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Accuracy of energy-use surveys in predicting rural mini-grid user consumption

Courtney Blodgett[a], Peter Dauenhauer[b], Henry Louie[c,*], Lauren Kickham[a]

[a] Vulcan Inc., Seattle, WA, USA
[b] Institute for Energy & Environment, University of Strathclyde, Glasgow, United Kingdom
[c] Seattle University, Seattle, WA, USA

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ABSTRACT

Mini-grids for rural electrification in developing countries are growing in popularity but are not yet widely deployed. A key barrier of mini-grid proliferation is the uncertainty in predicting customer electricity consumption, which adds financial risk. Energy-use surveys deployed in the pre-feasibility stage that capture present and aspirational consumption are intended to reduce this uncertainty. However, the general reliability and accuracy of these surveys has not been demonstrated. This research compares survey-predicted electrical energy use to actual measured consumption of customers of eight mini-grids in rural Kenya. A follow-up audit compares the aspirational inventory of appliances to the realized inventory. The analysis shows that the ability to accurately estimate past consumption based on survey or audit data, even in a relatively short time-horizon is prone to appreciable error — a mean absolute error of 426 Wh/day per customer on a mean consumption of 113 Wh/day per customer. An alternative data-driven proxy village approach, which uses average customer consumption from each mini-grid to predict consumption at other mini-grids, was more accurate and reduced the mean absolute error to 75 Wh/day per customer. Hourly load profiles were constructed to provide insight into potential causes of error and to suggest how the data provided in this work can be used in computer-aided mini-grid design programs.

Introduction

Current access to modern energy services is neither universal nor guaranteed. The World Energy Outlook (Birol, 2016) estimates that 1.2 billion people do not have access to electricity. Projections by the IEA suggest that efforts to electrify Africa will slightly outpace population growth but still leave leave half a billion still without electricity by 2030 (Birol, 2015). Overall investment levels are expected to reach US$30 billion annually in electricity access alone. Within the range of solutions, renewables-based mini-grids are a promising option owing to their relatively low initial investment levels, scalability, and suitability for rural areas.

While of considerable interest as a marquee solution, the practicalities of implementation and operation of mini-grids is challenging. Often located in remote areas with difficult terrain and impoverished customers, the sustainability of mini-grids is far from guaranteed. Issues such as limited local technical and managerial skills, low energy demand, poor availability of supply components, and unproven financing models have been noted as some of the problems facing rural mini-grids (Azimoh et al., 2017).

Mini-grids are often designed to be financially viable once installed and many developers are hoping this will pave the way for commercial funding. Mini-grids are established on the principle of providing affordable energy for the rural population in their service area while balancing the need for an acceptable level of reliability and financial viability. Estimates place the costs of mini-grid supplied energy above that from the centralized grid, ranging from US$1.35/kWh to US$2.04/kWh compared to US$0.41/kWh to US$0.80/kWh for grid extension (Action, 2016), although in some scenarios mini-grids are cost-competitive (Nerini et al., 2016). For proponents of mini-grids in developing countries, it is essential that financial viability is a top priority.

The design of a mini-grid determines critical project parameters such as mix of renewables, component sizing, and network design. Clearly, these choices have a large impact on the overall financial model and determine the cost of energy required to make the mini-grid profitable. A common design approach is to use software such as HOMER (Bekele and Tadesse, 2012; Díaz et al., 2011; Kolhe et al., 2015; Olatomiwa et al., 2015; Rajbongshi et al., 2017). However,

* Corresponding author.
E-mail addresses: CourtneyB@vulcan.com (C. Blodgett), peter.dauenhauer@strath.ac.uk (P. Dauenhauer), hlouie@ieee.org (H. Louie), LaurenK@vulcan.com (L. Kickham).

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this approach requires accurate predictions of consumption profiles to yield meaningful designs. Recent efforts to produce consumption profiles for design purposes have used simulation techniques to generate more realistic consumption profiles. However, the efforts are still reliant on surveyed data as a primary input data (Boait et al., 2015; Mandelli et al., 2016b). While the advantage of the simulation techniques is an increased accuracy (mainly by the inclusion of stochastic elements) of certain aspects of load variation, the fundamental inaccuracy of the primary input data is not addressed.

Operational information for existing mini-grids is sparse, but is becoming more common due to the use of low-cost data acquisition systems (Blanchard and Little, 2016; Louie et al., 2016). Technical design data that have been published are rarely accompanied with an evaluation of the design suitability after installation.

Neither over- nor under-designing systems is desirable and it may lead to a lack of sustainability. Given that many of the users will gain access to electricity for the first time in their lives, predicting consumption based on past use is impossible. Alternatively, a widespread practice is to employ energy-use surveys of potential customers to predict consumption (GIZ, 2016).

The energy-use survey approach is common but receives little coverage in the literature. As a result it is unclear how effective it is at predicting consumption. This paper draws attention, in particular, to the accuracy of the energy-use survey. It is of utmost importance how a few survey questions are converted into a consumption prediction for mini-grid sizing and the implications of errors in this process.

Importance of energy prediction in mini-grid design

Although consumption prediction is a key element of system design, critical reviews that compare predicted to actual values are rare. Yet, recent research indicates that prediction errors can be considerable; in Louie and Dauenhauer (2016) an average error of 305% was reported.

Over-prediction of consumption leads to an over-sized system, which reduces financial viability. Financial viability is widely noted as a critical premise for successful projects (GIZ, 2016; Krithika and Palit, 2013; World Bank, 2012). At best, a short-term problem of low revenues may occur as customer ability to pay can have an upper ceiling. Substitution of electricity with alternative energy sources and low ability to pay limit the ability of the mini-grid owner to raise prices to cope with low revenue generation. Failure of load growth materializing over time represents a major investment risk and can sink the project financially. In Louie and Dauenhauer (2016), it was found that increasing system reliability from 99.7% to 99.9% (in terms of total energy served) drastically reduced the number of systems which could be deployed with an equal investment.

Under-prediction of consumption lowers reliability and availability of the system, potentially leading to serious issues that undermine the technical sustainability of the system, for example, reduction in battery lifespan (Government of New Zealand, 2010; IEEE Working Group for Energy Storage Subsystems, 2007a; IEEE Working Group for Energy Storage Subsystems, 2007b). Under-sized systems can also present sustainability challenges that are non-technical. For customers, reduced availability of the system can be catastrophic when the loss of electrical service at, for example, a maternity ward, may jeopardize lives (World Health Organization and others, 2014). Businesses that cannot depend on the mini-grid will face economic consequences and may employ coping strategies by procuring diesel gen-sets (Rao et al., 2016). Lack of trust in the system to provide reliable electricity may prevent people from purchasing further appliances, thereby decreasing consumption growth.

Standard of practice of energy-use surveying

A survey-approach to energy estimation involves employing a structured questionnaire to: take an inventory of current appliances and likely (near-term) future appliances, determine power ratings and predict daily usage of these appliances (GIZ, 2016; Meier et al., 2010). An average daily energy requirement is then calculated and aggregated for the entire mini-grid. Daily profiles, for example with hourly resolution, can also be formulated if the surveys capture a prediction of what time of day each appliances is used.

This basic structure of energy-use surveys have been present in development programs at least since the 1990s (Ellegård and Nordström, 2001; ESMAP, 1999; Gustavsson, 2007). A comprehensive energy-use survey can be found in World Bank (2003). While this may offer more structure than other simpler surveys, crucially, all depend on respondent-supplied inputs. More recent literature imply that the practice is still prevalent (Alzola et al., 2009; Camblong et al., 2009; Ramchandran et al., 2016).

Challenges with measuring energy demand in low-income households in developing countries have been acknowledged (Brook and Smith, 2000). In their 2000 mini-grid design manual, ESMAP noted that "… *making load projections that reflect reality is frequency a difficult task to accomplish, especially for perspective consumers who have little experience with electrification*" (Inversin, 2000). Unfamiliarity with electricity, changes in behavior before and after installation, and difficulty projecting future energy growth have been noted as specific issues (Ustun, 2016). Furthermore, during design, hourly time-series data for load profiles are typically needed, making the task of estimating this even more difficult through a survey approach (Mandelli et al., 2016a).

Alternative prediction approaches

Alternative energy prediction approaches have been proposed, including use of experts, regression and census data.

The expert approach relies on expert knowledge and judgment to predict consumption using a black-box approach, without specifically collecting individual data (Ghafoor and Munir, 2015). Although simplistic, this approach has the benefit of low data gathering requirements.

Regression can be used to map electricity consumption to explanatory demographic variables, such as the number of people living in the household, and presence of a flush toilet (Fabini et al., 2014; Louw et al., 2008; Zeyringer et al., 2015). Census data of appliance ownership and usage levels can be used to infer likely usage patterns among newly connected customers. This method essentially assumes that the census samples and the target samples are drawn from the same population (Askari and Ameri, 2012; Nouni et al., 2008; Sen and Bhattacharyya, 2014).

Although these approaches produce a prediction of consumption, none attempt to quantify the error. For practical purposes, this leaves a mini-grid designer with few reliable options. These alternative approaches add complexity, additional data and analysis requirements, and costs. Expert-based approaches are the exception, though use of this approach in an actual mini-grid project would be questionable given the subjectivity involved. These obstacles reinforce the practice of energy-use surveying which, in essence, has not changed much in several decades and has not received sufficient critical attention. Consequently, the impact this has on sustainability of the underlying systems, clearly a important issue for furthering electricity access, is not fully known.

Study objectives and paper structure

This research evaluates the accuracy of the widely-employed energy-use survey prediction method. An improved understanding of the boundaries of error will assist mini-grid operators in assessing the risk of consumption prediction error at the design stage. Moreover, it provides them support for weighing the costs and benefits of conducting surveys. The research is based on responses from