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

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Decentralized energy systems- the future African energy?

While population growth rates in the developed world are stagnating, in developing countries, they are rising, particularly in Africa. With a rise in population, comes a rise in rural urban migration. This is because in many developing countries, resources, capital and opportunity is centered around urban areas.

Rising population numbers mean rising electricity demand and utility companies in Africa are faced with the challenge of powering economically meaningful production in the urban areas and the equally important residential need for energy. Unfortunately, many African utilities are unable to meet this task and this results in frequent blackouts in many countries. One suggested means that some utilities and government bodies are considering is to reduce the residential load by encouraging off grid electricity systems. This approach may have some potential as currently many households in some African countries use diesel generators due to this unreliable electricity supply. 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)

The market for diesel generators implies a market for Hybrid Renewable Energy systems(HRES). One tool that is useful in the design of HRES is HOMER . This Thesis project came about because of Asaduru a green building company that intended to build their pilot project of 25 homes in Accra, Ghana before scaling up to other urban areas in Africa. The challenge posed was to design an energy system that can be used for their pilot project in Ghana and be replicated in other urban areas without sufficient data.

In order to effectively design HRES that will last, there is the need for a model. Current models in energy planning for microgrids either estimate an average household energy rate by national values and extrapolate them. This method contains a degree of error as national numbers aggregate places with no electricity access at all (which is a significant portion in many African countries) with parts with electricity access (which as reported may be lower than they actually are due to shortfalls in electricity supply.

Some studies use national aggregates and equate those as the household energy use for each household(Adaramola, Agelin-chaab, & Paul, 2015) and other studies (Essah, 2011) estimate this number as a fraction or based off Western countries. This method raises questions about the quality of the data as many western countries have different end uses of electricity and differences in climate could result in very different rates of electricity use.

Many energy planning tools in research and in industry look at energy planning (LEAP, NEMS, GMM/MARKAL TIMES) from a national perspective. Although there are a few that allow for planning and cost estimates on a much smaller scale like DERCAM and HOMER. In order to create the inputs these tools require, there is the need to estimate the electricity supply needed has to be overcome.

In 2015, Rita Paleta to overcome this deficiency used Human Development Indices and electrification rates, data points that are easily available to estimate household energy demand for rural electrification. (Paleta, 2015)

However, between 2005 and 2012, McNeil and Letschert developed a methodology to estimate emissions and the effect of energy efficiency measures based on appliance diffusion. This model used macroeconomic variables to calculate the diffusion of appliances. (Letschert, Bojda, Ke, & Mcneil, 2012; Mcneil & Letschert, 2005; Mcneil, Letschert, & De, 2012)

Till now, no work has been done correlating these indices with urban areas of developing African 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, especially as some countries are planning to promote them for residential projects (Otu-Danquah, 2015).

Methodology

General Methodology for Estimates

In this study, household electricity use was estimated by the number of appliances in a household and their average usage. In order to calculate the number of appliances household income in urban areas was sought or estimated. Diffusion curves were plotted for the appliances in order to use them to check results with past data points and to estimate future electricity use.

Diffusion curves were plotted for the following household appliances:

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

From various national surveys, and a similar survey we carried out with 30 respondents, 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, this 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.

Calculations of the energy usage of the above appliances and comparing them to the results from the results of the survey, the Ghana living standards survey 6 (Service, 2014)and from Nzia (Nzia, 2013), the appliances listed above make up at least 80% of household electricity consumption in urban areas.

Diffusion curves were calculated in the manner below:

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:

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

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.
- k is a constant that represents the maximum value the function can take
- C represents is the starting quantity of the growing function

However, since this project focused 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, the maximum diffusion points were assumed to be the diffusion levels of the same appliances in USA, the largest global consumer of products and the information available from the BUENAS study(Mcneil et al., 2012). In order to generate a predictive function, each of the other factors; household income and electrification were plotted as linear functions of time for each of the countries selected for time since 2000. Making the final equation used:

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

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

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 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:

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

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

Assumptions

- 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.

Methodology for Case Study and calculating household energy demand

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.
- In the case of the countries used for the model, the diifusion rate that was calculated above was used as the household ownership rate.
- 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 BUENAS 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. This simulation was run multiple times to assume the behavior for a month.
- From this appliance curve, the average power needed and the maximum power needed were calculated to be fed into the HOMER simulation.

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 was determined by the Matlab program written and attached in the appendix.

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, at 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.

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 Ghanaian interest rate 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 LCOE is the minimum price at which electricity must be sold for an energy project to break even (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.

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)

Results & Discussion

Diffusion curves

The diffusion curves were plotted from the year 2000 to 2020. Below is a summary of the appliance diffusion according to the methodology above. The data points specifically focus on the years 2015 and 2020.

Table 1: Diffusion Curves obtained from Model

	Ghana		Kenya		Namibia		Nigeria		Rep .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

With these appliance diffusion rates the average electricity curve for a community of 25 residences was simulated and the results from the simulation are as displayed below.

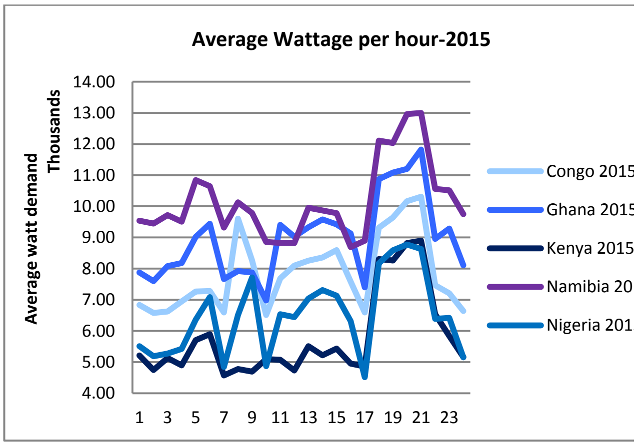

Figure 1: Average daily household electricity demand curve calculated for 2015

The electricity demand curves developed from the program are shown above. The curves for the countries differ from what was expected, in that there are significant curves in the afternoon for all countries except Nigeria and Kenya. These arise due to the use cooling equipment in the afternoon. 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. This effect 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.

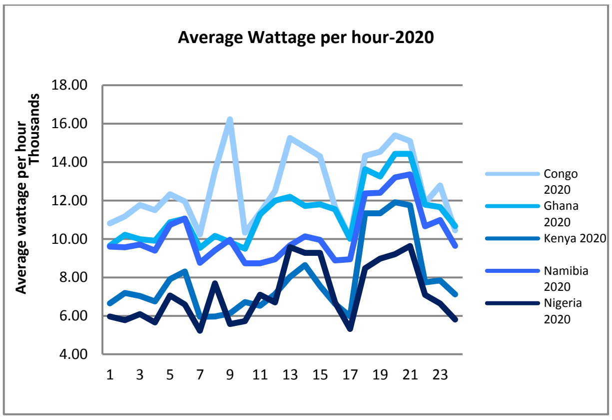

Figure 2: Average daily household electricity demand curve predicted 2020

In 2020, the effect of cooling equipment 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.

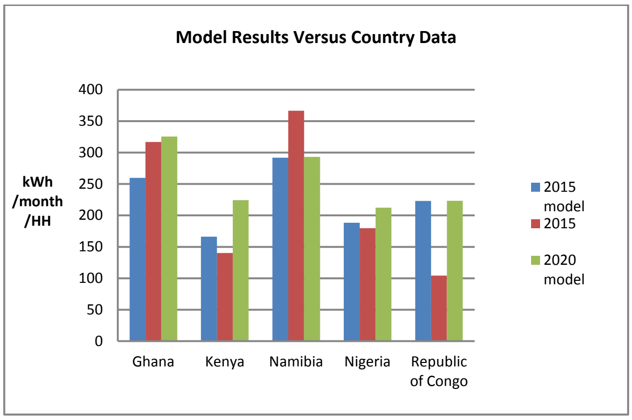

Figure 3: Comparison of Model results and real data

Energy profile simulation

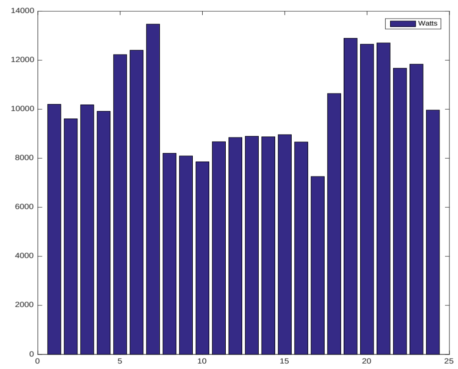

Figure 4: Household electricity profile-detailed equipment Ghana

There are two peaks that occur. One between 6-7 hours and another between19-22 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).

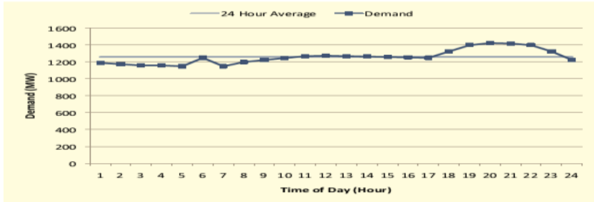

Figure 5: Total electricity demand curve Ghana (Adapted from Diawuo,2013)

These peaks and the general shape of the curve are consistent with data from Nigeria (Ezennaya, Isaac, Okolie, & Ezeanyim, 2014)and with work done by Diawuo in 2013 (Diawuo, 2013) where the total 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)

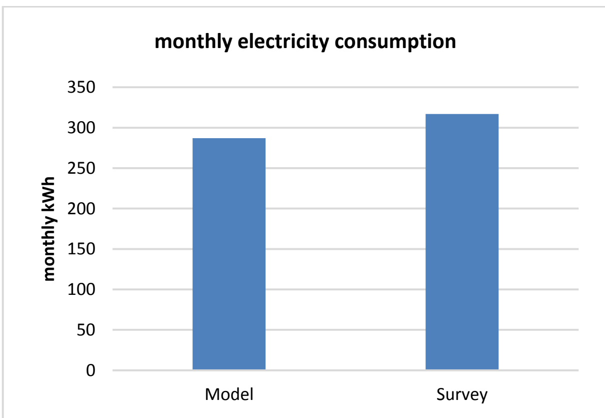

Figure 1: Homer Result and Survey Result

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).

Apart from the fact that the cited numbers 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.

HOMER Results

Under the load shedding conditions, only 6 systems were selected that supplied electricity to the project reliably.

1. 40 kW PV, 20kW diesel generator
2. 20kW diesel generator
3. 25kW PV, 400kWh storage
4. 40kW PV, 20 kW storage, 400kWh storage
5. 5kW diesel generator, 400kWh storage
6. 2MWh storage

Option one, with a COE of $0.27/kWh was the best choice as it had 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.

Under the scenarios run with no load shedding the following trends were observed. It was observed that the renewable fraction varied with the tariff price and with the difference between the tariff and the sell back price. 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.

Below are the systems that were selected by HOMER when the simulation was run. The term sellback refers to feed in tariffs which are currently not being implemented in Ghana but there are plans to write a policy with that focus.

Table 2: Homer results without load shedding.

Tariff	**Sellback**	**f(net tariff, tariff)**	**Ren. 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

The net Tariff function as used above is as follows:

$$f(net\ Tariff) = (Tariff - Sell\ back\ rate) \times Tariff$$

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.

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.

Conclusion

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. 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.

References

1. Adaramola, M. S., Agelin-chaab, M., & Paul, S. S. (2015). Analysis of hybrid energy systems for application in southern Ghana. *Energy Conversion and Management*, *88*(2014), 284–295. https://doi.org/10.1016/j.enconman.2014.08.029
2. African Business Review. (2012). Surge in business for Africa's Electricity Generator Industry. *African Business Review*. Retrieved from http://www.africanbusinessreview.co.za/leadership/202/Surge-in-business-for-Africas-Electricity-Generator-Industry
3. African Review of Business and Technology. (2015). "Gensets aiding economic growth in Africa."
4. Chuan, L., Ukil, A., & Member, S. (2014). Modeling and Validation of Electrical Load

Pro fi ling in Residential Buildings in Singapore, 1–10.

5. Diawuo, F. A. (2013). Modelling of Ghana Electricity Market and Power Generation Optimization. . *M.Sc Thesis Work* , Pages From - To.

6. Essah, E. A. (2011). Energy generation and consumption in Ghana.

7. Ezennaya, O. S., Isaac, O. E., Okolie, U. O., & Ezeanyim, O. I. C. (2014). Analysis Of Nigeria ' s National Electricity Demand Forecast (2013-2030), *3*(3), 333–340.

8. GRIDCo. (2015). *2015 Annual report*.

9. Letschert, V. E., Bojda, N., Ke, J., & Mcneil, M. A. (2012). E RNEST O RLANDO L AWRENCE B ERKELEY N ATIONAL L ABORATORY Estimate of Cost-Effective Potential for Minimum Efficiency Performance Financial Impacts, (July).

10. Mcneil, M. A., & Letschert, V. E. (2005). Forecasting electricity demand in developing countries : A study of household income and appliance ownership, 1359–1367.

11. Mcneil, M. A., & Letschert, V. E. (2010). Modeling diffusion of electrical appliances in the residential sector, (August).

12. Mcneil, M. A., Letschert, V. E., & De, S. (2012). Bottom-Up Energy Analysis System – Methodology and Results, (April).

13. National Renewable Energy Laboratory. (2013). NREL: Energy Analysis - Energy Technology Cost and Performance Data. Retrieved from http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html

14. Nzia, M. K. (2013). *END USE BASED MODEL FOR RESIDENTIAL POWER CONSUMPTION FORECASTING IN NAIROBI REGION*.

15. Otu-Danquah, D. (2015, July). Renewable Energy Policies in Ghana, existing and future plans. (I. Mannoh, Interviewer)

16. Paleta, R. D. C. (2015). *Remote Autonomous Energy Systems Design for Developing Countries*.

17. Service, G. S. (2014). Ghana living standards survey Round 6. *Ecosystems and Human Well-Being: A Framework for Assessment*, *12*(16), 81–87. https://doi.org/10.1007/s13398-014-0173-7.2