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

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Abstract— **Access to reliable and affordable energy is the backbone of advanced economies all over the world. Such an access is limited in Sub-Saharan African countries such as Uganda, Kenya, Nigeria, and South Africa due to lack of inadequate energy generation infrastructure. Infrastructure planning for energy generation requires accurate estimations of potential energy demand profiles. Such demand profiles are lacking in many developing countries all over the world. This paper presents a geospatial framework for estimating household electricity demand that could inform infrastructure-planning tools. This is an extension of our initial effort to estimate household electricity demand for Uganda. This paper presents power demand estimates for four African countries – South Africa, Nigeria, Kenya, and Uganda. Electricity demand estimates are generated using three (low, average, and high) appliance usage profiles. The analyses indicate 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 for the high usage profile 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 this region, which 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 countries to grow their economies and reduce poverty, there must be an increase in their respective per capita energy use [3]. Innovative ideas that promote and protect investments in the energy sector are needed. 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 investment of about $450 billion needs to be made in the region's 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 disparity in modern energy access. Adequate power/energy infrastructure planning requires robust and accurate power demand forecasting. Most energy demand projections for the region are based off developed countries, even though the 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 countries [4]–[9]. There is a need for increased studies in power demand forecasting, and benchmarking of available supply to meet the demand forecast in Sub-Saharan Africa.

Our contributions in this paper are to: (i) forecast household energy demand in four African countries – South Africa, Nigeria, Kenya and Uganda; (ii) develop the demand forecast for three different appliance usage profiles; and (iii) estimate the gap in energy generation for each of the four countries. The proposed approach is the first attempt to develop spatially explicit power demand estimates for developing countries. These estimates will inform energy infrastructure planning tools for identifying suitable areas for siting new power plants and for estimating the number of power plants that should be located. These electricity demand estimates become valuable resource-planning tools for governments, private investors, development agencies, and utility companies.

II. BACKGROUND – POWER INFRASTRUCTURE

This section provides some background information about our study areas.

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 [10]. 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 [10]. The remainder is provided through distributed generation such as generators, car batteries or solar photovoltaic units [11]. 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 [11].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 proposed to transform the country into a newly "industrialized middle-income" country through its "Vision 2030" [12]. This will require wide access to electricity and modern energy across the country in the manufacturing sector [13]. 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 [14]. 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 45% from hydro, 25% from thermal and 31% from other renewables [13], [15]. Kenya is striving to diversify its energy sources to reduce dependency on hydro and displace the use of expensive geothermal [14].

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 Nigerian 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, comprises 6 generating companies, 1 transmission company, and 11 distribution companies, all of which are jointly owned by the federal government and private entities [16]. 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 [17]. 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 [18].

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 [19]. 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 [20]. 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 limited the country's economic growth [21].

III. METHODOLOGY

Our computational framework is based on the understanding that electricity is needed where people live. We focus on the different ways in which households utilize electricity, which is primarily for powering home appliances, providing comfort, 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. The study areas are selected to incorporate varied income levels and electrification rates. Figure 1 shows the geographic location of the four countries along with their population distribution using LandScan population dataset [22]. The proposed framework is an extension of our initial effort to model household energy demand in Uganda [23].

A. Data

The foundational dataset for our approach is the population data. The population data for this paper was obtained from the LandScan 2016 dataset [22]. LandScan is 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 spatial resolution. The LandScan 2016 algorithm uses image analysis technologies and a multi-variable dasymetric approach to disaggregate census data within an administrative boundary.
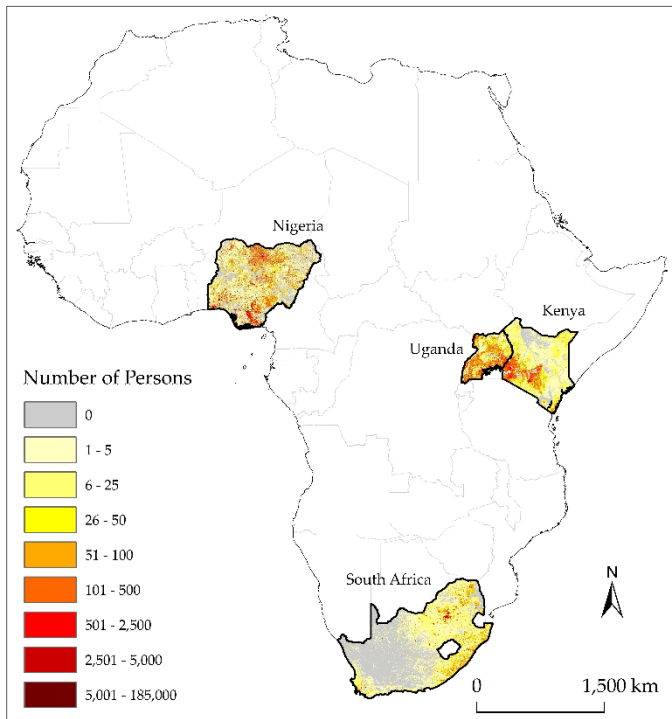
Fig. 1. Map of the study areas with their respective population distribution using LandScan 2016 data.

Average household size data from the latest national surveys conducted in the respective study areas [24], [25], [26], [27] was used together with LandScan population dataset to estimate potential number of electricity customers. 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 LandScan 2016 population dataset. Grids within a local geographic unit acquire similar household size values.

Typical electrical appliances among households in the study areas were considered for estimating energy demand. These appliances include refrigerators, television, radio, computer, DVD player, cell phone, lighting, and pressing iron. Ownership rates for these appliances were obtained for these countries. Depending on availability of ownership information for each specific country, additional appliances were included in the computation of instantaneous 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 unaffordable to most of the population. This may translate to very low ownership rates that may not significantly affect the calculated demand estimates. 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 (e.g., [28], [29] , [30], [31], [32]).

Power ratings for standard appliances were primarily acquired from Energy Saver which is a U.S. Department of Energy (DOE) consumer resource [33]. Power ratings not available through DOE were obtained elsewhere (e.g., [34]). Table 1

shows a list of the appliances used in each country, their power ratings, and ownership rates.

TABLE 1: APPLIANCE POWER RATINGS AND OWNERSHIOP RATES

| Appliance | Ownership Rates (% households) | | | | Appliance power rating (W) |
	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 appliance data for that country.					

B. Estimation of Electricity Demand

We estimate household electricity demand based on power wattage requirements for electrical appliances owned by the households. We calculate and sum the instantaneous 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 potential electric customers.

b) All the households in a defined geographic local district are of the similar size.

c) Households have similar electrical appliance types.

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 a factor of 0.25, 0.5, and 1 to calculate three possible demand scenarios. These scenarios may also showcase instantaneous peak demand under circumstances where 25%, 50% and 100% of households are using all their appliances at the same time.

IV. 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.

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 northeast, far-east, and a small area in the southwest. The demand estimates for Nigeria (Fig. 3) is somewhat evenly distributed throughout the country.
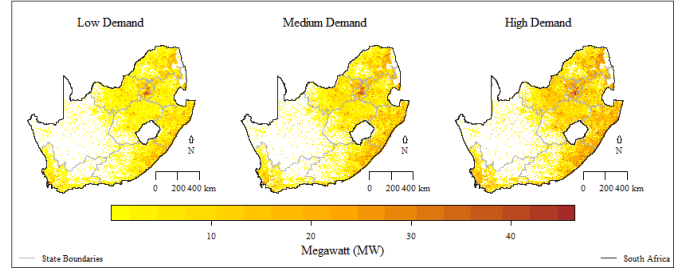

Fig. 2. Spatial distribution of electricity demand in South Africa. The white areas are the regions with zero population.
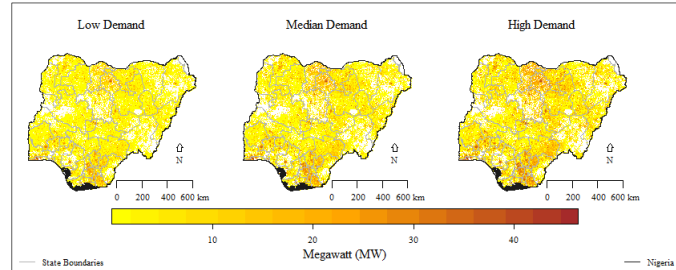

Fig. 3. Spatial distribution of electricity demand in Nigeria. The white areas are the regions with zero population.

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

Country	Peak Instantaneous Demand Scenarios			Installed capacity (MW)	Difference between Installed Capacity and Demand Estimate for high appliances usage scenario (MW)
	Low (MW)	Median (MW)	High (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

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.

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 the urban areas and with zero demand in areas with zero population. In most cases, the unpopulated areas are on water bodies, in 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 implies higher
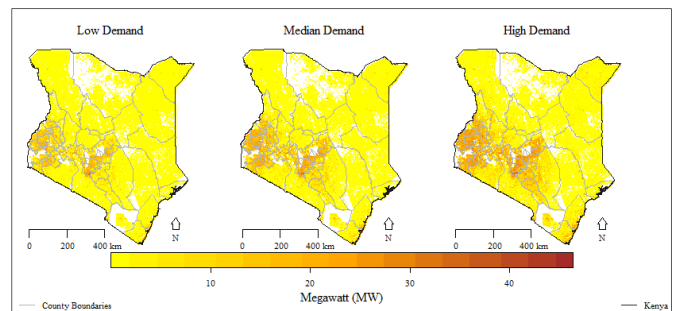

Fig. 4. Spatial distribution of electricity demand in Kenya. The white areas are the regions with zero population

In Kenya (Fig. 4), demand is concentrated in the central to western and coastal parts of the country with very low demand

in other areas. 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.
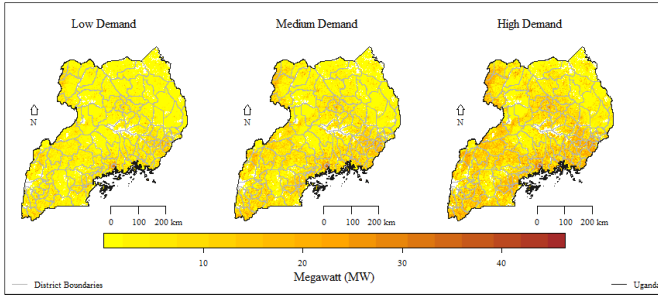

Fig. 5. Spatial distribution of electricity demand in Uganda. The white areas are the regions with zero population.

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 surplus by comparing the total estimated instantaneous peak electricity demand with the total generation capacity of the plants within the Voronoi regions. 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 other countries have most of their power plants and substations almost throughout the country. However, we still see deficits in most of these other countries, which means that electricity generated in other regions would be imported into the deficient regions.
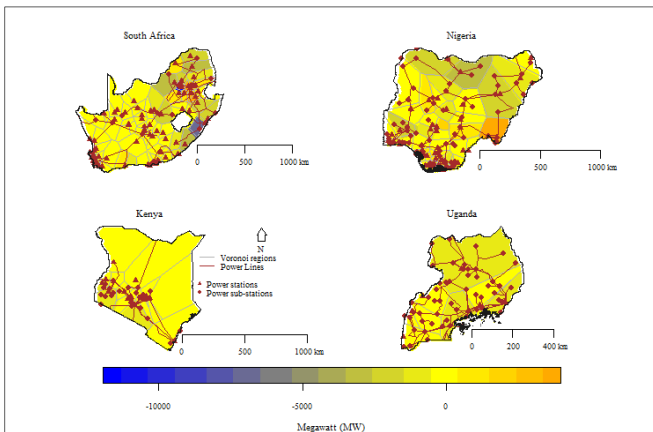

Fig. 6. Spatial situation of household electricity supply deficits and location of power plants and transmission infrastructure.

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.

V. 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 an instantaneous 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 instantaneous peak household electricity demand. Even at the low demand scenario, Nigeria, Kenya and Uganda are just a little over the existing generation capacity, with South Africa at about three times the demand estimate. We should note that these generation capacities are meant to meet demand needs from all sectors and not just from the 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 estimates presented in this paper may be applied for planning 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 will 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 generation capacity as it relates to potential demand. 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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