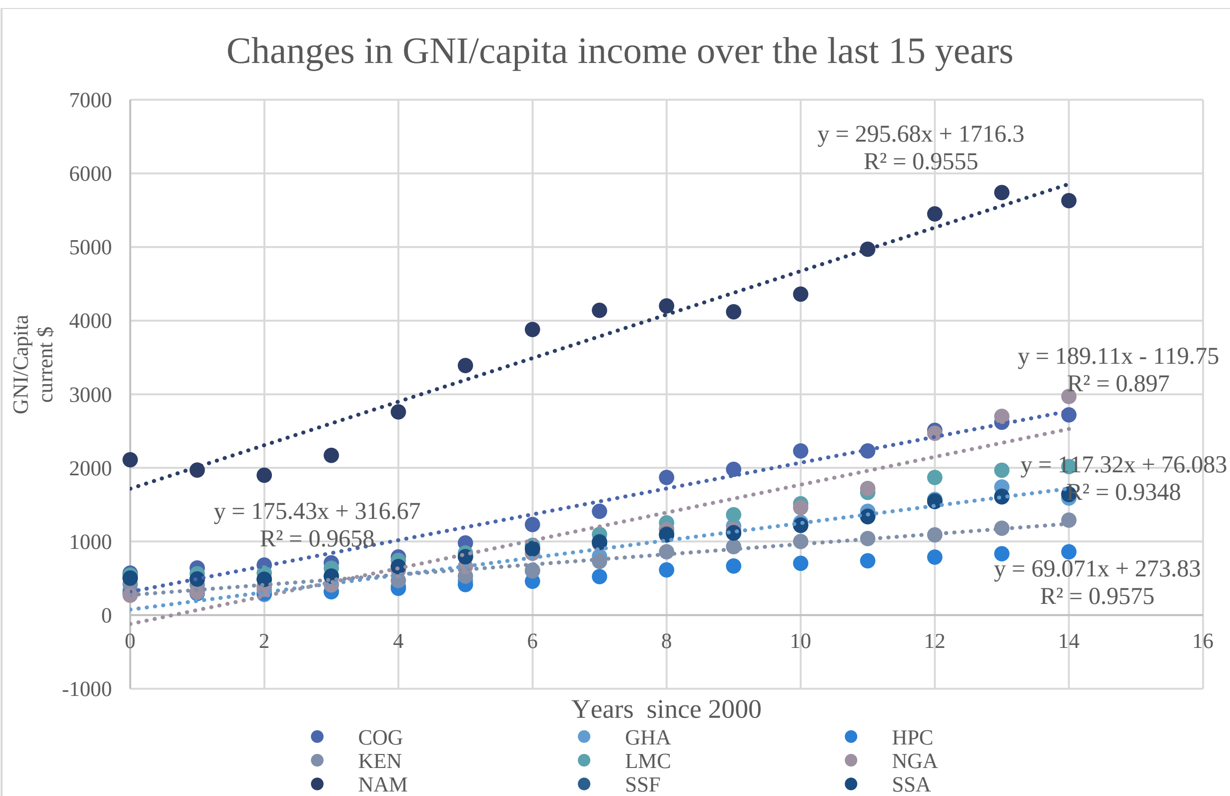


Figure 3: GDP per capita trends with time for selected countries

For countries without urban household income data available (Nigeria& Republic of Congo) the Gross National Income was used to calculate the household income in the following way:

- The GNI for a the most recent year with wealth distribution data was chosen, the corresponding wealth distribution data per quintile was also obtained from the world bank. This was used to plot Lorenz curves of income.
- Under the assumption that the urban fraction controlled a larger proportion of wealth than rural areas, the wealth controlled by the top fraction equivalent to urban fraction was assumed to be the urban wealth. That is, for a country with x% urbanization, the urban population would control the top x% of the wealth on the Lorenz curve.
- This percentage is then multiplied by the total GNI and then divided by the number of people in the urban areas to get the average urban income.
- This is multiplied by the average household size in the urban areas to get the household income.
- This can be represented mathematically by:

$$\frac{GNI \times (1 - x\%)}{Urban\ Population} \tag{4}$$

Data on electrification was also obtained from the world bank over the same time period and plotted to observe the behavior with time.

<u>Assumptions</u>

- Electrification rate is the same as lighting available in an area. This is based on the fact that lighting is the most common electrical use and it's spread generally follows the rate of electrification
- Household income changes are on average equivalent to changes in Gross National income per capita
- Behavior of household income change (in terms of current US$, Atlas Method) and behavior of electrification assumed to be generally linear. Hence this data was fitted to a linear curve over the last 15 years and the parameters were used to predict the values for the next 5 years

Analysis of Method

This method provides a simple means to estimate household energy consumption. Values that are fit into the curves are obtained from the World Bank, which regularly collects and calculates among others, macroeconomic variables of countries to track the development of a country. This data is easily available and updated as regularly.

The drawback to this method include that the correlation between household income and the gross national income varies with respect to inequality in the country. This is why the use of the Lorenz curves and the GINI coefficient is important. By using a measure of inequality of the country we can compensate for the lack of knowledge of how closely the gross national income correlates with household income

This model may also carry a bias towards countries that are still developing and urban areas with a larger population of low income households. This is because the inherent assumption behind this model is that households begin to purchase household appliances as they increase their income level. Yet realistically, beyond certain income levels, households cease to add new types of appliances to what they have and only replace existing appliances with more efficient models. In this case, a rise in household income overtime ceases to correlate in a rise in household energy consumption due to appliance purchase and may sometimes result in a dip in consumption with respect to household appliances used.

4. Results and Discussion

4.1. Energy Demand Profile

The results from the MATLAB model are as follows:

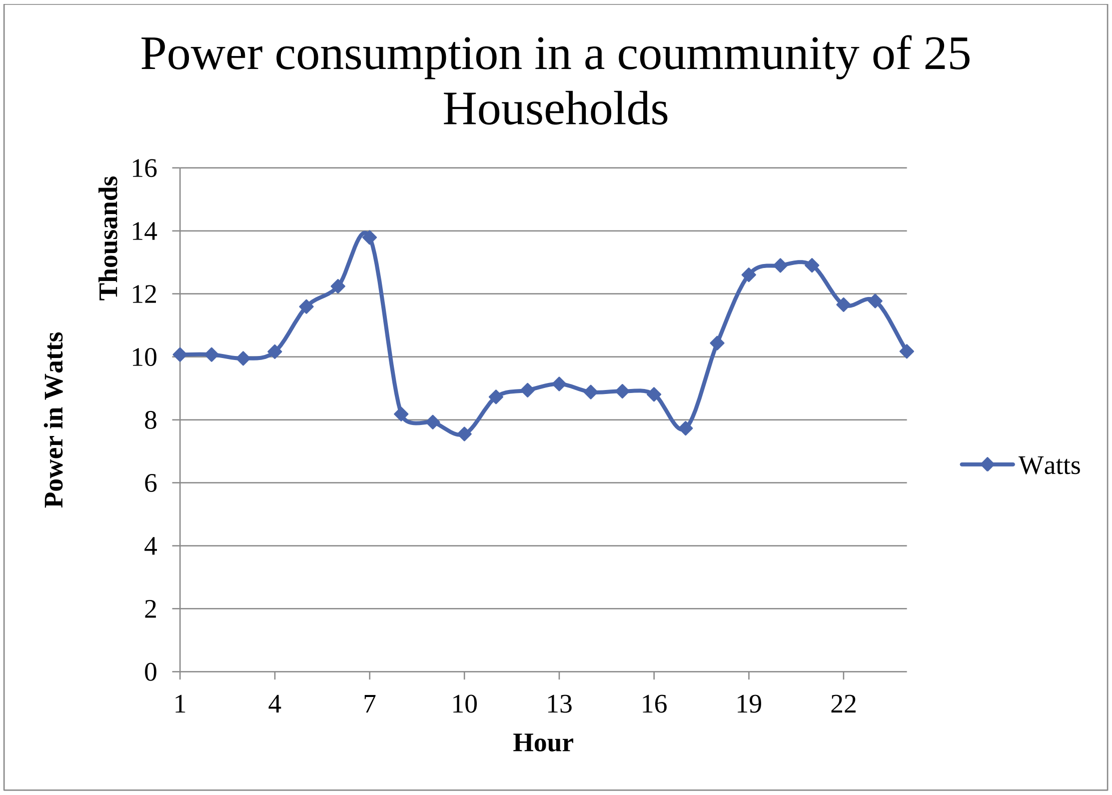


Figure 4: Demand results for 25 Household from Matlab simulation

There are two peaks that occur. One between 6-7 hours and anotherbetween19-22 hours, this is in correspondence with human behavior. The early peaks correspond to when people are rising and preparing to start their days and the later peaks correspond to activities people do at home to end the day, such as cook, entertainment and lighting (which is necessary at night).

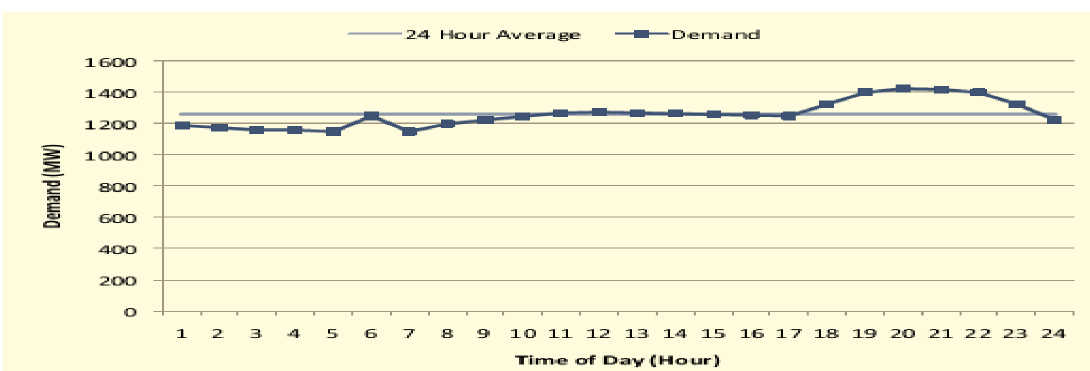


Figure 5: Total electricity demand curve Ghana (Adapted from Diawuo,2013)

These peaks and the general shape of the curve are consistent with data from Nigeria (Ezennaya, 2014) and with work done by Diawuo in 2013 where the national curve had two peaks one between 6-7h and the other between 18 to 21h which stemmed from residential use.

According to Ezennaya on a study on the demand in Nigeria, “the first peak period occurs between 0500hrs-0800hrs when people wake up in preparation for the day’s activities and as such so many home appliances are switched on. The second peak period occurs between 1800hrs-2400hrs and this is the period that people return from their respective places of work and put so many electrical appliances into use”. (Ezennaya 2014)

The electricity consumed in households in Ghana does not vary greatly from season to season. In fact, the maximum variance over the course of the year amounts to less than 5% of consumption (Diawuo, 2013)

[NM2]

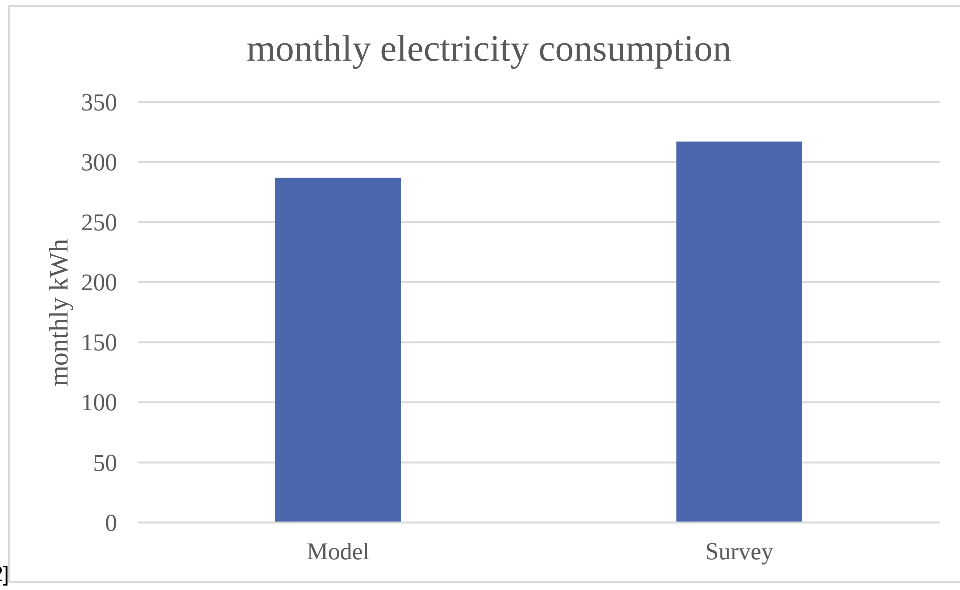


Figure 6: Homer Result and Survey Result

The results from a survey of Accra residents (20 respondents in Accra and 30 in total) after the end of load shedding (January 2016) represent to some extent the unfettered consumption in the city are as follows:

Table 5: Survey Responses

	GHS	kWh
Question : Do you know your last 3 electric bills? If yes, can you please give them below? (either in kWh-kiloWatt hours- on your bill or in currency values-please specify which you're using and separate each value with a comma).		289
		256
		239
		175
		180
		191
		235
		226
		238
	200	297,06
	150	222,79
	4000	5941,13
	350	519,85
	200	297,06
	80	118,82
	150	222,79
	200	297,06
	200	297,06
	148	219,82
	600	891,17
	550	816,90
	150	222,79
	200	297,06
	711	1056,03

However, the model gives a monthly consumption of 287kWh. While this result is slightly consistent with the results from the survey(317kWh) , with an error of 10%, it is inconsistent with published values of: 129.3kWh (Adaramola et al., 2015)and 150kWh (Essah, 2011). Below, is a table also extracted from the results of the survey, shows that when the average consumption is calculated solely from the monthly bill payments, the average consumption comes up to 322kWh per month for a household size of 5.4 members. [1]

For comparison average monthly household consumption in the USA 901kWh/month (US Energy Information Administration, 2015) for an average household size of 2.58 people and the average EU

[1] The data point 13 is data given by a respondent but assumed to be a typographical error as it is highly unlikely that a household would consume 6000kWh per month.

monthly household consumption is around 330 kWh with about 190kWh going solely to electrical appliances for a household size of 2.3 members (Lapillonne, Pollier, Gynther, & Motiva, 2015),(Eurostat, 2016). On the other hand other sources such as the World Energy Council pegged household electricity consumption at close to 50kWh/ month (World Energy Council, 2016)

Table 6: Occupancy of households that responded to survey in comparison to monthly electricity bill

Question:What is the average amount spent on electricity in a month in your household?	GHS	kWh/month	# occupants in household
1	40	59.400	5
2	200	297.000	11
3	150	222.750	3
4	350	519.751	6
5	200	297.000	10
6	80	118.800	5
7	150	222.750	2
8	200	297.000	2
9	20	29.700	10
10	200	297.000	2
11	148	219.780	2
12	600	891.001	8
13	4000	5940.006	10
14	550	816.751	4
15	150	222.750	5
Average	469.20	696.76	5.67
Average without data point 13	217.00	322.245	5.36

These results not only illustrate the the difference between electricity usage in the developing world and those of the developed world, but they also highlight the extent of lack of information in electricity consumption by households in developing countries. This lack of information leads to many different means of calculation and results in vast disparity in the stated monthly household consumption used in modelling microgrids. With regard to the the values stated for Ghanaian household consumption, other reasons for the various discrepancies between the value that was obtained and the values stated in various sources of literature. Apart from the fact that the cited numbers in the works of Adaramola, Essah and WEC are national aggregates, combining both rural and urban consumption, another hypothesized reason for the disparity is the fact that between 2011 and early 2016, there was severe load shedding in Ghana. This was especially pronounced in urban areas, which have the largest loads. In such areas, the load shedding schedule was on average 24 hours of electricity every 48 hours and at its worst 12 hours of electricity every 36 hours. This is evidenced by the GridCo report which claims that out of a demand of 16.03 TWh in 2015, 11.69 was supplied to customers.(GRIDCo, 2015).

Hence, these reported figures show what was consumed under these constraints, which are especially restricting for urban areas and does not show the unfettered consumption of people in the urban areas.

The survey was taken in March 2016 when load shedding had been temporarily halted since January. As of July 2016, load shedding was officially re-announced. Data collected during this period are likely to reflect consumption of electricity without much interference from load shedding

In addition to this, respondents of the survey were mostly people with access to computers, those with computers are more likely to be in a higher income range and higher electricity consumption range.

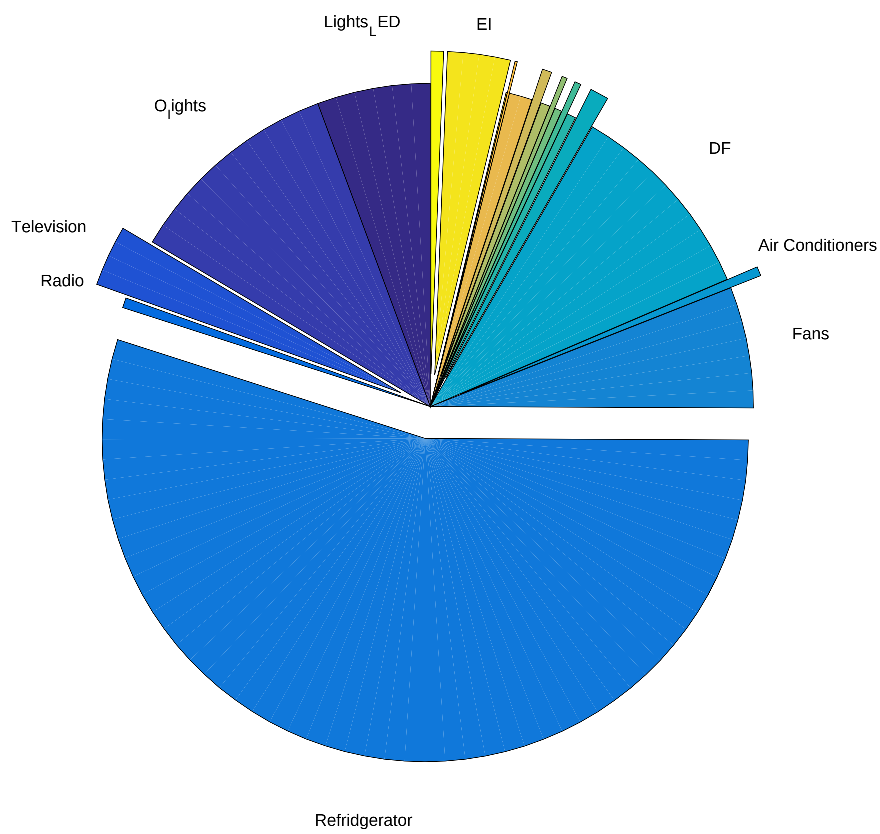


Figure 7: Household appliances and the percentage of energy composition

The main electrical consumers in the “average” urban household are as follows:

- Refrigeration
- Lighting
- Climate control
- Televisions

These are indicators of which sectors to target efficiency efforts in, in order to reduce consumption and also a predictor of the efficacy of demand side management achieved through incentivizing when consumers use appliances.

4.2. Neighborhood differences

The model above is based on national data on urban areas. Thus, if all urban areas in Ghana were represented by a community of 25 houses, the resulting energy demand curve should be similar to what has been generated above. As there is no such thing as an “average” neighborhood, the following changes were made based on the appliance distribution numbers and based on the classification of neighborhoods into low income (appliances with diffusion greater than 0.6) medium income (appliances with diffusion greater than 0.15) and high income (all appliances).

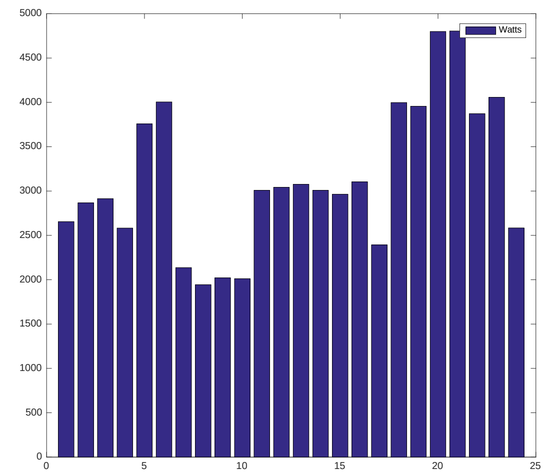
A summary of the results obtained is below.

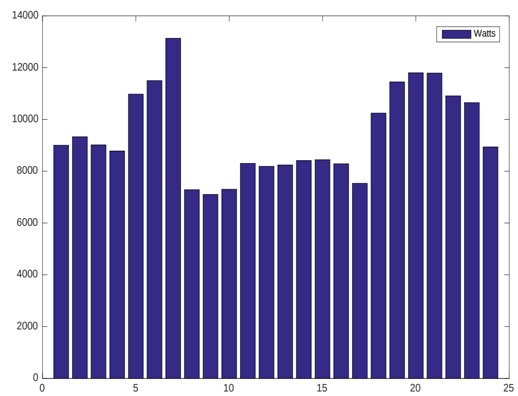
Table 7: Monthly Electricity Consumption in Modeled Households

Scenarios	monthly kWh	Difference
Low Income	91.45	0.71
Medium income	257.49	0.19
High Income	313.78	0.01
Survey result	316.93	

From the above it can be concluded that the survey was filled by mostly people of a higher income bracket. This is a valid conclusion as the survey was sent out by email and social media and hence only those with internet access and possibly a computer filled the survey. As the latter of these two necessities is equipment more likely to be found in a household of higher income, it is reasonable that the survey result be in line what the model predicts for high income households.

Electricity demand per hour, various income levels (clockwise from left: Low Income, Middle Income, High Income)





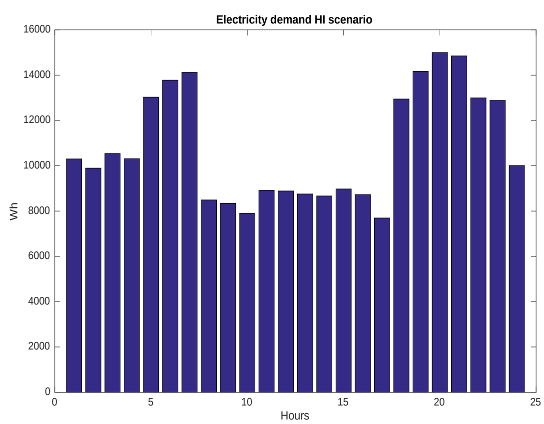


Figure 8: Modeled Household daily electricity demand

Peaks for the low income model correspond with peaks noticed earlier, what is significant about these is that unlike the other two scenarios, the morning peak is much smaller than the evening peak. This signifies that activities in the morning which require electricity, are done using other means of energy. For example, cooking and water heating services may be provided by using gas or traditional cook stoves or they may be provided without the use of added energy (using cold water or eating food that does not require cooking). The monthly electricity consumption is on average 90kWh per household and about 1080kWh per year. Other studies based in Africa such as (Nzia, 2013) place low income households in urban areas as households that consume less than 1000kWh per year. This is on the high end, but still conforms with this grouping.

Medium income households, from the model use approximately, 257kWh per month. Summing up to an annual 3084kWh per year. Again, when compared to the work done by (Nzia, 2013)it is on the upper limit of consumption for the middle class which she ranged between 1000-3000kWh.

With regard to points of peak demand, The morning peak of the low income group occurs at 6am whereas the morning peak the relationship between both peaks in the medium income demand and high income curve differ from the relationship between the peaks in the lower income curve (where the morning peak is much smaller 85%, 114%, 92% . This is mainly because of the use of appliances whose main purpose is to generate heat: irons, microwaves. High income homes according to the model use 313 kWh month and approximately 3760kWh annually. The breakdown of appliance consumption per income group is shown in table 8 below. The weakness in this method is that, due to lack of data on appliance diffusion by income group, the same appliance diffusion is assumed for all income groups. This method may obscure the true means of accounting for appliances and a more robust method needs to be found. The bolded sections represent sections that were used in the section on modelling.

Table 8: Household Appliance Fraction of Household Energy Consumption

	LI	MI	HI
Lights(LED)	**12.28%**	**7.50%**	**8.81%**
Outdoor lights	**11.75%**	**8.20%**	**10.12 %**
Television	**9.79%**	**3.36%**	**6.16%**
Radio	1.63%	0.59%	0.99%
Refrigerator	**44.62%**	**62.32%**	**51.23%**
Fan	**19.94%**	**6.70%**	**5.67%**
Air Conditioner	**0.00%**	**0.00%**	**0.47%**
Deep Freezer	0.00%	5.79%	9.52%
Desktop Computer	0.00%	0.00%	0.94%
Laptop	0.00%	0.23%	0.38%
Washing machine	**0.00%**	**0.00%**	**0.25%**
DVD players	0.00%	0.40%	0.34%
Water heater	0.00%	0.00%	0.22%
Blender	0.00%	0.50%	0.45%
Microwave	0.00%	0.00%	0.44%
Vacuum cleaner	0.00%	0.00%	0.12%
Electric Iron	0.00%	3.66%	3.08%

Rice cooker	0.00%	0.76%	0.56%

The bolded sections comprise between 80% to 98% of electricity consumption depending on the income range of the household. Specifically, they are: 82.71%, 88.08%, 98.37% for High income, Medium Income and Low income households respectively. Hence, these appliances appear to be the right choice when using appliance diffusion curves to simulate electricity demand. There is little room for shifting the demand curve to make it more flat especially in the low income households and medium income household, This is because most of the demand comes from non-flexible loads and equipment such as lights, and refrigeration.

4.3. HOMER results

4.3.1. Current Scenario

Under current conditions of tariff costs and no sell back tariff, the lowest cost of electricity (0.18$/kWh) is achieved by the use of the grid and a diesel generator for all diesel price sensitivities. This is because in the case study of Accra, which is highly electrified (88%)it is much easier to extend the grid connection to the intended site of the project.

At a tariff price of 0.2$/kWh and a sell back price of the same amount, it becomes more attractive to use renewable energy sources. This results in a renewable fraction of 71% the maximum for all scenarios tested. The renewable fraction value is obtained and considered optimal for all cases where the following two conditions are fulfilled:

Electricity tariff is greater than or equal to 0.2$/kWh

Ratio of sellback price to electricity tariff is greater than 0.66.

(in the unlikely scenario of sellback tariff being higher than regular tariffs, these observations do not apply)

Other fractions of sell back produce the following results:

- 1/2

Tariff	Sell back	COE	Ren Fraction
0.1	0.05	0.11	0
0.2	0.1	0.21	0
0.3	0.15	0.22	0.47

Figure 9:Relationship between Feed in tariff to tariff and effect on renewable fraction

- 1/3

Tariff	Sell back	COE	Ren Fraction
0.15	0.05	0.16	0
0.3	0.1	0.26	0.34

Figure 10: Relationship between feed in tariff and renewable fraction

Generally, independent generation becomes more attractive at higher tariffs and when the tariff prices exceed the cost of electricity. The end of this section includes a table which summarizes the effect of the tariff on the optimal system selected by HOMER in terms of the cost of electricity.

4.3.2. No grid

In order to compare the the cost of going completely off grid to the scenarios of grid connection, a simulation was run to observe the results.

It is to be noted that for completely off grid systems, the COE is much higher because of battery storage needed. The same variations were run as before except in this case there was no simulation for grid extension.

The results below display the costs of electricity in dollars, and the system renewable fraction compared to the electricity tariffs being paid.

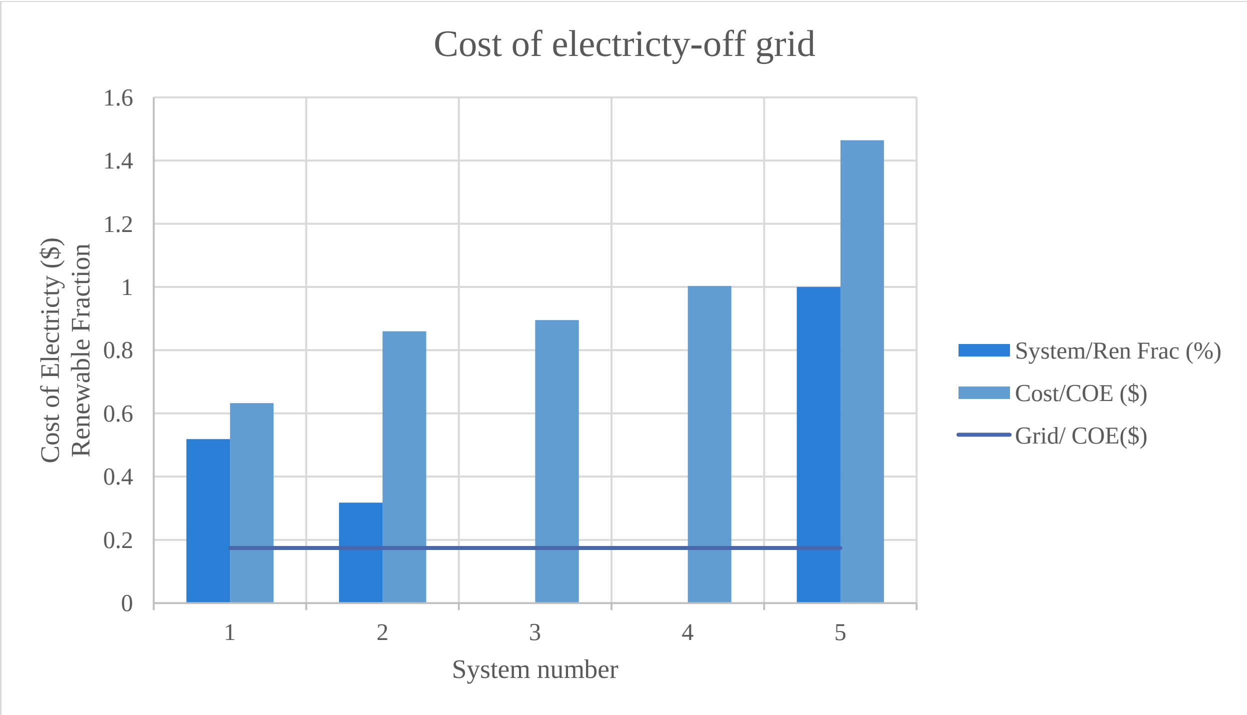


Figure 11: Cost of Electricity results off-grid simulation

Description of the systems used are below:

- 50 kW solar PV, 10kW diesel generator, 400kWh storage
- 50kW solar PV, 25kW diesel generator
- 20kW diesel generator, 400kWh storage
- 25kW diesel generator
- 100kW PV, 2MWh storage

If the objective is to minimize costs, among the off grid options studied, system 1 is the most applicable with a COE of 0.63 and renewable fraction of 0.51.

If the objective is to maximize the renewable fraction, then the most applicable system is system number 5 with a renewable fraction of 1 and a COE of 1.46

Constant use of the generator is expensive and gives COEs between 0.9 and 1.00$/kWh. The COE from the grid at 0.174 is shown for comparison.

4.3.3. Homer optimization-load shedding

A simulation was run to mimic the effect of load shedding in Accra to observe the results on the optimal system. In order to achieve this, HOMER was programmed to give 180 outages each lasting on average 12 hours into the system.

Tariffs for the following optimized solutions were set at 0.174, 0.2 and 0.3 $/kWh and the sellback prices were 0 and 0.174$/kWh.

Below is a list of the systems that were feasible under all scenarios.

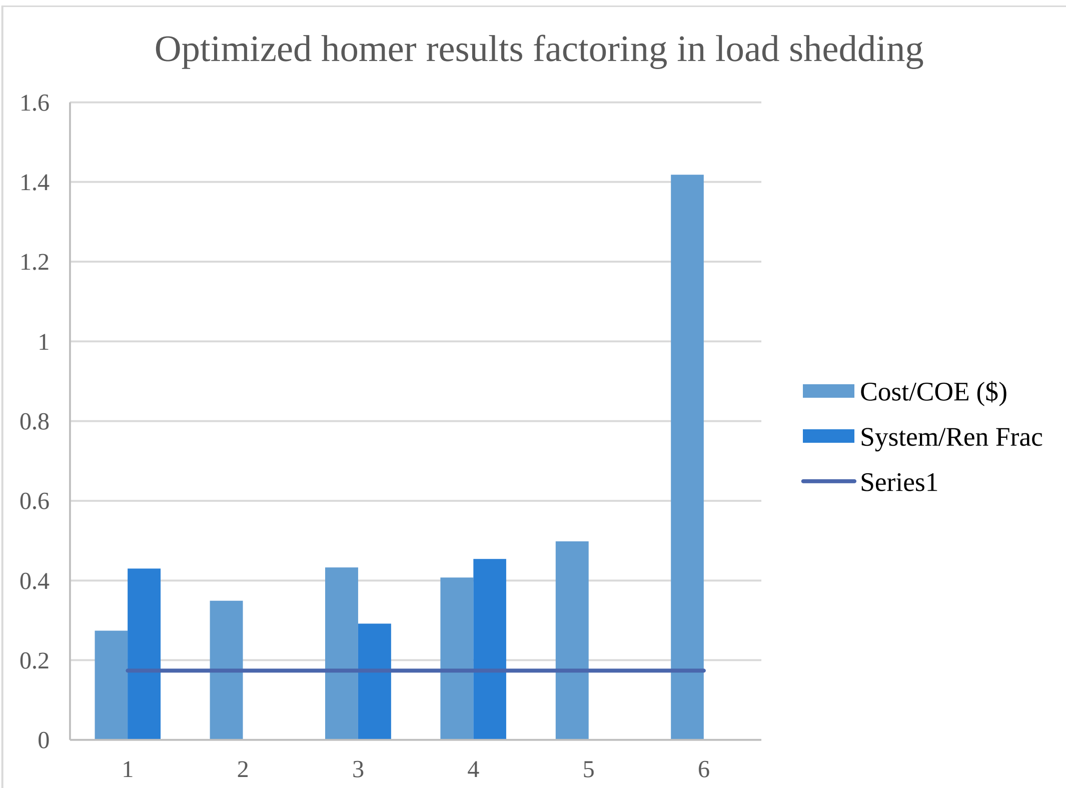


Figure 12:Homer results including Load shedding

Descriptions of the systems numbered above are as follows:

- 40 kW PV, 20kW diesel generator
- 20kW diesel generator
- 25kW PV, 400kWh storage
- 40kW PV, 20 kW storage, 400kWh storage
- 5kW diesel generator, 400kWh storage

- 2MWh storage

Under these conditions, option one, with a COE of \$0.27/kWh is the best choice as it has the lowest COE and the second highest renewable fraction. This is in contrast to what was obtained without input of load shedding parameters. According to this simulation, it is optimal to use solar PV panels with a diesel generator. It is interesting to note that under the conditions of load shedding the COE (under using just diesel generators- the most common solution) rises to \$0.35/kWh.

Table 9: Percentage of household uses that own an independent electricity generator

Does your household have independent electricity generating equipment? (e.g. diesel Generators, Solar PV etc)		
Answer Options	**Response Percent**	**Response Count**
No.	68,2%	15
Yes, Diesel Generator	22,7%	5
Yes, Solar PV	0.0%	0
Other (please specify)	9,1%	2
	answered question	**22**
	skipped question	**8**

4.3.4. All scenarios - no load shedding

As mentioned earlier, it was observed that the renewable fraction varied with the tariff price and with the difference between the tariff and the sell back price.

It is observed that, when the opportunity cost of independent production through renewable and of selling back to the grid is higher than dependence on the grid or on diesel fuel the renewable fraction is higher.

Net Tariff function:

A net tariff function was created, that gave equal weighting to the net tariff and the electricity tariff. This is because the renewable fraction appeared to have a relationship with both of these functions working together, but not to any of them when plotted individually.

The net Tariff function is as follows:

$$f(net\ Tariff) = (Tariff - Sell\ back\ rate) \times Tariff \tag{4}$$

Threshold of tariff beyond which this pattern emerges is not included in the range of values tested, but appears to be at 0.20$/kWh. Hence beyond a tariff rate of $0.20/kWh under the conditions tested, the adoption of renewable electricity resources is attractive financially.

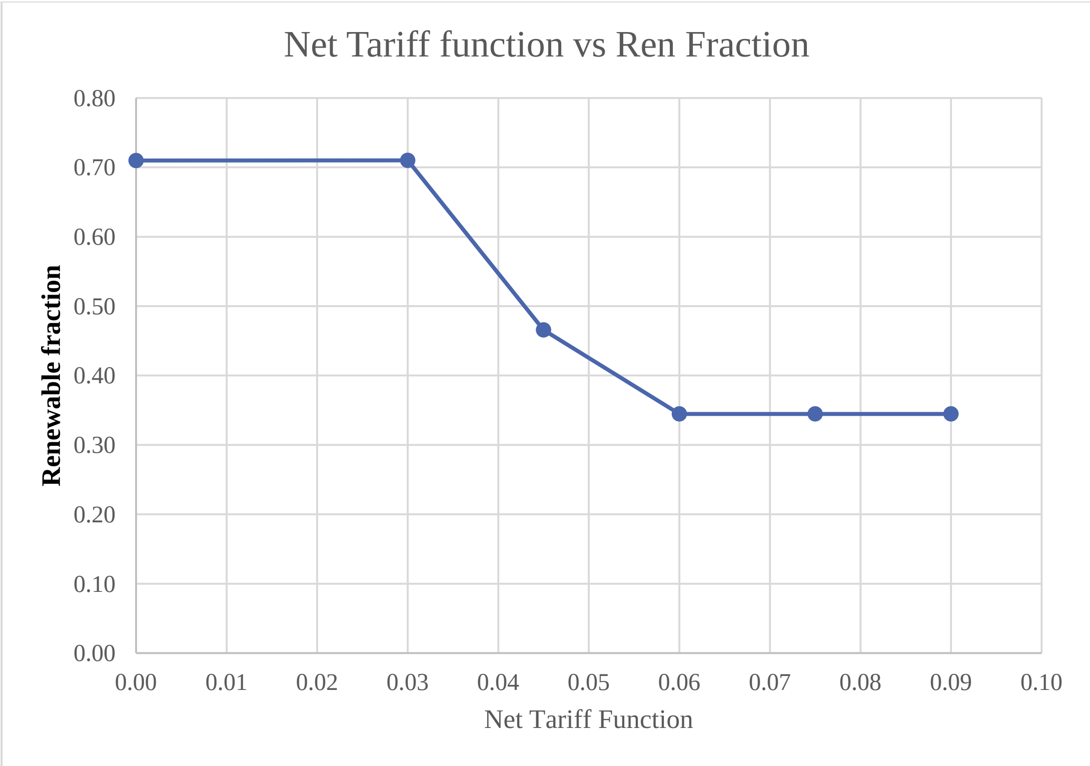


Figure 13: Relationship between net tariff and renewable fraction

It appears that for the simulations ran, and within the ranges they were run, it is not possible to encourage full renewable energy systems using motives of finance unless tariffs are higher or fee-in tariffs rise.

However, if higher tariffs were included such as 0.4$ kWh and onward, a vastly different curve would be obtained as these higher tariffs will allow for the opportunity costs involved in switching to independent generation to be higher. These curves could probably have a maximum that allows for full renewable application. It is interesting to note that under the conditions of load shedding the real tariff for those who use diesel generators rises to $0.35/kWh hence the optimal system under this condition has a renewable fraction of 40%.

Similarly, a net COE function was developed to observe the behavior of the effect that the net COE has on the choice of system.

The function used is as follows:

$$Net\ COE\ function = (COE\ of\ system - Tariff)^2 \tag{5}$$

Below is the graph achieved by plotting this function against the renewable fraction of the systems

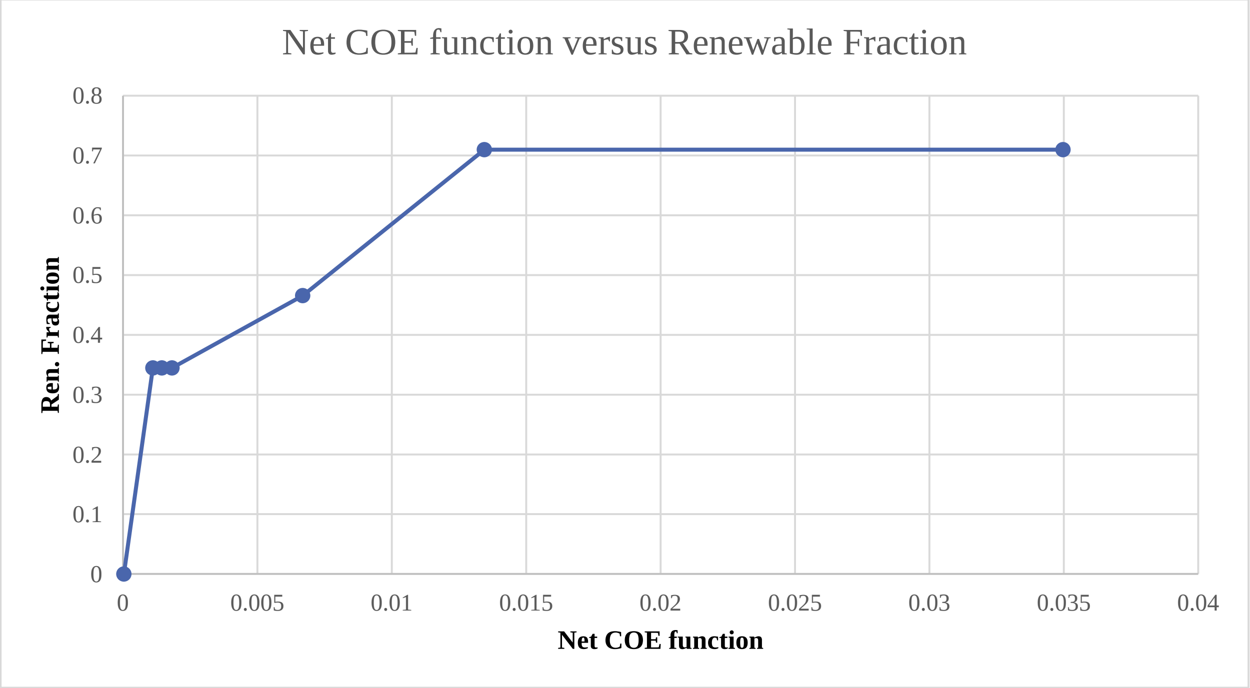


Figure 14: Relationship between net COE function and renewable fraction

Net COE function as used in the graph above is simply the square of the difference between the Tariff and the cost of electricity. This value was used as an indicator of how much savings is achieved by using the alternative option rather than connecting to the grid and paying the tariff. Intuitively, as the tariff rises, there are more savings to be made by producing electricity independently. Hence the renewable fraction rises with the Net COE marker, leveling out at 0.71. This may be an indication that tariffs may need to be higher in order to encourage more reliance on independent and renewable electricity production, yet, this recommendation needs to take into account the drawback to higher tariffs; that is, they increase the financial burden on poorer households and instead of encouraging more financially stable households into self production, may result in extreme situations like poorer households having their connection cut off due to their inability to pay the bills.

A summary of the viable results obtained from the HOMER simulation is displayed below:

Table 10:Summary of Homer results

Tariff	Sellback	f(net tariff,tariff)	Renewable fraction	Solar	COE
($/kWh)	($/kWh)			kW	($/kWh)
0.17	0.00	0.03	0.00	0.00	0.18
0.20	**0.20**	**0.00**	**0.71**	**100**	**0.08**
0.30	**0.20**	**0.03**	**0.71**	**100**	**0.11**
0.30	0.15	0.05	0.47	40	0.22
0.30	0.10	0.06	0.34	25	0.26
0.30	0.05	0.08	0.34	25	0.26
0.30	0.00	0.09	0.34	25	0.27

This information is useful to policy makers as it displays the possible effect of subsidies on improving the spread of off-grid systems in the private sector. While it makes economic sense intuitively, the work above provides a means to visualize this effect.

4.4. Appliance Diffusion Curves

The logistic curves obtained for each country based on the behavior of the country in the last 15 years is shown below:

4.4.1. Ghana

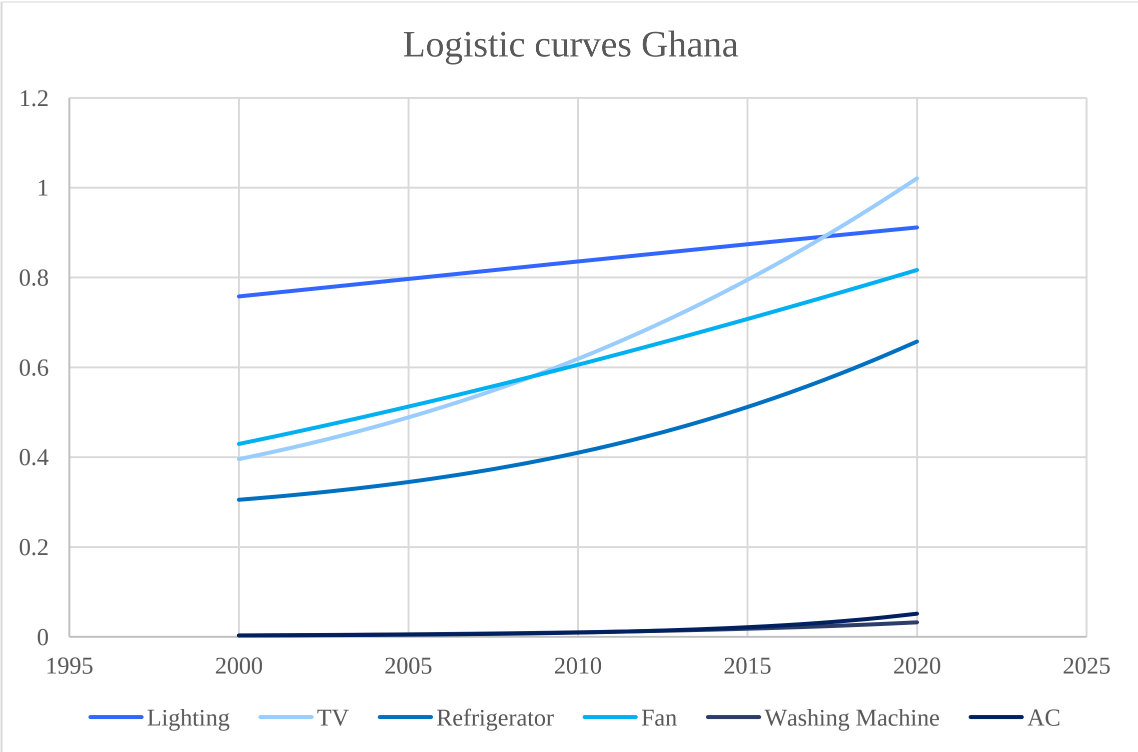


Figure 15: Diffusion curves Ghana

Lighting, which closely follows electrification, is seen to rise linearly, as it has been doing for the last 15 years. This can be thought of as a consequence of the countries electrification plan, which plans to reach 88% by 2020. From the model, it seems that the country is on track to do so, if it continues the way it has been going.

Televisions are rising sharply and by 2020. if things continue the way they are, there will be on average one television per urban household. Likewise, refrigerators show a 30% rise between 2015 and 2020. This is a consequence of the increase in the wealth of people increase and a fall in technology prices.

Fans show almost a linear, rise which is a consequence of their purchase being driven by climate conditions rather than the societal influential behavior that drives technology adoption curves.

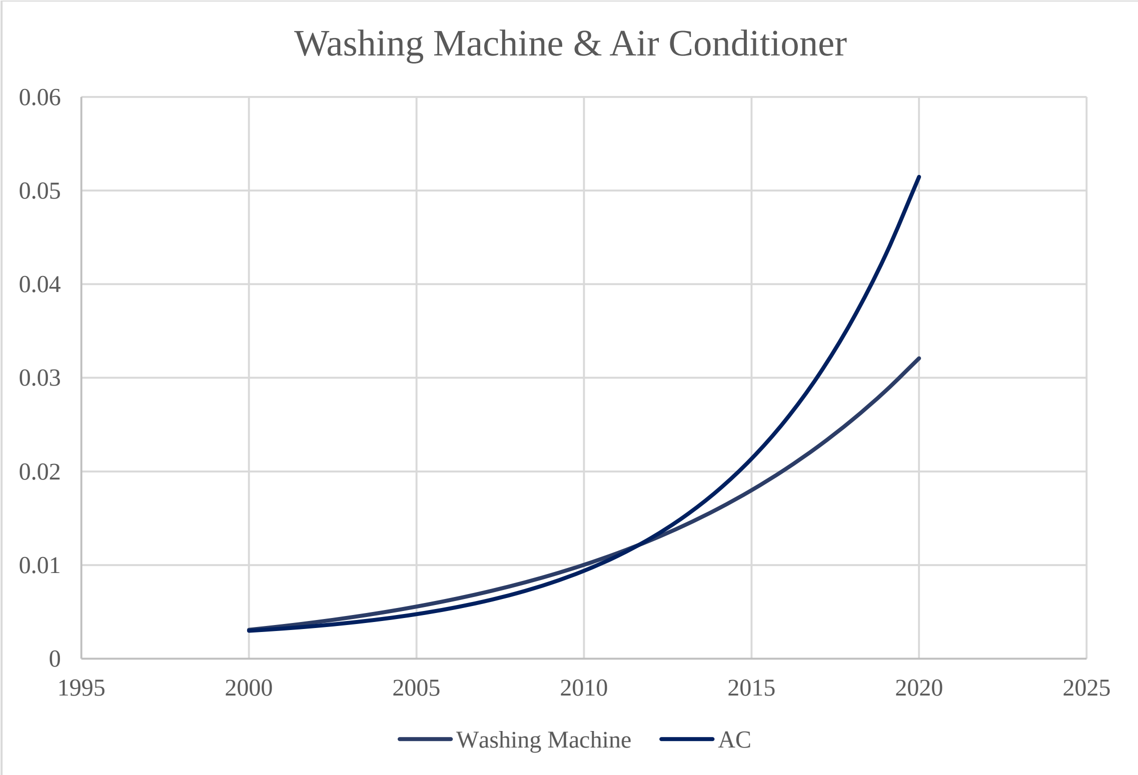


Figure 16: Diffusion curves for Washing machines and Air conditioners Ghana

Washing Machines and Air Conditioners are considered expensive to the average African household. However, studies (Letschert, Bojda, & Mcneil, 2012) have shown that the presence of these machineries are set to rise in households in the coming years due to the benefits they provide. Some studies (Barthel & Gotz, 2013) predict a 105% increase all over Africa by 2020 compared to the numbers in 2013.

These technologies are predicted to rise in the near future, and with their rise, the need for demand management, as these appliances tend to use higher wattage that other household appliances and have loads that can be shifted throughout the day in order to balance the demand curve from residential appliances. That is, if these residences are still to be connected to the grid.

All curves in the Ghana model, were fit to data from the Ghana Living Standards Survey (Arch, 2013; Ghana Statistical Service, 2008) published in 2000. 2008 and 2014. All information about household income was also derived from the same source.

4.4.2. Kenya

In order to plot the diffusion curves for Kenya, it was necessary to plot household income. However, only one point of household income was found (2009), hence, under the assumption that the household income behaved similarly to the gross national income, household income values were plotted for the years 2003 and 2014. These years correspond to other years in which demographic surveys were run in Kenya.

The urban electrification rate in Kenya is rising slowly. Kenya is a relatively large country unlike Ghana and has many cities spread around the country. Kenya's current effective installed (grid connected) electricity capacity is 1,429 MW. Electricity supply is predominantly sourced from hydro and fossil fuel (thermal) sources. This generation energy mix comprises 52.1% from hydro, 32.5% from fossil fuels, 13.2% from geothermal, 1.8% from biogas cogeneration and 0.4% from wind, respectively. Current electricity demand is 1,600 MW and is projected to grow to 2,600-3600 MW by 2020 (https://energypedia.info/wiki/Kenya_Energy_Situation#Energy_Situation).This makes the cost of electricity distribution much higher and promotes the case for decentralized energy generation. Generally, Kenya supports distributed generation projects, to help reduce the pressure on the government.

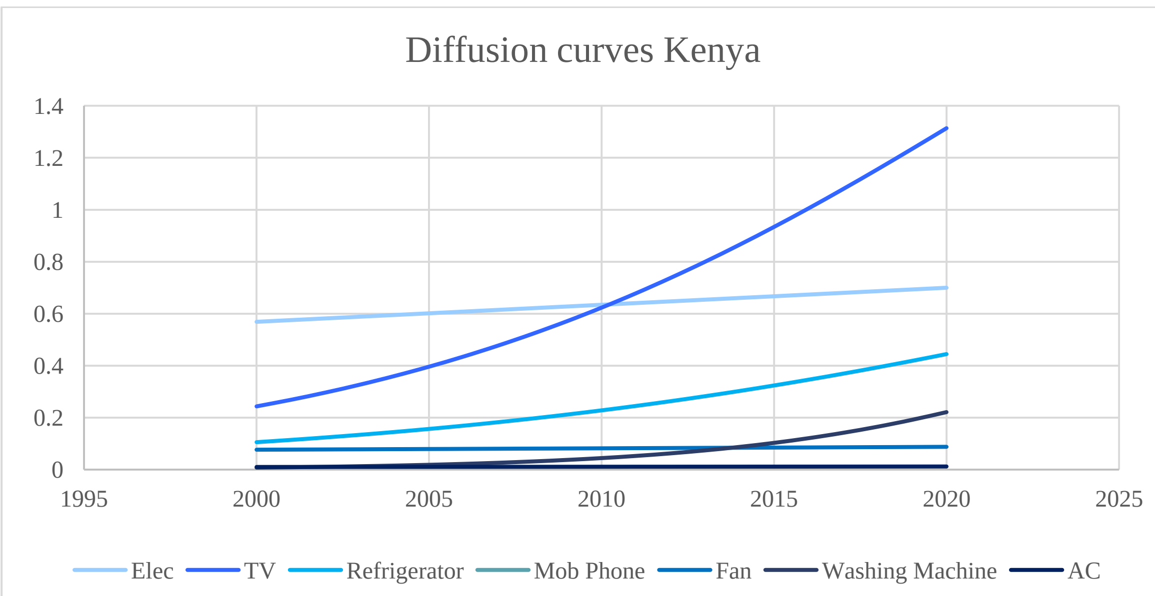


Figure 17: Diffusion curves Kenya

Appliance curves for televisions, lighting and refrigerators were fitted to data from the Demographic and Health Survey that is sponsored by the USAID. For data points on Washing Machines, Fans and AC, data from (Nzia, 2013) survey was used. However, there was only a single time point for this data.

It appears that climate control equipment is not very popular in Kenya. This due to the low need of them as there are few cooling degree days annually. Out of the cities studied, Nairobi in Kenya had the least amount of cooling degree days. Cooling degree days above 25C of the capital cities of each of the countries selected is shown below. The use of climate control equipment is expected to drop with the number of cooling degree days

Table 11: Cooling degree days above 25 degrees Celsius

City	CDD
Abuja, Nigeria	963
Accra, Ghana	921
Brazzaville, Republic of Congo	644
Nairobi, Kenya	78
Windhoek, Namibia	413

4.4.3. Namibia

Curves developed for Namibia are shown below. As Namibia is generally more well off than the other countries studied, the nature of many of its curves is not surprising. That is, most of the appliances studied in Namibia display a flat curve because they are past the point of the exponential growth portion of diffusion curves and lie in the linear growth portion of the curves, where the new purchases of equipment is driven by the need to replace them and by the late few on the technology adoption curve.

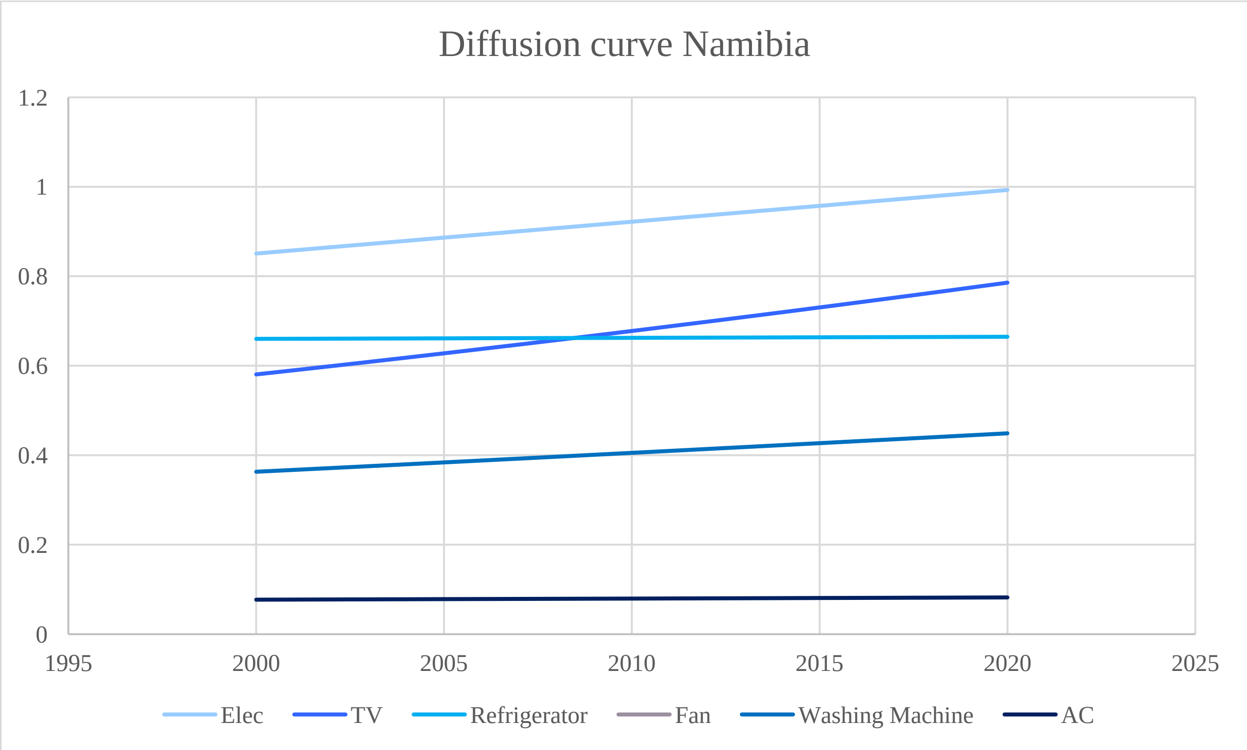


Figure 18: Namibia appliance diffusion curve

Namibia, like most of Southern Africa has a high electrification rate. This is evident in the curve for lighting in urban lighting. Televisions rise by 8% between 2015 and 2020. Refrigerators and Air conditioners remain fairly constant

Like data for Kenya, the DHS survey by USAID provided 3 data points for Namibia (MoHSS, 2003; MOHSS, 2008; Namibia Statistics Agency, 2010)), whereas data for Air conditioners and washing machines were assumed to be similar to those of South Africa, a neighboring country of Namibia, with a similar past, similar culture and in the same range of GDP. This was the best estimation that could be made as there was no easily accessible data for Windhoek.

4.4.4. Nigeria

Nigeria has a high urban electrification rate. However, like Ghana, there is a large amount of power outages due to the inability of the generation to meet the demand. This inability has been prolonged and severe that according to the energy commission of Nigeria, as at 2009, 60 million Nigerians owned diesel generators. The enormity of this number is evident when compared to the urban and national populations of Nigeria at this time which were 66million and 155 million respectively.

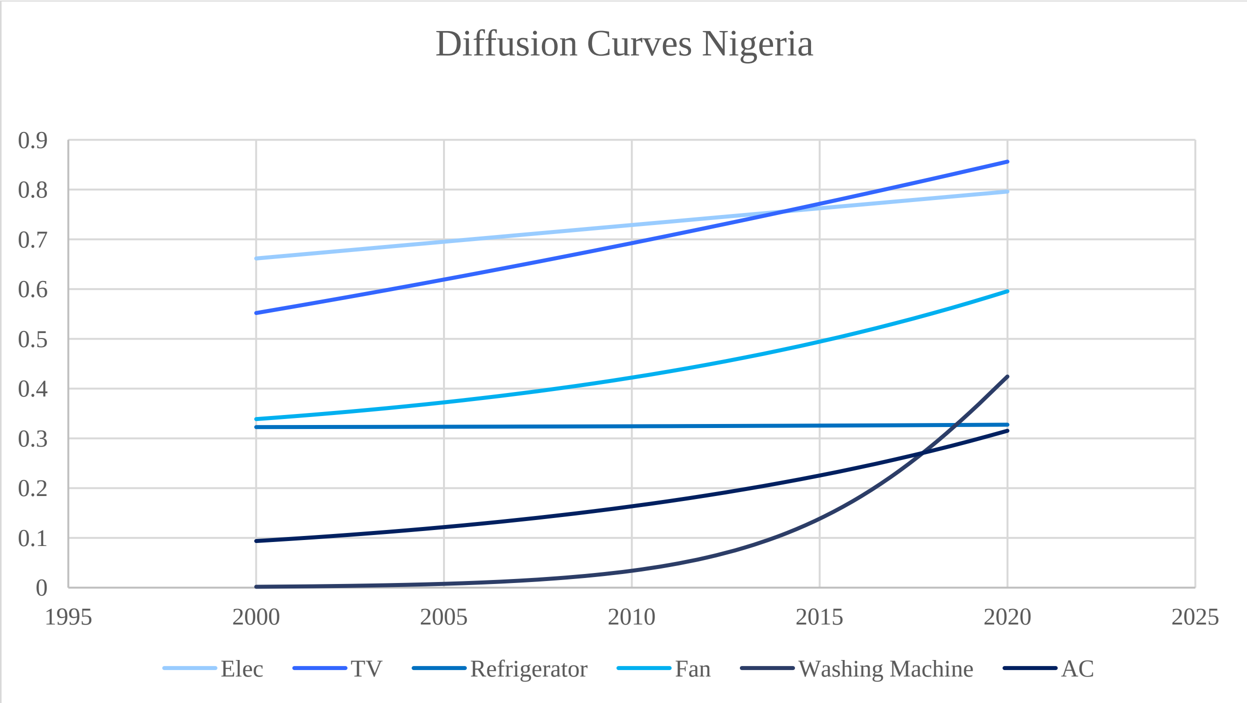


Figure 19: Diffusion curves Nigeria

Like all the other countries studied, purchase and usage of Televisions undergo a steady, almost linear rise. Fans and ACs, the only climate control equipment studied, will undergo a similar slightly exponential rise based on their past behavior. Washing Machines, like in every country studied, except Namibia, are expected to have the greatest rise in the next 5 years.

Data used for plotting these curves were taken from the Demographic and Health Survey for Nigeria in 2003, 2009, 2013(National Population Commission, 1999, 2014). For data on Climate Cooling Equipment and Washing Machines, data was taken from a bank study on the middle class urban consumer in Urban areas of Nigeria. (Robertson, 2011)

4.4.5. Republic of Congo

Congo recently started rebuilding after political strife and civil war in 1997. Appliance diffusion values are low and all curves are exponential due to this rebuilding process. In fact, Republic of Congo has the highest growth rates for all appliances except the television sets among the countries studied.

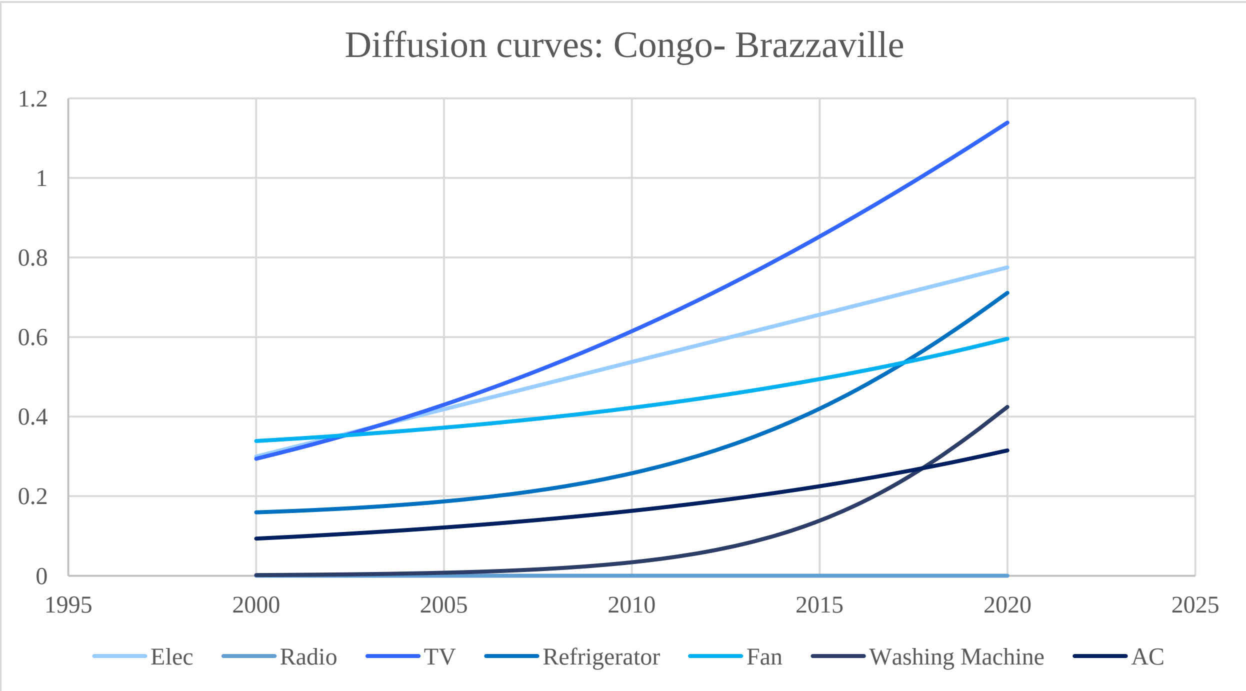


Figure 20:Diffusion curve Republic of Congo

Televisions continue the trend of exponential rise and by 2020. there should be on average 1.14 television sets per household if trends continue the way they have been in the past 15 years.

Refrigerators have a significant rise with time, in fact, in Congo, the have the highest rate (69.2%) of growth between 2015 and 2020.

Data on Climate cooling equipment and Washing Machines were not easily accessible for Republic of Congo or its neighboring countries. Hence data from Nigeria was used as, it has a similar GDP per capita to Congo among the countries studied. This is a very rough estimation and introduced a large error in the calculations for Republic of Congo as will be seen in the results section.

It is also worth noting that the rise in the number of climate equipment is attributed to a rise in wealth. However, in reality this may not be strictly the case. Climate control equipment are a stronger function of the number of cooling degree days than of household income. In this test, they are plotted as a function of household income which will rise with development rather than of the climate which does not rise as sharply as income. Hence the effect of these appliances in the afternoons, when the sun is at its peak , are greatly pronounced.

All these curves are predicted based on an as is scenario, but with Moore's law of technology and an unpredictable global economic climate, especially in Africa, they are far from a determinant of what will happen. They only suggest that if things continue in these countries as they have for the last decade, these are the diffusion rates of appliance to expect.

The table below is a summary of all the diffusion curves above focusing on 2015 and 2020. This information was fed into the program created in section 3.1 to view the effect on electricity demand.

Table 12: Diffusion states of various equipment in various countries

	Ghana		Kenya		Namibia		Nigeria		Republic of Congo	
	2015	**2020**	**2015**	**2020**	**2015**	**2020**	**2015**	**2020**	**2015**	**2020**
Lighting	0.87	0.91	0.67	0.70	0.96	0.99	0.76	0.80	0.66	0.77
TV	0.79	1.02	0.93	1.31	0.73	0.79	0.77	0.86	0.85	1.14
Fridge	0.51	0.66	0.32	0.44	0.66	0.66	0.33	0.33	0.42	0.71
Fan	0.71	0.82	0.08	0.09	0.00	0.00	0.49	0.60	0.49	0.60
Washing Machine	0.02	0.03	0.10	0.22	0.17	0.18	0.14	0.42	0.14	0.42
AC	0.02	0.05	0.01	0.01	0.08	0.08	0.23	0.32	0.23	0.32

4.5. Electricity Demand Planning with Diffusion Curves

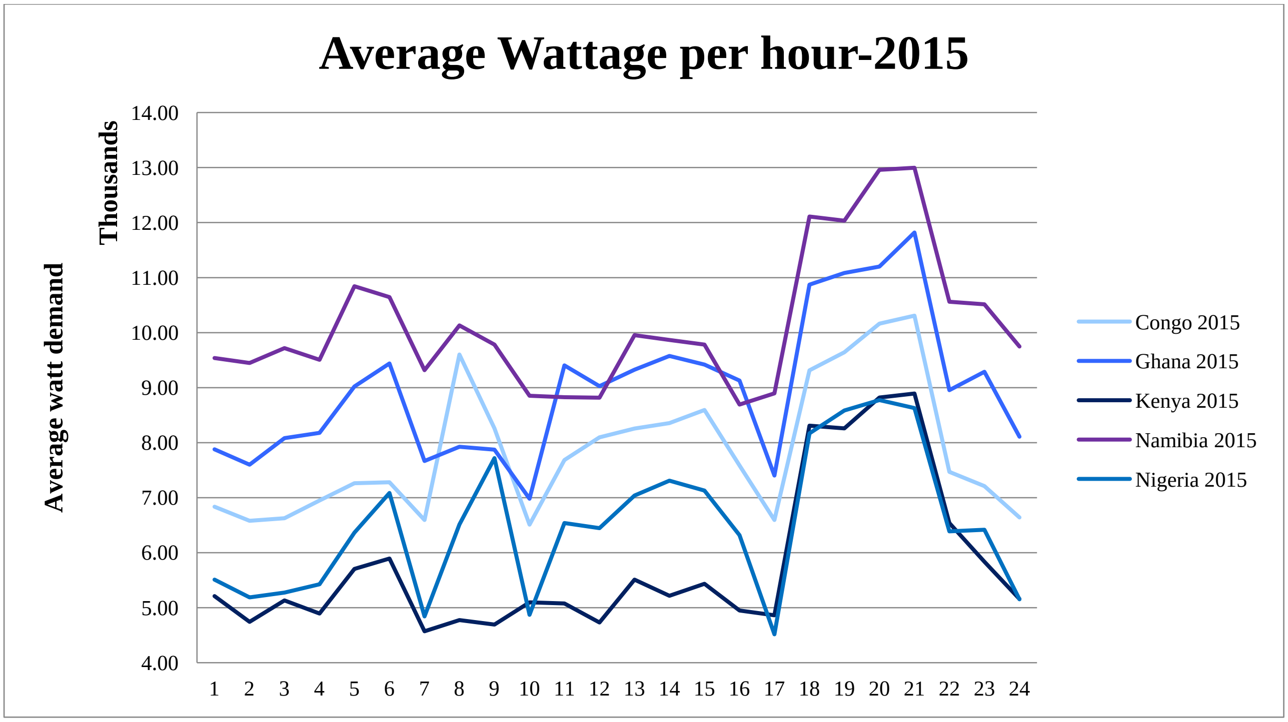


Figure 21: Average Wattage for a community of 25 households

The electricity demand curves developed from the program are shown above. With the exception of Namibia and Kenya, these curves differ from what was simulated in section4.1 in that there are significant peaks in the afternoon. These arise due to the use cooling equipment in the afternoon and due to the fact that there was reduced separation based on income level. The results above, display an estimate of what to expect, if Asaduru, the Swedish company, were to decide to build their pilot project in the urban areas of any of the countries listed above. Below, the program was rerun for the predicted values for 2020. The effect on the curve from cooling systems can be seen although the curves are smoother in the afternoon. This effect from cooling is especially pronounced in Nigeria, with the highest cooling degree days and the highest diffusion of Air Conditioners. It is also quite evident in the curve for Brazzaville, which was simulated using data from Nigeria.

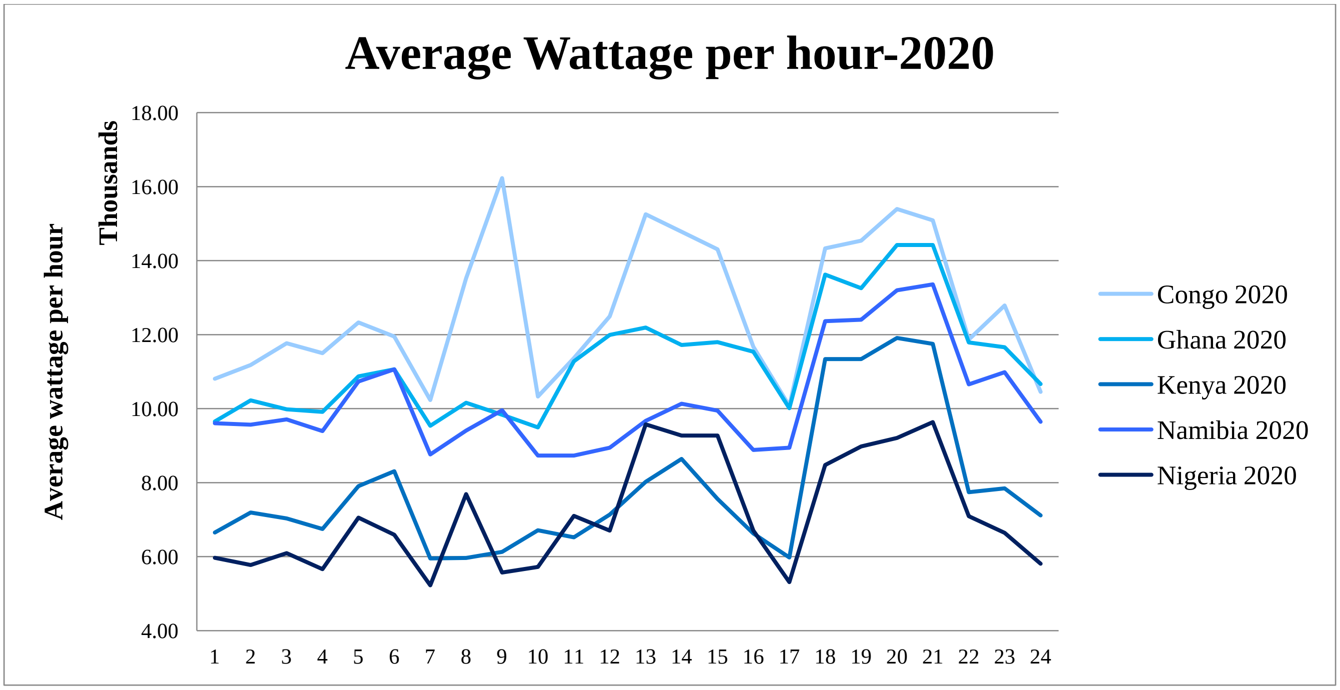


Figure 22: Average Wattage for 25 households 2020

In 2020, the effect increased wealth on the curve gets more pronounced as more households have access to funds to purchase more equipment. This raises the peaks within the curve. However, this can be avoided with programs in demand side management.

4.6. Validation of models

The table below displays the results from the MATLAB program compared to the data obtained on monthly electricity consumption in 2015. Where, 2015 data was unavailable, data from the year closest to it was used.

The large error for Congo, stems from the fact that data from Nigeria was used in estimating the diffusion of Fans, Washing Machines and Air Conditioners

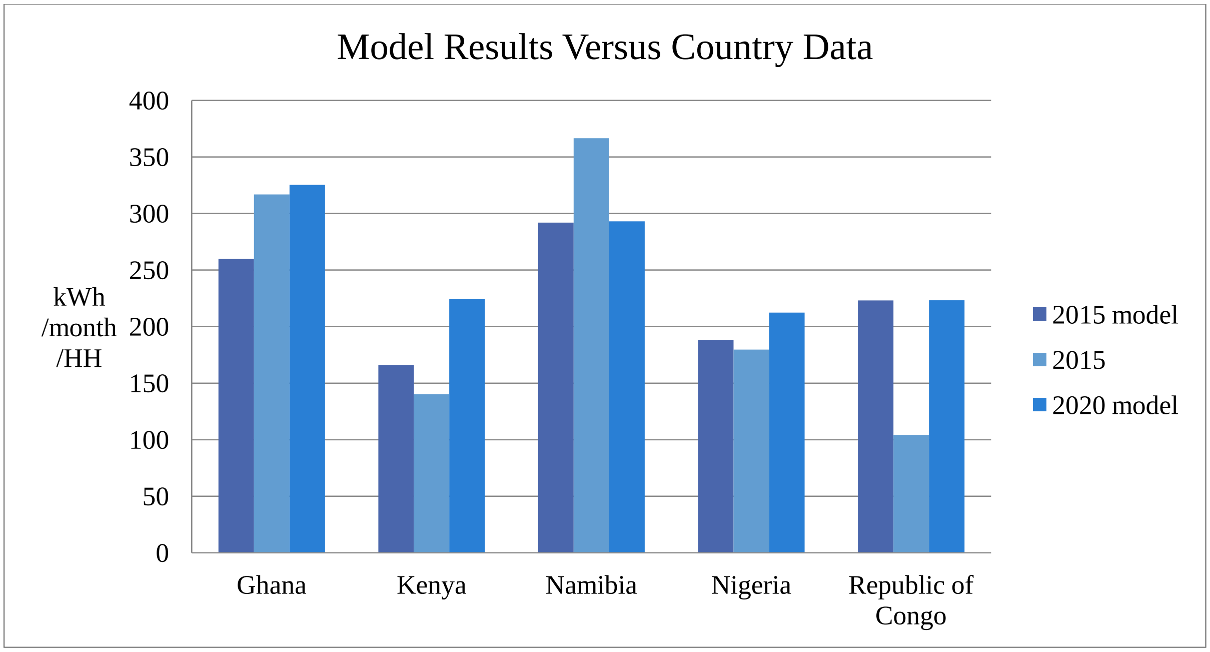


Figure 23: Comparison of results from model and from data

Table 13, shows the calculated increases in household energy consumption from 2015 to 2020. On average, there is a 15% increase in household energy consumption.

Table 13: Increase in average household consumption

	2015	2020	Increase
Ghana	259.8	325.4	0.25
Kenya	166.1	224.3	0.35
Namibia	291.9	293.1	0.00
Nigeria	188.3	212.4	0.13
Republic of Congo	223.1	223.3	0.00
		Average	0.15

Table 14 shows the values above and the error embedded in the values. For most of the cases studied, the error was within 30% of data. The case of the republic of Congo had an error of over a 100%.

Comparing the results from Ghana, using the 6 labeled equipment, to the results obtained from using all the equipment listed in the surveys by the national statistics office, we can conclude that using the 6 equipments is a satisfactory way to estimate the household electricity usage under a particular household income level. This model did not seem to work when it came to Namibia as there was very little change (2kWh) between the 2015 simulation and the 2020 simulation. This is probably because Namibia has a very high per capita income and household income. It had the highest household income of the countries studied. Hence, households in the urban areas are likely to have most of these equipments already, so the diffusion curve does not show much growth in the equipments that and the diffusion curve will be more useful in tracking other equipment that households begin to purchase once the necessities are gotten. These smaller equipment, while they may consume less tend to add up overtime[NM3] to enlarge the consumption of a household. Unfortunately, as these were not tracked in the case of Namibia, it is not possible to predict the future energy consumption for Namibia with this model.

	Model results		Data	Net error	Data Source
kWh/month/HH	2015	2020	2011-2015	**2015 range**	
Ghana	259.8	325.4	316.93	**24.35%**	[Survey]
Kenya	166.1	224.3	208.45	**25.50%**	(Nzia, 2013)
Namibia	291.9	293.1	366.55	**20.37%**	(Oertzen, 2015)
Nigeria	188.3	212.4	179.67	**4.80%**	(Ezennaya, Isaac, Okolie, & Ezeanyim, 2014)
Republic of Congo	223.1	223.3	104.17	**114.18%**	(DEKAMBI MAVOUNGOU, NDINGA OSSONDJO Guy Serge - NIAMA NGOMA, & BELZILE, 2015)

Table 14: Comparison of results

This presents a problem for the other countries studied. As household wealth continues to increase, this model will need to be expanded to improve its utility.

4.7. Policy implications

Policy implications that can be drawn from this survey include:

- Effect of finance on the spread of renewable energy systems.
  - If countries are determined to increase the spread of household independent generation, it is necessary to modify the tariff structure of the country to encourage this. If this is not done, people are more likely to purchase diesel generators as this is the most common solution as at now and is likely to continue till the price of diesel is too high to sustain it.
  - It also highlights the need for countries to create competitive financing methods whether through subsidies or other means in order to encourage independence.

- According to GridCo: “At the same time, it is important that the market structure and tariffs ensure that electricity is properly valued on both the supply side and the demand side, incentivize reliability and an appropriate mix of generation and transmission resources, and ensure that electricity is as affordable as possible within the context of reliability. Ghana’s market structure and tariffs must be reviewed, recognizing that in the medium to long term, flawed economics creates an unhealthy industry that is not sustainable” (GRIDCo & Power Systems Energy Consulting (PSEC), 2010)

- Effect of efficiency measures on household equipment
  As can be seen above, for many developing countries, the household consumption of electricity can be roughly calculated with the use of a few equipment. Countries that want to reduce electricity consumption or CO2 emissions can therefore put efficiency limits of the equipment tested in order to minimize the household consumption of electricity

- The efficacy of demand side management programs can be estimated from the category of equipments studied. According to a classification made by Vanthournout et al, the appliances studied fall into the following groupings:
  - *High flexibility potential with few comfort and/or performance impacts*: washing machines, residential air conditioners
  - *Smaller flexibility potential and/or larger comfort/health impacts*: refrigerators
  - *Only emergency flexibility potential*: lighting.

(Vanthournout, Ectors, Claessens, Maagøe, & Viegand, 2015)

Hence in assessing the possibility of the effectiveness of demand side management, there is a window of opportunity in within washing machines and climate cooling equipment.

5. Conclusion and Future Work

This study sought to utilize development aggregates to estimate electricity demand in urban areas of developing countries. It is hoped that further research into this sector will lead to the ability to be able to forecast consumption in sectors of the economy and aid in the provision of more uniform estimates of household electricity consumption.

However, in order to be able to do this accurately, there is a need for more data to aid in plotting diffusion curves. This model can also be run under different scenarios to assess the effects of energy policy that focusses on appliance usage. This study linked econometric data with appliance ownership in households and from there used that to predict the household consumption in urban areas. A more detailed version of the model was used to run a case study in Accra on behalf of ASADURU, a Swedish construction company. It was found that houses consume about 290kWh/month, which is much higher than many estimates in literature. Yet these estimates in literature are based either on national aggregates or on estimates that compare developing countries to developed countries. Hence, they vary greatly between them. This phenomenon illustrates the need for models that consider developing countries more thoroughly and consider the discrepancy between urban and rural areas which are much more pronounced that in developed countries.

The model studied in this thesis only serves as a starting point for future studies. While there are studies that look into how electricity powers economic growth in the commercial industry, there are fewer that look into how households in developing countries will change as the countries attain economic growth. The macroeconomic model used in this study was based on an assumption of linear economic growth and hence was not extended far out into the future. In light of this, further studies may look into better correlation of economic growth and household electricity consumption. There is also an avenue created through this work to explore how far in the future this model is valid. This model used the behavior of macroeconomic variable over the last 15 years (and in some cases 25 years) to predict what they would look like in 5 years. This was based on the assumption that over the last 15 years, the macroeconomic variables have followed a relatively uniform progression; hence we can expect that same uniform progression in the near future barring unusual events or catastrophes. However, it becomes more risky to extend this assumption further into the future as long term economic progressions are rarely linear.

The load profile was placed into HOMER to find the economic viability of the ASADURU project. It was found that, the tariff on electricity and the feed-in tariff of the system have an interesting effect on the limit of renewables in a system. It was also discovered that, factoring in load shedding in the HOMER system, change the optimal system selected and increased the real cost of electricity that customers pay for. There is a dilemma with respect to the case study on Ghana, considering the fraction of electricity that is from hydroelectricity (43%), and if the Ghanaian government is able to solve their load shedding problem, it may be more environmentally friendly and cost effective to connect to the grid. Yet in light of recent policies to push new residential construction to be self producing in terms of electricity, companies interested in construction in Ghana may need to consider microgrids that may cost slightly more to start with and have relatively the same renewable fraction level. In order to promote this and to make companies more willing to approach this challenge, the Ghanaian government may need to make self production a more financially attractive choice by either adjusting the electricity tariff levels or the government subsidies on diesel. Another policy tool to be considered, if the network in Ghana is capable of doing so, is the prospect of feed in tariffs. This thesis examined these options with HOMER and found that under current tariff levels, and with the same equipment setup used in the modeling section, if there is no desire to have renewable energy generators, then it isn't financially attractive to set up renewable independent production and the renewable fraction goes to zero.

On the other hand, if tariffs were higher and self producers could receive payments for the electricity that is sold into the grid at the same price that is the tariff rate, the maximum renewable fraction of the system that would be most financially attractive would be 0.71. This indicates that either tariffs have to be raised or there is the need to implement feed in tariffs to get more investors into the residential renewable energy generation sector.

This observation also highlights an important aspect of electricity planning; support of the government. With regard to industrial use, this model may serve as a preliminary planning tool for companies like ASADURU or for microgrid planners. The focus on urban areas and on residential sectors fills a gap that is rarely addressed in microgrid electricity planning. It is a helpful tool for policy planning and for project planning

In conclusion, this study begun as a prompt from ASADURU to aid in planning the first pilot project in Accra, Ghana. To do this, data on the living standards in Ghana was taken from the Ghana living standards survey and used to model a daily usage curve for a community of 25 households. The Electricity demand curve for this community was put into HOMER to simulate and estimate the most cost effective means of providing electricity to this pilot project while having some component of renewable energy to fit with the new direction of Ghana's policy for residential construction projects.

This study then was expanded to other urban centers in Africa, in light of the lack of information about residential living standards online, data was taken from the world bank and the demographic and health survey database of the USAID. This data was used to estimate the living standards and the prevalence of certain household appliances in the urban areas of these countries, in some cases using inequality measures. With information about the prevalence of household appliances available, the household electricity consumption was estimated for the year 2015 and predicted for 2020. The latter methodology introduces a method that may be useful in planning electricity systems in places where information may be scarce. This is because the World Bank and the USAID data base are regularly updated and accessible to all.

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Annex I: Survey Results

In what city do you live?

Answer Options	Response Count
	30
answered question	30
skipped question	0

Number	Response Date	Response Text
1	mai 14, 2016 7:42 AM	Port Harcourt
2	mai 13, 2016 10:59 AM	Maputo
3	mai 10, 2016 2:21 PM	Greater Accra
4	mai 4, 2016 11:37 AM	Tema
5	abr 29, 2016 9:48 AM	Akosombo
6	abr 29, 2016 9:40 AM	Accra
7	abr 28, 2016 4:20 PM	Accra
8	abr 28, 2016 3:38 PM	Accra
9	abr 28, 2016 3:06 PM	Senchi - Amanfrom Near Akosombo
10	abr 28, 2016 2:44 PM	Accra
11	abr 28, 2016 2:34 PM	Accra
12	abr 28, 2016 2:13 PM	Accra
13	abr 28, 2016 2:02 PM	Tema
14	abr 26, 2016 11:28 AM	Accra
15	abr 22, 2016 12:04 PM	Accra
16	abr 22, 2016 11:40 AM	Tamale
17	abr 22, 2016 10:28 AM	Accra
18	abr 22, 2016 10:23 AM	Accra
19	abr 22, 2016 9:59 AM	Accra
20	abr 22, 2016 9:55 AM	Yaoundé
21	abr 22, 2016 1:01 AM	Accra
22	abr 21, 2016 9:21 PM	Accra
23	abr 21, 2016 7:56 PM	Arcueil
24	abr 21, 2016 5:17 PM	Accra
25	abr 21, 2016 4:45 PM	Yaoundé
26	abr 21, 2016 4:32 PM	Accra
27	abr 21, 2016 4:03 PM	Kigali
28	abr 21, 2016 3:57 PM	Accra
29	abr 21, 2016 3:48 PM	Accra
30	abr 21, 2016 3:33 PM	Philadelphia

Electricity Use in Residential Sector

Do you know your last 3 electric bills?		
Answer Options	Response Percent	Response Count
Yes	70.0%	21
No	30.0%	9
	answered question	30
	skipped question	0

Electricity Use in Residential Sector

If yes, can you please give them below? (either in kWh-kiloWatt hours- on your bill or in currency values-please specify which you're using and separate each value with a comma).	
Answer Options	Response Count
	15
answered question	15
skipped question	15

Number	Response Date	Response Text
1	May 14, 2016 7:59 AM	N60000, $200
2	May 10, 2016 2:34 PM	March 2016 - GHS40.58
3	Apr 29, 2016 9:48 AM	Not Applicable
4	Apr 29, 2016 9:41 AM	GHC600 currency values
5	Apr 28, 2016 3:47 PM	Approximately GHs350 a month
6	Apr 28, 2016 3:12 PM	711,GH¢ GHS80, GHS80, GHS80
7	Apr 28, 2016 2:51 PM	Currency: Ghana Cedi
8	Apr 28, 2016 2:30 PM	GHS 147.00, 154.00, 149.00
9	Apr 26, 2016 11:34 AM	GHc200
10	Apr 22, 2016 11:44 AM	kwh
11	Apr 22, 2016 10:44 AM	289kWh, 256kWh, 239kWh
12	Apr 22, 2016 10:27 AM	175kWh, 180kWh, 191kWh
13	Apr 21, 2016 4:41 PM	Prepaid- 2,000 Ghana cedis for 2 weeks
14	Apr 21, 2016 4:09 PM	100 Ghana cedis
15	Apr 21, 2016 3:38 PM	235, 226, 238

Annex II: MATLAB CODES

Electricity Profile function

```
function [loads, st]=country(n)
%% Energy load profile program
nhouses=1*n;
%Appliances are in order (Lights(2), Television,
% Refridgerator, Fan, air conditioner,  Washing Machine)
%%
quant=[4
2
3
1.4
2
1
1];
quantLI =[];
quantMI=[];
quantHI=[];

WatApp=[11.5
16
47
360
70
540
1800];% watts of each appliance
%%
spread=[0.77487
0.77487
1.13896101
0.710872862
0.595634398
0.424256092
0.315151776];
%% probability of equipment being in household
Peqp=[0.5
    0.5
    0.18
    0.13
    0.24
    0.09
    0.01]; %% probability of equipment being on


% %Peqp=[0.5 %Lights_LED
% 0.5 % Flourescent_Outdoor_lights
% 0.5 %Outdoorlights
% 0.5 %Television
% 0.6 % Radio
% %
% 1 % Refridgerator
% 0.7 %Fans
% 0.3 %AirConditioner
% 1 %DeepFreezers
% 0.4 %Computer
```

```
% %
% 0.1 % Laptop
% 0.3 % Washer
% 0.2 %DVDplayers
% 0.1 %Waterheater
% 0.5 % Blender
% %
% 0.6 % Microwave
% 0.2 % CookerElectric
% 0.2 %Vacuum cleaner
% 0.1 %Tumble dryer
% 0.6 %Electric Iron
% %
% 0.05 %Dishwashing machine
% 0.1 % Electric mixer
% 0.3 %Hi-fi/ stereo system
% 0.05]; % Rice cooker
%%
eqpruntime1=[1,1,1,1,1,0.5,1];% factors in weekly use?
%% Load profiles
% Certainties
Lights_LED=[0   0   0   0   1   1   0   0   0   0   0   0   0   0   0   0   0
1   1   1   1   1   1   0];
Flourescent_Outdoor_lights=[1   1   1   1   1   1   0   0   0   0   0   0   0
0   0   0   0   0   0   1   1   1   1   1];

Refridgerator=ones(1,24);
% Uncertainties

% P television
ptv=Peqp(4);% guess
ptvw=zeros(1,24);
for i=1:24
    x=rand;
    if i>=18 && i<=21;
        ptvw(i)=1;
    elseif x < ptv
        ptvw(i)=1;
    else ptvw(i)=0;
    end
end
Television=ptvw;
% Television=zeros(1,24);

%Fans
pfan=Peqp(5);
pfanw=zeros(1,24);
for i=1:24
    x=rand;
    if i>=11 && i<=16;
        pfanw(i)=1;
    elseif x < pfan
        pfanw(i)=1;
    else pfanw(i)=0;
    end
end
```

```
Fans=pfanw;

%AC
pAC=Peqp(6);
pACw=zeros(1,24);
for i=1:24
    x=rand;
    if i>=13 && i<=15;
        pACw(i)=1;
    elseif x < pAC
        pACw(i)=1;
    else pACw(i)=0;
    end
end
AC=pACw;

%Washer %discuss about the one week issue with Carlos Silva
pwash=Peqp(7);
pwashw=zeros(1,24);
for i=1:24
    x=rand;
     y=rand;
    z=1/7;
   if y<z && i>=8 && i<=9;
        pwashw(i)=1;
    elseif x < pwash
        pwashw(i)=1;
    else pwashw(i)=0;
    end
end
Washer=pwashw;




%%
Appl_list2=[Lights_LED
Flourescent_Outdoor_lights
Television
Refridgerator
Fans
AC
Washer];% state of equipment(on= 1 off=0)
Appl_list2;
%%
Wattage=zeros(6,24);% watt per appliance per hour
 for i=1:numel(WatApp);

Wattage(i,:)=Appl_list2(i,:)*WatApp(i)*quant(i)*spread(i)*eqpruntime1(i)*nhous
es;
 end
%for the whole neighbourhood, not just a house
% each row is the wattage used by an appliance each hour (appliance,
% on/off)
% each column is the different watts at each hour
 TWattage=sum(Wattage);% total energy use per day
 % AvDayTwattage=3600*TWattage/1000;%(*nhouses);%(kW)
```

```
 size(TWattage);
 plot(TWattage);

 %loads=AvDayTwattage
st=Wattage;
loads=TWattage;
end
```

Time function

```
clear, clc
x=30 ; %(time average)
A=zeros(24,x);
R= zeros(24, 7, x);
we=zeros(24,7);
n1=25;
 for i=1:x
   [t,l] = country(n1);
   A(:,i)=t';
   R(:,:,i)= l';
 end
B=mean(A'); %Average Watts every hour
B
figure
% subplot(3,1,1)
bar(B)
Av=mean(B)/n1;% Average watts per day per household
mokWH=Av*24*30/1000;
Peak=max(B)/n1;% peak power consumption?
w=[289,256,239,175,180,191,235,226,238,297.0563204,297.0563204,816.9048811,891
.1689612,219.8216771,222.7922403,297.0563204];
Compa=mean(w);
dev=abs(mokWH-Compa)/Compa
dev2=mokWH/Compa
% subplot(3,1,2)
% h=[mokWH,Compa];
% bar(h)
t2=sum(R,2);% sum or average??
t21=zeros(24,x);
for i=1:x
    t21(:,i)=t2(:,:,i);
end
t211=mean(t21');
labels={'LightsLED'
'Flights'
'Olights'
'Television'
'Radio'
'Refridgerator'
'Fans'
```

```
'Air Conditioners'
'Freezer'
'Computer'
'Laptop'
'WashM'
'DVD'
'WaterHeater'
'Blender'
'MiW'
'CE'
'VC'
'TD'
'ElecIron'
'DishW'
'EM'
'Stereo'
'RiceCooker'};
%explode=5*[0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1,0,1];
% subplot(3,1,3)
% pie(t211,explode,labels)
% TesC=Av/n1;%Watts per household
% AnkWH=TesC*24*365/1000; %annual kWh
% compar=(2000/365); %kWh/day
% AvWat=compar*1000/24;% Watts per household
% Tes=Av*24/(1000*n1);%kWh/day
% %% Comparisons
% 410;%kWh/capita
% 410*4.4;
%% recommend solar water heaters
%% sensitivity analysis
% profile of energy & peak pie chart
%decision variables: no of panels sixe of battery
% linear optimation
% connection
%possibility of shifting the load
%propose ways to make a more level curve
%DC/DC networks-equipment review
%sensitivity analysis  on errors
%other country-validate with other country data
mokWH
filename='Congo2020.xlsx'
xlswrite(filename,B,1)
```

Annex III: Diffusion Curve Data

All values below are in percentages.

Ghana	**2014**	**2008**	**2000**
%			
Television	75.5	56.2	39.5
WM	1.6	0.8	0.3
Fan	69	55.9	43.5
Fridge	48.8	38	30.5
AC	1.8	0.7	0.3
Computers	19.4	5.1	0.0045
Lighting	88.6	78.5	77.4

Congo Brazzaville	**2005**	**2011**
%	Urban	Urban
Electrification	50.8	58.9
Clock/Watch		
Radio	67.1	58.7
TV	43	65.8
Mobile phone	54.1	91.9
Land line	2.1	1.6
Refridgerator	18.7	28.1
Computer	2.4	8.6

Kenya			
	2014	**2009**	**2003**
	Urban	Urban	Urban
Electrification	68.4	65.6	50.2
Radio	73.5	82	80.6
TV	56	57.1	40.6
Mobile phone	94.2	85.6	32.7
Refridgerator	12.7	21.2	13.4

Namibia	**1992**	**2000**	**2006**	**2013**
	urban	urban	urban	urban
electrification	66	73.2	77.6	72.2
Radio	78.4	82	82	73.3
Television	46.5	60	65.6	66.6
Mobile Phone			77.9	95
Telephone		41.4	33.3	15
Refrigerator	56.8	64.6	68.9	64.9

Nigeria(urban)				
Year	**1999**	**2003**	**2008**	**2013**
Lighting	84.3	84.9	84.8	83.6
Refridgerator	33.6	36.1	32.4	32.5
Iron		57.3		
TV	52.7	58.6	69	73.2
Radio	77.6	85.3	83.5	77.7
Mobile phone		11.8	76.1	88.6