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Analyzing grid extension and stand-alone photovoltaic systems for the cost-effective electrification of Kenya

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ABSTRACT

The declaration of 2014–2024 as the Decade of Sustainable Energy for All has catalyzed actions towards achieving universal electricity access. The high costs of building electric infrastructure are a major impediment to improved access, making stand-alone photovoltaic (PV) systems an attractive solution in remote areas. Here, we analyze the cost-effective electrification solution for Kenya comparing grid extension with stand-alone PV systems. We use micro-data from a national household survey to estimate electricity demand for households that are within reach of electricity infrastructure and to predict latent demand in unconnected households. These regional demands are used in a spatially explicit supply model to seek for a least cost electrification solution. Our results suggest that decentralized PV systems can make an important contribution in areas, with low demand and high connection costs. We find that up to 17% of the population can be reached cost-effectively by off-grid PV systems till 2020.

Introduction

The achievement of the United Nations Millennium Development goals is strongly associated with access to electricity. This is also reflected in a recent declaration by the United Nations General Assembly for the decade 2014–2024 as the Decade of Sustainable Energy for All (United Nations General Assembly, 2011). In 2011, 45% of the urban population and 82% of the rural population did not have access to electricity in sub-Saharan Africa. The rate of electrification in Kenya is currently below the average of sub-Saharan Africa. 81% of the households (42% in urban and 93% in rural areas) have no access to electricity in their dwellings (Organisation for Economic Co-operation and Development and International Energy Agency, 2013). Consequently a large majority of the population still relies on firewood for cooking and paraffin for lighting (Kenya National Bureau of Statistics, 2005). Change is slow, since incentives to invest in rural areas are low due to high connection costs, low latent electricity demand and low incomes.

This article identifies least-cost options for electrification of households in Kenya. Many households cannot access electricity due to non-availability of electric infrastructure and thus their demand is unknown. For cost-effective planning of electricity infrastructure, which in many developing countries involves a choice between grid extension and the implementation of stand-alone systems, it is crucial to estimate electricity demand. We use detailed micro-data from the Kenyan Integrated Household Budget Survey (KIHBS) of 2005/2006 to estimate latent demand for electricity in Kenyan households (Kenya National Bureau of Statistics, 2005). In a second step, we use the demand model to predict electricity demand for all districts of Kenya in the year 2020. The data generated serves as an input into an electricity supply optimization model determining whether electric grid extension or the implementation of off-grid photovoltaic systems is the cost-

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effective solution for each grid cell. We consider off-grid PV as being representative for stand-alone systems, in general. The choice between grid extension or off-grid supply is a longer term decision not taken by individual households. By contrast, a national planning authority does not need to decide on the specific option(s) for off-grid supply; this can even be done at a household or community level.

This article contributes to recent scientific literature on electricity planning for countries with low electrification rates. In particular, we are interested in determining household electricity demand in areas where electricity supply is currently not available and in assessing if grid based supply or a combination of photovoltaic panels and batteries are more cost-effective in covering demand. There exists a significant body of literature on electricity demand estimation in developing countries. However, the literature on residential electricity demand in developing countries is more limited. Some examples of literature at the household level describing factors determining fuel choice are the following: Davis (1998) analyzes a household survey in South Africa to identify the effects of access to electricity of rural households on fuel choice. Masera et al. (2000) use data from a case study in a Mexican town and from a large-scale survey from four states of Mexico to find a model describing the transition from traditional to modern fuels. They show that a multiple fuel model or in other words the accumulation of energy options describes this move better than the standard energy ladder model. Tatiétsé et al. (2002) evaluate households' actual electricity energy needs in three Cameroonian cities. Their aim is to improve distribution grid planning in order to prevent frequent network interruptions and non-profitable investments. They form three classes based on criteria such as socio-professional category, income level and dwelling type. They carry out a survey collecting data on several characteristics affecting electricity consumption. From data on household appliances they calculate load profiles. Filippini and Pachauri (2004) estimate price and income elasticities of urban households' electricity demand using disaggregate household level survey data for India. The motivation of their research is to get an understanding of the key factors that influence electricity demand at the household level. Pachauri (2004) performs an econometric analysis using household survey data from India and finds that household socio-economic, demographic, geographic, family and dwelling attributes influence the total household energy demand. Ekholm et al. (2010) use a choice model to analyze the determinants of fuel consumption choices for heterogeneous household groups in India incorporating factors such as preferences. Louw et al. (2008) use sampled household data to assess the parameters affecting the electricity usage in electrified households for South Africa. Previous studies develop methodologies to explain energy consumption in developing countries, but they are very limited for sub-Saharan Africa. Moreover, none of the papers estimate currently uncovered electricity demand due to non-availability of supply. On research for electricity planning for countries with low electrification rates, until recently, there have been only a few isolated studies comparing grid connected versus stand-alone systems (Kaundinya et al., 2009; Narula et al., 2012). Studies for sub-Saharan African countries are still very limited. Zvoleff et al. (2009) determine costs of rural electrification through settlement patterns for several of the African Millennium Villages sites. Kocaman et al. (2012) propose an algorithm to minimize overall electricity infrastructure costs based on spatial distributions of demand points studying nine sites in sub-Saharan Africa. Szabó et al. (2011) compare electrification costs of distributed solar and diesel generation with grid extension for Africa through means of a cash flow model and geographic information systems. Levin and Thomas (2012) determine the percentage of population for which decentralized systems would be the cost-effective solution for 150 countries. They compare the costs of centralized generation calculated via a minimum spanning tree to decentralized generation. Fuso Nerini et al. (2014) undertake a techno-economic analysis to determine the best electrification solutions for the Amazon region in Brazil. They then evaluate those electrification options in a multi-criteria-analysis based on weights obtained from an interview process. Rosnes and Vennemo (2012) build an optimization model to determine the least cost supply options covering demand in 43 sub-Saharan countries. Deichmann et al. (2011) and Parshall et al. (2009) propose a geographically explicit methodology in order to decide between stand-alone systems and grid electrification based on cost minimization in Kenya. Kemausuor et al. (2014) uses a similar approach for Ghana. These models are strong on the engineering side, but lack a detailed analysis and modeling of the demand side: Fuso Nerini et al. (2014) use one average consumption of a 'standard household'. For new connections Rosnes and Vennemo (2012) use two average annual consumption categories, one for rural households and one for urban households. Levin and Thomas (2012) assume that newly electrified regions will consume electricity at the same rate as the currently electrified population. Deichmann et al. (2011) assume a fixed quantity of electricity demanded for two categories of households: rural and urban, whereas Parshall et al. (2009) propose four different exogenous electricity demand values depending on income and population distribution. Kemausuor et al. (2014) also use four average demand categories.

The literature review shows that there is no study combining thorough demand estimations with a supply side electrification model. Furthermore, from the literature and to our knowledge our approach of estimating latent electricity demand due to non-availability of electricity supply is novel. Similar econometric approaches to latent demand estimation have been applied in other sectors such as Briand et al. (2010) for water in households but not to estimate electricity demand. With this research we are attempting to close the gap of predicting electricity demand at a district level and using it in a supply-side cost optimization model to choose between grid extension and stand-alone PV systems.

The article is structured as follows. The Data and methodology section provides data and methodology for the demand estimation and the supply optimization model. In the Results section, we present the results of both models. The Discussion and conclusions section provides policy conclusions as well as an outlook on future research.

Data and methodology

Kenya with a geographical area of 569,250 km^2 is located in Eastern Africa on the equator. The country is divided into eight provinces and 46 districts. The Kenyan Bureau of Statistics states a provisional number of 40.7 million inhabitants for 2012 (Kenyan Bureau of Statistics, 2013). According to the KIHBS, the average population density varies depending on the district between 2.5 inhabitants per km^2 and 4500 inhabitants per km^2. One out of five Kenyans lives in urban areas (Kenya National Bureau of Statistics, 2007). The public Kenyan Power and Lighting Company (KPLC) is responsible for transmission, distribution and retail of electricity. About 80% of national electricity is generated by the state owned Kenyan Electricity Generating Company (KenGen) (Kenya Electricity Generating Company, 2014). KenGen sells the electricity to the Kenyan Power and Lighting Company (KPLC) (Kenya Electricity Generating Company, 2014). The total installed power generation capacity amounts to 770 MW of hydropower, 610 MW of thermal energy, 200 MW of geothermal energy and 26 MW of cogeneration (provisional numbers for 2012) (Kenya National Bureau of Statistics, 2014). In the Rural Electrification Master Plan (REM), the government aims at an electrification rate of 33% until 2018 and 40% until 2020 (Ministry of Energy et al., 2009).

Fig. 1 gives an overview of the data and methodology that are described in more detail in the Electricity demand estimation of Kenyan households and Electricity supply optimization model sections. We use an exponential regression model in order to predict electricity demand for households without access to electricity. The predicted electricity demand in every grid cell (2000 km^2) serves as an input parameter in a supply-side optimization model, which determines the