Computer-based Decision Making Systems for Improved Energy Access in Sub-Saharan Africa

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***Abstract*—Nearly 20% of the world's, and 60 to 80 % of Sub-Saharan Africa's, population does not have access to electricity, and because of the prohibitive cost of constructing traditional generation, transmission and distribution systems, it is unlikely many of these people will be connected to the electrical grid for many years. Consequently, highly distributed off-grid electrical systems will be the only way a large percentage of the unreached households will have even basic electrical service in the foreseeable future. Nevertheless, most governmental programs in emerging economies are focusing exclusively on the development of the electrical grid with larger-scale grid-connected power supplies. Private investors for generation facilities are wooed with long-term power-purchase agreements and grid power is heavily subsidized. In contrast, few incentives offered for deploying off-grid power, so these projects have been carried out with donor funding rather than private investment. New technologies and business models are needed to provide first-access to energy that is economically and environmentally sustainable. Recently, some private companies have begun to offer off-grid household and micro-grid systems with business models designed for rural customers in emerging economies. However, all of these projects are tailored-made, one-time applications with no interest in scalability or replicability. There is an absolute need to create a toolbox for Energy Access Planning in underserved locations. With the help of these tools, a systematic approach can be developed for planning, studying and sizing Renewable Energy projects. This paper explains the developed Computer-based First-access Demand Estimation tool. It is a step towards creating a complete Energy planning toolbox which can support systematic Energy planning.**

***Index Terms*—off-grid microgrids, renewable energy, planning tools, energy policy, sustainable development, rural electrification**

I. INTRODUCTION

The electrification rate in developing and under-developed countries is very low both in urban and rural areas. It is not uncommon to see communities which are completely left in the dark when the sun is down [1]. On the other hand, some electrified villages have limited access to this type of energy in health centers and schools only. Despite feeding critical infrastructure components, these primitive energy sources may not be able to constitute a reliable supply. Consequently, basic needs such as lighting and mobile phone charging cannot be easily met. These, in turn, may lead to larger problems such as respiratory problems due to constant smoke from burning kerosene for lighting, or higher death rates in rural areas where health clinics cannot provide basic services due to lack of energy [2].

Certainly, there are efforts to break this stalemate by the governments, organizations and private companies. The situation in Sub-Saharan Africa (SSA) does not have a trivial solution in terms of energy project development [3]. Many parameters differ from those in developed countries. For instance, demographics is a characteristic example. In contrast with mostly urban populations in developed countries with small growth rate, developing and under-developed countries tend to have more rural population and the growth rate is significantly larger. Developing countries have means to procure technological devices and the personnel who possess the necessary know-how to design, operate and maintain them. However, developing and under-developed countries possess neither the technology nor the personnel in large quantities. As expected, the purchase power of developed countries is very high while developing and under-developed countries suffer from weak purchase power.

The above picture may look too gloomy, however, there are good news as well. Private investors are looking into ways of making rural electrification financially viable and possible. The untapped energy resources present in SSA and the large populations constituting the potential market manage to attract entreprenuers. These small projects are tailor made for a specific location and a particular context. Scalability is by no means the hallmark of these designs. For instance, DC microgrids deployed in southern sector of Rwanda have no scalability nor does the company have such a vision [4]. If SSA's energy crisis is to be solved with renewable energy (RE) based distributed generation, there is an urgent need for an adaptable and scalable solutions. There are four main barriers that should be tackled to achieve this:

- Forecasting demand: In contrast to the industrialized world where the demand for electricity can be projected reasonably well into the future, how demand will evolve from the starting point of no demand is not well understood. In other words, It is easy to predict future when

Manuscript received April 7, 2015; revised June 17, 2015.

doi: 10.18178/joace.4.3.247-251

there is ample information about the past and the trends associated with it. It becomes a difficult problem to estimate the demand of a `not-yet-electrified` location since there is no historical data. The problem is compounded by the fact that the evolution of demand is influenced significantly by the way electricity is provided such as Solar based microgrids, solar home systems, grid connected electricity etc.

- Technical capacity: The developing world is a graveyard of projects that were sustainable only so long as expatriate expertise was present to keep things going. Creating sustainable first-access energy systems, especially for regions that are far from the grid, requires a commensurate development of technical capacity to maintain these systems. There have been success stories regarding capacity building as well. Also alternative capacity building (training) methods prove to be useful. For instance, in Tanzania, old women were sent to India for Power Electronics training. Old women proved to be sustainable because they did not leave the village to work in the cities. This ensured the sustainability of technical capacity. India proved to be a very cost-effective solution since the associated costs were a fraction of what they would have been in the developed world.
- Value chains: The deployment and economic sustainability of first-access energy systems requires robust incentives and markets. It is likely that new business models will be needed to create the necessary on-going flow of financial and technical resources. The current status of electricity markes and power-purchase agreements (PPA) do not provide necessary incentives for private investors to shoulder the risks associated with rural electrification in SSA.
- Lack of relevant data: Another major barrier is lack of good data pertaining to RE potential in SSA Countries. Potentials of wind, biomass, even solar and hydro, are not well documented as they are in the developed countries. This makes it extremely difficult to make educated predictions into the future whether it be related to generation capacity or population growth and demographics.

These challenges can be overcome with a series of hybrid solutions. For instance, it is possible to use some global databases to extract relevant climate information. Then, some other resources can be utilized to model the demand based on recent experience with communities that are considered similar. Electrical modeling can be done with several optimization software while some other tools can be utilized to determine figures in PPAs, credit-risks and turn-around times. This paper is a part of large research project which discusses what software can be used to achieve above-mentioned steps. Another focus of research is to develop a holistic approach to Rural Electrification Project Development in SSA. It is aimed that such an approach will help realize `scalable` and `duplicable` energy project for first-access energy situations. The rest of the paper discusses a Computer-based First-access Demand Estimation tool developed to mitigate risks and challenges mentioned above. It is a step towards creating a complete Energy planning toolbox which can support systematic Energy planning.

II. Methods and Challenges of Forecasting Electrical Demand

One of the key challenges that are unique to first-access systems is the estimation of post-electrification demand and its evolution in time. Traditional forecasting hinges on the fact that there is historical data which can be used to model the system. Then, this model can be adapted to changes expected to appear in the future. Finally, the adapted model can be simulated to create future data based on the past data that is present. For instance, Fig. 1 below shows Australia's energy consumption forecast performed by Australian Electricity Market Operator. This forecast builds on the information gathered in past years and uses several models (adaptations) into the future for making meaningful predictions.

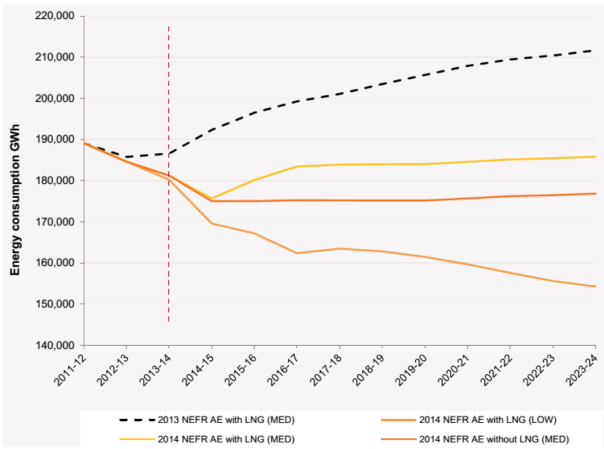

Figure 1. National electricity market energy forecast (Australia) [5]

In this approach, it is crucial to have information about what changes have caused what consequences in the system. For instance, if the increase in LPG prices encouraged residential consumers to start using `electricity` as the fuel of choice for cooking, then this would be seen as a significant increase in the residential electricity demand. The significance of the increase depends on several parameters such as the share of residential consumers in the entire electricity demand, the acceptance rate of electrical cooking appliances by the consumers, the net price difference between LPG and electricity. For this reason, these parameters need to be detected and included in the system. For instance, it is possible to learn electricity acceptance patterns by the consumers by making use of the events in the past. This can be mapped and/or scaled to future events as well.

Fig. 2 below shows the migration rate from LPG cooking to electricity. As shown, a price difference of 5 % in the past have encouraged 10 % of the population to migrate to electrical cooking appliances. Learning from this event, it can be estimated that another 5 % of price difference in the future may lead to 10 or 15 % of the population to migrate. Here, 10 % is an absolute mapping of a past event without considering any additional parameters. However, this is not true in real life. The same price drop may trigger larger technology migration (e.g. 15 % rather than 10 %) since commercialization of electrical appliances might decrease the purchase and maintanence costs, or the positive experience of the first 10 % fraction may create an avalanche effect where larger masses may be encouraged to use this `already-tried and proved` technology. Fig. 2 shows future projections beyond red broken line, for absolute and real-life calculations.

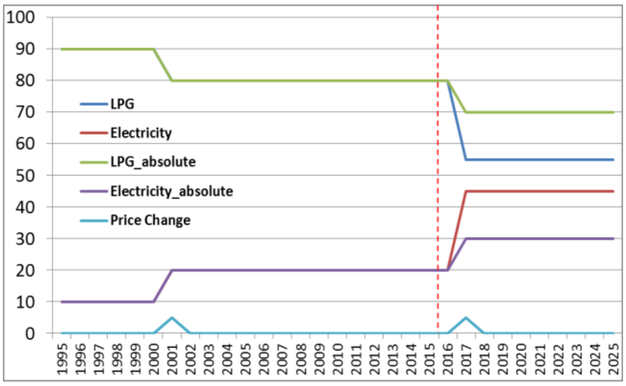

Figure 2. Migration prediction from LPG to electricity cooking

In this fashion, the change in the electricity demand can be easily predicted for the future. The trends and events in the past can be utilized, albeit there is a need for scaling. As it should be clear now, first-access energy systems have no historical data for energy consumption patterns or important events from which some lessons can be learned. There are several approaches to solve this situation. One traditional approach is to visit potential consumers in their houses and conduct surveys to understand what might be the electricity use if the village was to be electrified. Despite being easily implementable and its attractiveness at first sight, this approach has important drawbacks.

TABLE I. PITFALLS OF SURVEY BASED LOAD ESTIMATION

Challenges	Type
Absence of Electrical Loads	Pre-Electrification
Users' unfamiliarity with Electricity	Pre-Electrification
Electricity Use Trends	Post-Electrification
More Consumption that Survey Data	Post-Electrification
Future Extension	Post-Electrification

Firstly, there is no correlation between pre-electrification surveys and post-electrification behavior. Asking residents of an unelectrified village for what would they use their electricity once first-access is available is not realistic. Since they do not have electricity in the village, their answers tend to be very simplistic such as a lamp or two lamps. However, after getting electricity and experiencing its benefits, they tend to consume more than what they have elaborated in the survey. Table I summarizes the challenges related to surveying and their type as occurring before or after electrification.

Data analytics can be utilized to tackle this problem. With the help of data, purchase power of a community and its electricity consumption can be extracted. For instance, the data of GSM account credit top-ups can be an indicator of the purchase power, assuming that such data is available. The frequency and amount of credit top-ups can be easily extracted from GSM operators' databases [6]. The presence of location information in GSM networks is an invaluable asset since this financial actions can be correlated to physical locations. Fig. 3 below shows a typical village in western Tanzania (Image courtesy of Google).

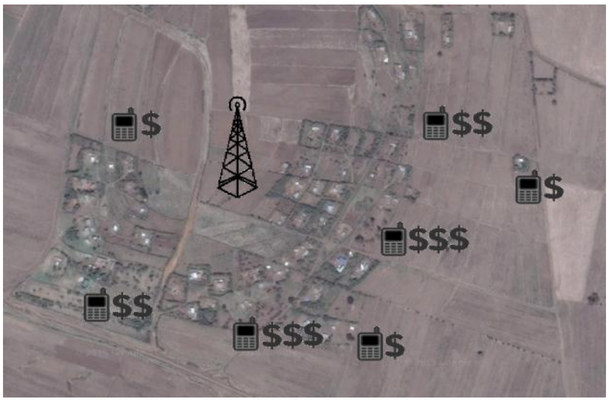

Figure 3. Use of GSM networks for purchase power and phone charging load estimation

The GSM tower in the middle is the anchor point where all local mobile phone traffic and credit top-up requests are processed. As shown, mobile GSM accounts can be utilized to extract financial information about this particular village. Another obvious information that can be extracted is the number of mobile phones in the village. This is of special interest, since mobile phones are electrical devices and need to charge. In rural areas, lighting and mobile phone charging make up the most of the residential load.

The lighting needs to be estimated for this village as well. In other words, the number of LED lights required to illuminate a house or the village needs to be estimated. There are a couple ways of doing this. Firstly, the primary source of illumination can be utilized for the estimation. For instance, if kerosene is used for lighting, then weekly or monthly sales in the village can be taken as a basis for lighting requirement. The drawback of this approach is that not all of the villagers use kerosene for lighting. Most of the time villagers use biowaste from the fields for in-house lighting, although this causes serious health problems. This makes it hard to achieve an accurate estimation. The only solution seems to be correlating building types and sizes with potential lighting load. However, due to large variety of communities, cultures and life styles in isolated communities, it is very difficult to find a common factor for relating building sizes to lighting load. A rural house in Burkina Faso may have completely different demographics when compared with another house, of same size, in Zambia or Tanzania. This difference can be the number of residents in the house, their life styles, education level and purchase power.

In short, this section summarizes the techniques used for estimating load in rural areas in SSA. These techniques are far from offering a complete solution due to several challenges. Accordingly, in the next section, the developed systematic approach that makes use of computer based decision making is explained.

III. Systematic Approach for Load Estimation in Rural Areas

It is possible to tackle the above-mentioned challenges by making use of Computer-based decision making systems. It is possible to process large amounts of data, do large number of computations and comparisons by using the high processing power of computers [7]. When these techniques are combined with the collection of big data, it is possible to come up with more realistic post-electrification load estimates. The developed automated system is shown in Fig. 4.

The process starts with looking at which continent (or in general, where) the rural electrification project will be realized. Then, satellite image of the selected community is taken. Image processing techniques are utilized to determine the sizes of the buildings, their types and expected uses such as houses, factories, schools, district offices, health centers etc. This extracted data is essential in estimating the load of the community. The data is sent over the PC where this decision-making scheme is running to a Server which is connected to a database. This database is essential for the successful estimation. The server tells database to look for similar communities in similar cultural, geographical and economical set ups. If a match is found, i.e. if a similar village which is electrified is found, then the characteristics of this community are sent back to the PC where automated decision-making scheme is running.

This approach solves the problem of no-history by keeping track of recently electrified communities and mapping candidate communities onto these known situations. The key here is to determine how accurately this mapping can be performed. There are several parameters that need to be taken into account so that when the satellite image of a community is processed the extracted data can be correlated with the load estimation. Table II lists parameters that can be used to characterize a site. This characterization serves both for finding similar sites as well as final estimation purposes.

Following from Table II, a site is characterized by its Nh, S, Nclass, H, Nclinicroom and DA, Noffice parameters. This is true for both first-access sites and the sites present in the database. When a new site is fed into the system, Satellite image processing creates these seven parameters and sends to the server. Server searches for similar sites in the database based on these seven characteristic parameters. When a match is found, the remaining six parameters that are required for the base load calculation, i.e. N_{ph}, N_{light}, $N_{appliance}$, N_{school}, $N_{medical}$ and $N_{poweroffice}$, are gathered and sent back to the system.

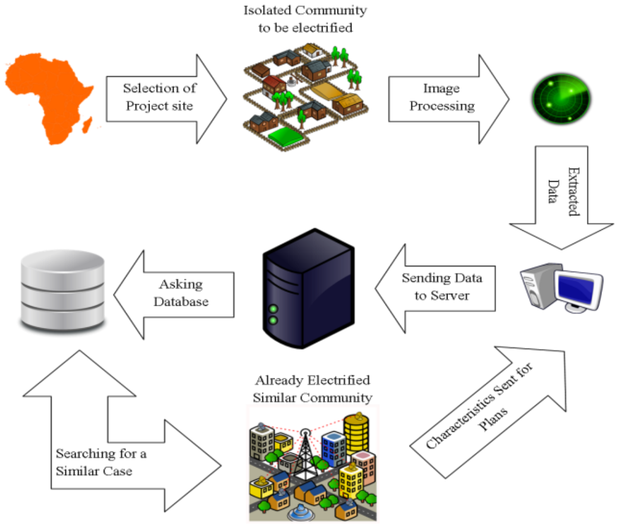

Figure 4. Proposed system for first-access electricity load estimation

TABLE II. Important Parameters in Satellite Image Processing and Data Extraction

Parameter	Notation	Remarks
Number of households	N_h	Extracted from the Satellite Image
Number of people per household	N_{ph}	Gathered from Similar Sites
Number of lights required per person-household	N_{light}	Gathered from Similar Sites
Number (Power Consumption) of Electrical appliances per person-household	$N_{appliance}$	Gathered from Similar Sites
School and number of classrooms	S, N_{class}	Extracted from the Satellite Image
Power Need for Lights and PCs per classroom	N_{school}	Gathered from Similar Sites
Health Clinic and number of rooms	H, $N_{clinicroom}$	Extracted from the Satellite Image
Power Need per room in Health Clinic	$N_{medical}$	Gathered from Similar Sites
District Administration, number of offices	DA, N_{office}	Extracted from the Satellite Image
Power Need per room in District Administration	$N_{poweroffice}$	Gathered from Similar Sites

The system follows the mathematical model given in (1) to calculate the first-access eletrical load of the community for which the study is being conducted.

$$Pfirst-access=\sum_{i=1}^{Nh}\begin{array}{l}Nph\times(Nlight+Nappliance)\\+(S\times Nclass\times Nschool)\\+(H\times Nclinicroom\times Nmedical)\\+(DA\times Noffice\times Npoweroffice)\end{array}\qquad(1)$$

where S, H and DA are Boolean variables and values 0, 1 represent school, health clinic and district administration being absent or present, respectively.

Table III below shows a typical output of the system for the community shown in Fig. 3. The second column on the right shows the characteristics of a `similar community` present in the database. As evident, this village has 38 households where an average of 5 people live in each house. Lighting load per person-household is 2 Watts which makes an average of 10 Watts per household in this community since there are 5 people. Similarly appliances add up to 5 Watt per household (approximately one mobile phone). There is a school with three classrooms and a very small dispensary with a single room. Correlating the Real values pertaining to community 1 with relative values in community 2, the total energy demand of the site can be found as in (2).

$$Pfirst-access=\sum_{i=1}^{38}5\times(2+1)+(1\times3\times20)+(1\times1\times15)+(0\times0\times0) \quad (2)$$

TABLE III. OUTPUT OF THE COMPUTER-BASED DECISION MAKING SYSTEM

Community 1 (from Image)	Real Values	Community 2 (from database)	Relative Values
N_h	38	N_{ph}	5
S, N_{class}	1, 3	N_{light}	2
H, $N_{clinicroom}$	1, 1	$N_{appliance}$	1
DA, N_{office}	0, 0	N_{school}	20
		$N_{medical}$	15
		$N_{poweroffice}$	N/A

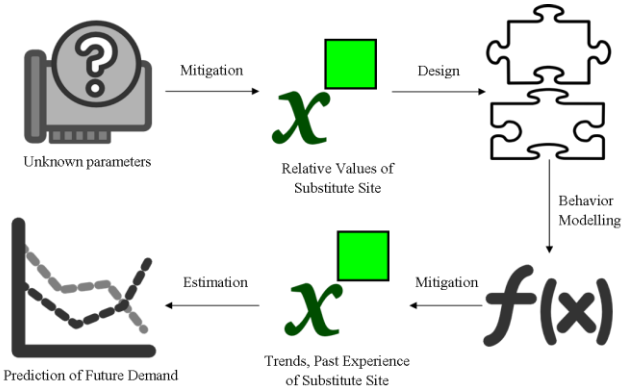

Figure 5. Benefits and mitigation scheme of the developed system.

The benefits of the developed system are not limited to pre-deployment calculations only. Depending on the cultural, financial and social similarities between the communities, the electricity consumption pattern in the future can also be estimated. For instance, if the power demand of a community doubles in the first two years of first-access (due to positive effects of electricity use on people's lives), then this can also be mapped from the `similar site` in the database on the candidate site which is being studied. This mitigates the issue of not having historical data as shown in Fig. 5.

IV. CONCLUSIONS

Energy crisis in SSA has the potential for changing the future of electric energy systems, not just in the developing world, but in the entire world. There is a tendency to view innovations that emerge out of necessity in the developing world as "stop-gap" measures that will disappear once the legacy technologies from the West can finally be deployed. There was a time that mobile phones were thought to be necessary in Africa and Asia only until a sufficient landline network could be installed, and mobile money was just for the poor to use in Kenya until they could get real bank accounts. A similar view prevails for first-access energy systems—off-grid systems are just a stop-gap until the remote poor can finally get connected to the grid. It is now clear there will never be a telephone landline network in Africa and conventional banking will be usurped by new financial services based on mobile technology.

The lack of legacy power systems in developing countries gives us the opportunity to explore brand new ways of generating and delivering electricity. And it's possible some of these innovations will lead the way for the rest of the world. In this paper, a novel first-access demand estimation approach has been developed and explained. This system mitigates the specific problems associated to first-access systems, such as lack of historical data for characterizing present and future trends, are mitigated by mapping from similar past sites. Such an approach will make rural electrification project development more systematic and standard. This way rural electrification based on renewable energy can pick up the pace and standard solutions, instead of custom-made, site-specific approaches, may flourish in underserved areas.

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