Geospatial Framework for Estimating Household Electricity Demand for Urban Infrastructure Planning in Select African Countries

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Abstract— **Power infrastructure planning in Sub-Saharan Africa requires accurate power demand estimates. However, these estimates are lacking in most countries which compounds the effects of unreliable electricity supply. This study utilizes a methodology that was used to forecast power demand in Uganda and extends it to other African countries of interest; Kenya, Nigeria, and South Africa. The goal of the study is to create spatial power demand maps that can be used for power infrastructure planning. The proposed approach utilizes a global population database at a fine resolution of 1 km^2 as the foundational input data. The analysis indicates a deficit of about 22,630 MW (South Africa), 20,213 MW (Nigeria), 4,153 MW (Kenya), and 2,508 MW (Uganda) compared to the current installed capacity to meet the highest power demand scenario.**

Keywords—Infrastructure planning, load forecast, stable power supply, Nigeria, South Africa, Uganda, Kenya

I. Introduction

Sub-Saharan Africa is rich in energy resources but poor in energy supply because most of these resources have not been exploited [1]. Wide access to reliable and affordable energy is crucial for the economic development of the region that accounts for 13% of the world's population. However, Sub-Saharan Africa still faces acute energy scarcity accounting for only 4% of the world's energy consumption [1], [2]. In order for Sub-Saharan Africa economies to achieve economic growth and reduce poverty, there has to be an increase in the level of per capita energy use [3]. Deliberate measures need to be taken to ensure that energy supply is sufficient to meet basic needs and provide a much better standard of living. In addition, governance reforms that promote and protect investments in the energy sector need to be implemented. The International Energy Agency (IEA) estimates that an influx of cash investment of about $450 billion needs to be invested in the power sector to achieve universal access to electricity and boost the region's economy by 30% in 2040 [2].

To be able to assess current and future energy demand, it is imperative to measure the extent of the disparity in modern energy access. Adequate power/energy infrastructure planning requires robust, accurate, power demand forecasting. Most energy demand projections are based on developed countries and yet sub-Saharan African countries have different economies and energy needs[1], [3]. Much of the existing work in power/energy demand on Sub-Saharan Africa focuses on Western and Southern Africa [4]–[9]. There is a need for increased research on power demand forecasting and benchmarking of available supply to meet the demand forecast in Sub-Saharan Africa. The authors first proposed and utilized Geographical Information Systems (GIS) coupled with LandScan 2016 data [10], [11], a high resolution geographical population database, to forecast and develop power demand maps for Uganda [12]. This methodology was then applied to three other countries in Sub-Saharan Africa (Kenya, Nigeria and South Africa) with diverse energy needs, electrification rates and economies in addition to Uganda.

II. Power System background

A. Uganda

Uganda is a landlocked country in east Africa with one of the lowest per capita electricity consumption rates in the world at 150kWh/year [13]. According to the IEA 2014 report, only 14% of the Ugandan population has access to electricity [1]. In the rural areas where over 85% of the population lives, only two percent have access to electricity. Less than half of the electricity in the rural areas is provided through the grid [13]. The remainder is provided through distributed generations such as generators, car batteries or solar photovoltaic (PV) units [14]. The country has an installed capacity of about 896 MW of which only 746 MW is licensed for use. The electricity generation portfolio of Uganda is heavily reliant on hydroelectric power which makes up 93% of the licensed capacity [14].The remaining 7% is from cogeneration (5%) and heavy fuel oil thermal power (2%).

B. *Kenya*

Kenya is the fourth largest economy in Sub-Saharan Africa with an estimated nominal GDP of 55 billion USD in 2015. The government of Kenya has set forth to transform the country into a newly "industrialized middle-income" country through its "Vision 2030 [15]." To do this will require wide access to electricity and modern energy across the country in the manufacturing sector and transforming lives[16]. Kenya has a current installed generation capacity of about 2,341 MW. Kenya's per-capita energy consumption is at 161 kWh compared to 126 kWh in Nigeria which has a per-capita GDP 3 times higher [17], [18]. Electricity in Kenya accounts for 9% of the total energy consumption with 23% of the population having direct access to it. This electricity penetration rate is worse in rural areas where only 12% have access to it. The electricity generation mix is currently at 45% from hydro, 25% from thermal and 31% from other renewables[16], [18]. Kenya is striving to diversify its energy sources to reduce the dependency on hydro and displace the use of expensive geothermal [17].

C. *Nigeria*

Nigeria is a mid-to-large sized country located in the Western part of Africa, and part of the Economic Community of West African States (ECOWAS), a regional economic union of fifteen countries located in West Africa. According to the IEA, more than 55% of the population (93 million people) do not have access to grid electricity; however, the population without access to any form of electricity is smaller, as there is widespread use of distributed generation, specifically backup fuel/diesel generators [1]. The Nigerian power sector has undergone many transformations since the initial introduction of power in 1896. The modern power sector, established in 2005 through the Electric Power Sector Reform (EPSR) Act of 2005, is comprised of 6 generating companies, 1 transmission company, and 11 distribution companies, all of which are jointly owned by the federal government and private entities [19]. The EPSR Act of 2005 was an attempt to privatize the power sector. Currently, there is an estimated 23 grid-connected generating assets in operation in Nigeria, installed and available capacity of about 10,396 MW and 6,056 MW respectively [20]. This capacity is broken down as follows, with thermal based generation having an installed capacity of 8,457.6 MW (available capacity of 4,996 MW) and hydropower having 1,938.4 MW of total installed capacity with an available capacity of 1,060 MW [21].

D. *South Africa*

South Africa has the highest electrification rate on mainland Sub-Saharan Africa [1]. 90% of all the households have access to electricity [22]. South Africa's energy sector is critical to its economy as the country relies heavily on the energy-intensive coal industry. South Africa has an installed grid-based capacity of 53 GW. Coal is a staple in South Africa's energy system meeting about 70% of the country's energy demand and 76% of the domestic installed electricity capacity [23]. Large coal resources allow the country to be a coal exporter (top 10 producers worldwide) to the Pacific and Atlantic coal market. The remainder of the electricity generation mix is from petroleum (7%), hydropower (5%), non-hydro renewable generation (6%), and nuclear power (4%) from the continent's only nuclear power plants [1].

Although it has one of the highest electrification rates in Africa, South Africa has been struggling with a constrained electricity system especially over the last decade. This is because the margin between peak demand and available supply is extremely narrow. Reserve margins are low due to aging coal plants, insufficient investment in infrastructure and mismanagement of the sector. Load shedding was introduced between 2013 and 2015 and the lack of electricity security has affected the country's economic growth [24].

The objective of this work is to use LandScan 2016 data, a high resolution geographical population database as the foundational input data for power demand forecasting in Uganda, Kenya, Nigeria and South Africa. The electricity demand maps generated are valuable resource planning tools for governments, private investors, development agencies and utility companies.

III. DATA AND METHODS

The analysis was performed for four countries in Africa including South Africa, Nigeria, Uganda and Kenya. The countries were selected to incorporate different income levels of low (Uganda), low-middle (Kenya, Nigeria) and high-middle (South Africa) income as well as relatively low to high electrification rates.

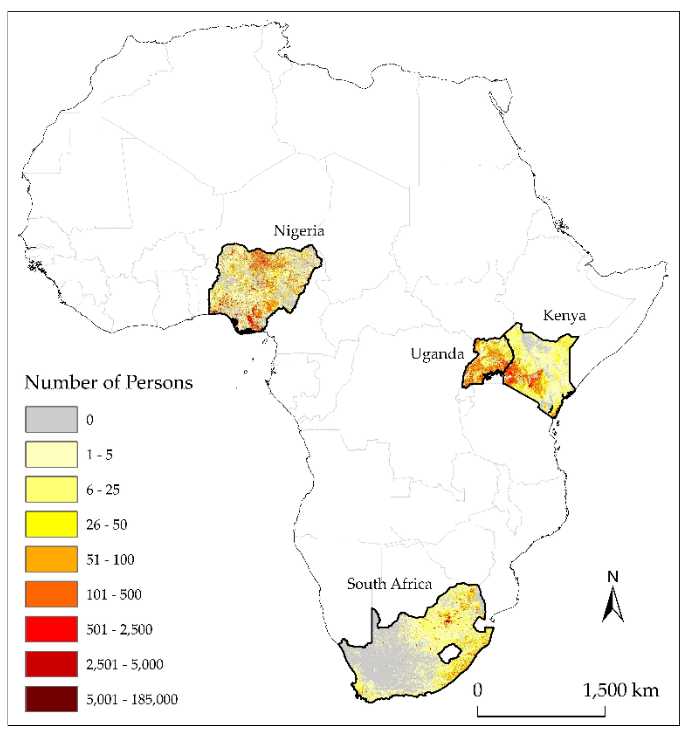

Fig. 1. Map of the study areas with population data per square kilometer using LandScan 2016 data.

Our computational framework is based on the understanding that electricity is generally needed where people are and depends on their capacity to utilize electricity. We focus on the different ways in which households utilize electricity which is basically for powering home appliances and lighting. Given different levels of development among the selected countries, it is expected that households will have varied rates of electric appliance ownership hence diverse electricity demand levels. Figure 1 shows the geographic location of the countries in Africa and displays spatial distribution of population counts. The model is a continuation of the method used by Ajinjeru, Odukomaiya, & Omitaomu, [12] to model electricity demand in Uganda.

Population count was obtained from the LandScan 2016 dataset [25], a global population database developed at Oak Ridge National Laboratory. LandScan 2016 utilizes an innovative approach with Geographic Information System (GIS) and Remote Sensing to estimate global population distribution at approximately 1 km^2 resolution. The LandScan 2016 algorithm uses spatial data and image analysis technologies and a multi-variable dasymetric approach to disaggregate census counts within an administrative boundary.

Average household size data from the latest national surveys conducted in the countries was used [26], [27]. The data is aggregated at local province, state, county, and district levels for South Africa, Nigeria, Kenya, and Uganda respectively. The average household size data was converted to a spatial grid raster data format to match the spatial resolution and extent of the LandScan 2016 population dataset. Grids within a local geographic unit acquire similar household size values.

Typical electrical appliances among households in the studied countries were considered for estimating energy demand. These include refrigerators, television, radio, computer, DVD player, cell phone, lighting, and pressing iron. Ownership data for these appliances was available for all the countries. Depending on availability of ownership information for each specific country, additional appliances were included in the computation of peak electricity demand. It is possible that the inadequacy of information on some of the appliances especially the microwave oven, electric stove, dishwasher, washing machine, dryer, and vacuum cleaner may be due to their high cost of purchase and maintenance unaffordability to the majority of the population. This may translate to very low, possibly insignificant ownership rates that may not affect the calculated demand. Household appliance ownership rates were acquired from published national survey reports as well as independent survey reports believed to be representative of the general population. The main sources were [28]–[30].

Power ratings for standard appliances were primarily acquired from Energy Saver which is a U.S. Department of Energy (DOE) consumer resource [31]. Power ratings not available at the resource were obtained from [32]. Table 1 shows a list of the appliances used for each country, their power ratings and ownership rates.

TABLE 1: APPLIANCE POWER RATINGS AND OWNERSHIOP RATES

	Ownership Rates (% households)				**Appliance power rating (W)**
Appliance	***Nigeria***	***Uganda***	***South Africa***	***Kenya***	
Refrigerator	19.2	14	75.3	17	225
Television	50.2	28.9	81.5	28	150
Radio	61.2	24.8	67.5	74	30
Computer	4.8	ND	ND	3.6	100
DVD Player	38.7	16.5	59.3	38	17
Cell Phone	78.9	31.4	88.9	63.2	5
Lighting	59.34	38	84.7	35.8	75
Microwave	2.96	3.3	54.9	ND	1500
Iron	41.8	24.8	ND	34	1100
Electric Stove	3.4	ND	89.9	4	1500
Dishwasher	ND	ND	13.5	ND	330
Washing machine	1.5	ND	39.5	ND	3000
Tumble Dryer	ND	ND	14.0	ND	2790
Vacuum cleaner	ND	ND	18.2	ND	542
Desktop Computer	ND	22.3	18.5	ND	75
Laptop Computer	ND	17.4	23.3	ND	25
Electric Shaver	ND	2.5	ND	ND	12
Hair Dryer	ND	2.5	ND	ND	710
Electric kettle	ND	15.8	ND	ND	1200
Portable Water Heater	ND	ND	ND	3	1000
Shower booster	ND	4.1	ND	ND	400
ND - No data for the appliance in that country.					

IV. ESTIMATING ELECTRICITY DEMAND

We estimate household electricity demand based on power wattage requirements for electrical appliances owned by the households. We calculate and sum up the instantaneous peak power demand in megawatts (MW) for the country using equation 1.

$$\text{Power (MW)} = \sum_{i=1}^{n} (\text{Power rating (MW)} * \text{Ownership}(\%) * \text{Households}), \quad (1)$$

where *i* is the appliance, *n* is the total number of appliances, power rating is the continuous power requirement for appliance *i*, ownership is the percentage of households that own appliance *i* and households is the potential number of electrical customers. The potential number of electrical customer is calculated by dividing the population count by the average household size for that area as shown in equation 2.

$$\text{Households} = \frac{\text{Population count}}{\text{Average household size}}, \quad (2)$$

where population count is the total number of people within a square kilometer grid area defined by the LandScan 2016 population dataset cell size, average household size is the average number of people per household. Each local district in a country is assumed to have a uniform average household size.

To arrive at a spatial distribution of electricity demand, several assumptions were made:

a) The number of households is equal to the number of electric customers.
b) All the households in a defined geographic local district are of the same size.
c) Households have similar electrical appliances of the same kind.
d) The rates of electrical appliance ownership are similar for both rural and urban households. While there are studies that show higher rates of ownership among urban households compared to rural households, our analysis did not differentiate between the two. A simple differentiation is instead made by multiplying the estimated demand by 0.25, 0.5, and 1 to calculate three possible demand scenarios. These scenarios may also showcase peak demand under circumstances where 25%, 50% and 100% of households are using all their appliances at the same time.

V. Results

Estimated demand under the three scenarios is shown in Table 2. Compared to the current installed capacity, the countries have demand deficits of 22,630 MW (South Africa), 20,213 MW (Nigeria), 4,153 MW (Kenya) and 2,508 MW (Uganda). These deficits are based on the scenario where we assume all the households in the countries are using all their appliances at the same time. Nigeria, Kenya and Uganda show demand deficits greater than the installed capacity while South Africa's deficit is about half of the installed capacity. Given that these installed capacities are distributed to all the sectors in the countries, households receive much less than the installed capacity. This means even greater deficits in terms of electricity supplied to households.

TABLE 2: ESTIMATED HOUSEHOLD ELECTRICITY DEMAND SCENARIOS AND DEFICITS FOR EACH COUNTRY

	Peak Instantaneous Demand Scenarios				
Country	***Low (MW)***	***Median (MW)***	***High (MW)***	***Installed capacity (MW)***	***High demand deficit (MW)***
South Africa	17,004	34,009	68,019	45,389	22,630
Nigeria	7,652	15,304	30,609	10,396	20,213
Kenya	1,612	3,225	6,451	2,298	4,153
Uganda	851	1,702	3,404	896	2,508

The spatial distribution of electricity demand under the three scenarios is shown in Fig. 2 (South Africa), Fig. 3 (Nigeria), Fig. 4 (Kenya) and Fig. 5 (Uganda). Increased demand is observed in highly populated areas especially around urban areas with up to zero demand in areas with no people. In most cases, the unpopulated areas are on water bodies, forests and protected areas and on deserts. Rising demand from the low to median and to high can be observed in the maps as amplified intensity which we describe to imply higher household electricity demand. The spatial maps are important in understanding and guiding regions where more electricity is needed and therefore where the development of energy infrastructure is most needed. In South Africa, for example (Fig. 2), demand is mostly in the north-eastern and far-east and a small area in the south-west.

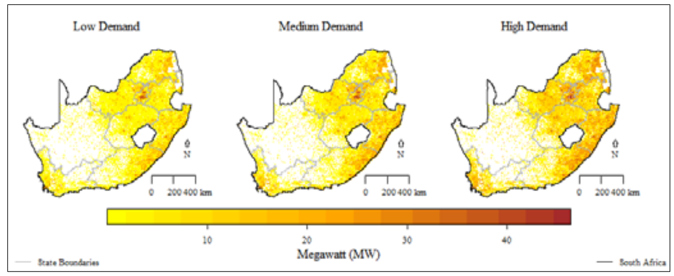

Fig. 2. Spatial Distribution of electricity demand in South Africa. The white areas are the regions with no population.

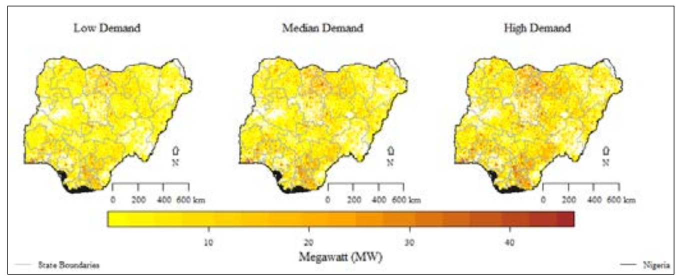

Fig. 3. Spatial Distribution of electricity demand in Nigeria. The white areas are the regions with no population.

Nigeria's demand (Fig. 3) is somewhat evenly distributed throughout the country. In Kenya (Fig. 4), demand is concentrated in the central to western and coastal parts of the country with very low demand in the rest of the country. Like Nigeria, demand distribution in Uganda (Fig. 5) is throughout the country. The spatial distribution of demand is mostly influenced by the distribution of the population.

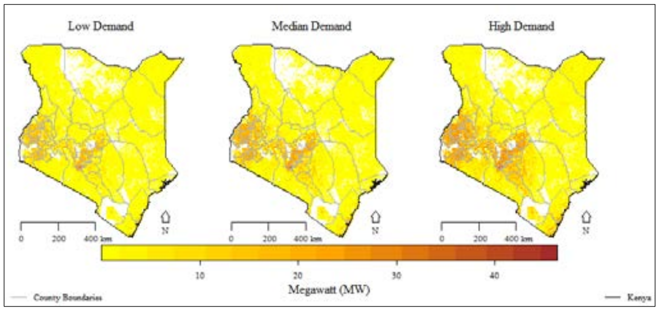

Fig. 4. Spatial Distribution of electricity demand in Kenya. The white areas are the regions with no population

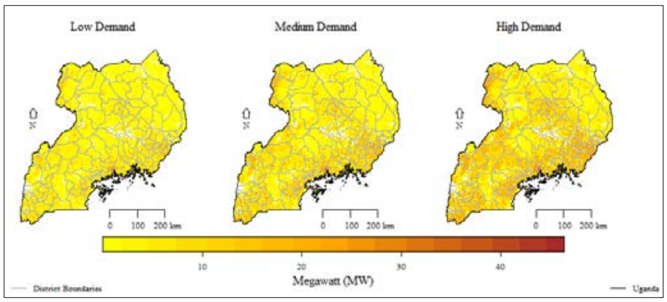

Fig. 5. Spatial Distribution of electricity demand in Uganda. The white areas are the regions with no population.

In Fig. 6, we illustrate under the high demand scenario, demand deficits for different regions of the countries by considering the location of the power generating plants. By their closeness to a generation plant, areas are designated as deficits or leads by comparing the total estimated peak electricity demand with the total generation capacity of the plants within the voronoi regions depicted with dark lines. This comparison is significant in planning infrastructure requirements especially power lines to minimize electricity transmission losses which are still relatively high in developing nations. Given Kenya for example, all power plants are in the central and western parts. The rest of the countries have most of their power plants and substations almost throughout the country. However, we still see deficits in most of these areas which means that electricity generated in other voronoi regions would be imported into the deficits regions and incur significant losses.

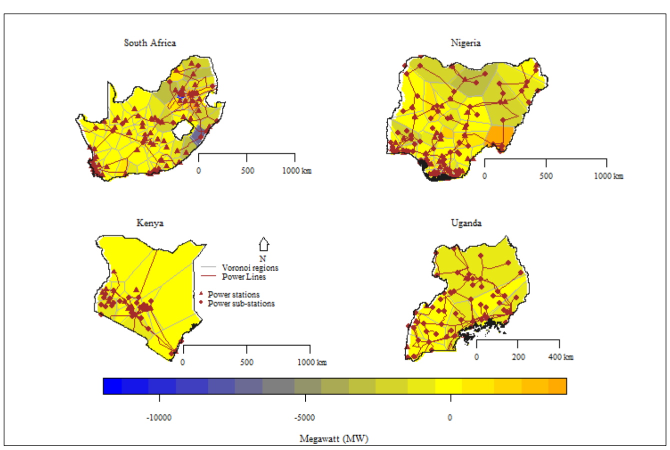

Fig. 6. Spatial situation of household electricity supply deficits and location of power plants and transmission infrastructure.

The disparities observed in the spatial distribution of power plants and transmission lines translates directly to the status of electricity demand and supply and reflects infrastructure needs required to fulfill household demand needs.

VI. DISCUSSION AND CONCLUSION

Using electrical appliances ownership rates for households in four countries, we show a geospatial framework for estimating household electricity demand. By summing up power ratings for all appliances owned by the households, we approximate a peak household electricity demand for the country. This represents the highest demand possible from the household sector assuming all the appliances are operated at the same time. Two other scenarios are presented where we assume half and a quarter of the households are operating their appliances at the same time. Obvious disparities are observed between the production capacities of the countries studied and the estimated peak household electricity demand. Even at the low demand scenario, Nigeria, Kenya and Uganda are just a little over the production capacity, with South Africa at about three times the demand amount. We should note that these production capacities are meant to meet demand needs from all sectors and not just from residential customers. It is therefore far from enough to meet the household demand. Meeting this demand requires structured infrastructure spatially balanced to reach all households, more importantly the high demand zones. The spatial maps presented in this paper are a prototype geospatial framework that may be applied for planning purposes in trying to reach all households in a cost-effective way by focusing on the high concentration demand zones while also reaching out to other households. While it is not possible to have power generation stations all over the country, there is the desire to reduce electricity transmission and distribution losses. Yet, we register deficits within the vicinity of the generation plants, requiring power to be transmitted from other plants. Proper siting of sub-stations in these cases can be of great value in reducing power distribution loses and associated costs.

An important next step for this study would be to understand the electricity needs of the other sectors of the economy including commercial and industrial sectors to fully understand the implications for current production capacity as it relates to demand needs. It is in our plan to extend this modeling framework to other African countries and later investigate electricity demand for other sectors beyond households.

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