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Effects of load estimation error on small-scale off-grid photovoltaic system design, cost and reliability

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ABSTRACT

The proliferation of off-grid photovoltaic (PV) systems is rapidly increasing in the least developed countries. The sizing of system components—primarily PV panels and batteries—is critically influenced by the expected daily load. However, accurately estimating incipient electrical load of rural consumers is fraught with challenges. Load estimation error is propagated through the design phase, potentially resulting in a system that is unduly expensive or fails to meet reliability targets. This article investigates the effects of daily load estimation error on system design, cost and reliability. Load and insolation data from seven off-grid systems in Malawi were collected. The systems were redesigned using three different intuitive design approaches considering different levels of load estimation error, ranging from ±90% of the actual measured load. The cost of each design is estimated from in-country prices. The reliability of each design is determined from an hourly simulation using the measured data. The results show that PV array and battery sizing scale proportionately with load estimation error and that the cost of load over-estimation is approximately US$1.92 to US$6.02 per watthour, whereas under-estimation can precipitously degrade reliability. A cost-*versus*-reliability analysis shows that for the Malawi systems, on average 46% of the PV and battery costs are used to improve the simulated hourly reliability from 99% to 100%. Moreover, the results point to the challenges with intuitive design approaches, showing that consideration of average load alone can lead to over- or under-designed systems.

Introduction

As is articulated by the UN Global Goal Seven, universal energy access is a critical global objective (Project Everyone). Sufficient access to clean and sustainable energy underpins many if not all development objectives in least developed countries (LDCs). Achieving universal access is an ongoing struggle for LDCs, where national electrification rates are less than 10%, and less than 1% in rural areas (International Energy Agency, 2015). Different solutions are being proposed, piloted, and rolled-out by a wide-range of actors: multilateral aid agencies, individual countries, private companies, civil society, universities, communities, and individuals. Progress is being made, since 2000, over 145 million people in Africa alone gained access to electricity (International Energy Agency, 2014).

Off-grid renewable energy projects utilizing photovoltaics (PV), wind energy, biomass or hydro deployed in stand-alone systems or mini-grids are a widely promoted solution to universal energy access. The International Energy Agency has estimated that off-grid solutions will provide 59% of first-time access to electricity (International Energy Agency, 2011), requiring US$50B per year invested until 2030. The stakes are high for these projects; failure to address the ongoing sustainability challenges will undermine these investments and impacts they can have.

By definition, off-grid systems have no connection to the national grid. As such, they must be designed to independently balance energy supply with the anticipated load over the short and long term. The PV array must be sized appropriately to satisfy the load (inclusive of losses), and the battery capacity must be sufficient to buffer against periods of decreased insolation and increased load. Over time, batteries and PV arrays suffer from both aging effects and load increases, putting further pressure on the system to deliver an adequate level of reliability.

Approaches to sizing the PV array, battery and other components vary in their sophistication from simple *ad-hoc* ('rule of thumb') methods to the use of simulation-based computer programs (*e.g.* HOMER, Hybrid2, PVSyst) which optimize cost or reliability. In the literature, several approaches to PV system sizing have been established and are classified as intuitive, numerical, and analytical (Khatib et al., 2013; Posadillo and Luque, 2008a).

The intuitive method, as highlighted within this article, involves a simplified set of calculations for the PV sub-systems to reduce the

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modeling complexity. Simplifications include modeling solar radiation based on the single worst month in the year, ignoring dynamics of the charging cycle, and disregard a reliability optimization. Daily load profiles are commonly reduced to a single value, the average daily energy use, despite research showing the impact different load profiles have on reliability and cost of the designed system (Celik, 2007; Treado, 2015; Osaghae et al., 2015). Various iterations on the method have been documented throughout the literature (Chapman, 1987; Salame et al., 2013) while the specific sizing approach investigated in this paper is found in (IEEE recommended practice for sizing lead-acid batteries for stand-alone photovoltaic (PV) systems, 2007; IEEE guide for array and battery sizing in stand-alone photovoltaic (PV) systems, 2007).

Numerical methods involve detailed simulation of energy supply and load over a specified length with the objective of minimizing costs or loss of load probability. Numerical solutions will typically involve modeling stochastic elements such as in Cabral et al. (2010); Posadillo and Luque (2008b).

Analytical techniques optimize reliability by adjusting array and battery size using deterministic input data as shown in Fragaki and Markvart (2008); Labed and Lorenzo (2004); Celik et al. (2008); Jakhrani et al. (2012). These methods seek to model the reliability of the system mathematically. Under certain assumptions, closed form equations can be derived (Abouzahr and Ramakumar, 1991; Bucciarelli, 1984); other approaches rely on fitting parametric equations to simulated data (Barra et al., 1984; Khatib et al., 2012).

Both the numerical or analytical techniques will produce more exacting sizing than the intuitive approaches. However, intuitive methods remain widespread among practitioners in LDCs due to the tractability of the method, ability to provide rough but seemingly accurate results, and lack of sufficient data to support more advanced techniques. Intuitive methods in particular are more often applied to small-scale systems—typically less than 2 kW—where the additional effort of numerical or analytic design approaches may not be justified.

Regardless of the sizing approach, the resulting design is intimately tied to and dependent on the estimate of average daily load, which is notoriously difficult to estimate in the context of LDCs (Díaz et al., 2011; Mandelli et al., 2016a; Cross and Gaunt, 2003; Howells et al., 2002). Constant daily loads are often assumed within the optimization techniques for simplicity despite the uncertain and variable nature of newly electrified customers. The problem can be addressed from three angles. First, the load estimate can be assumed based on past experience of similar installations (Sen and Bhattacharyya, 2014). However, these data are rare, not widely available and perhaps not generalizable. Second, an econometric model with existing consumers that estimates, for example, the demographic variables correlating to energy consumption, can be used to hypothesize loads for potential future locations (Pachauri, 2004; Zeyringer et al., 2015). The selection of the predictor variables is non-trivial, for example Dauenhauer and Louie (2015) showed there exist a wide variety in consumption patterns even within the same customer class. Third, a bottom-up approach can be used to build up an aggregate load from expected appliance duty cycles and various customer classifications, often employing a field survey as a basis for current and future load.

Surveys of 'aspirational' load can be conducted to provide insight into what electric appliances and loads a consumer anticipates on purchasing and how frequently they would be used (Mandelli et al., 2016a; Adeoti et al., 2001; Boait et al., 2015). The ability of an individual without prior access to electricity and often irregular income to accurately predict their future appliance purchases and usage pattern is questionable. There is little, if any, rigorous research on the accuracy and potential biases of the survey method, but there is at least anecdotal evidence within the practitioner community that surveys can be inaccurate and unreliable (Blodgett, 2016; Sloughter et al., 2016). Loads can be added or removed over time, and human behavior is difficult to predict. For example, it has been reported that on average, a person switches electric devices on and off hundreds of times per day, mostly unaware that they are doing so (Meier, 2005). Not surprisingly, researchers have called for improved methods for estimating load (Díaz et al., 2011; Cross and Gaunt, 2003; Howells et al., 2002), but a practical and proven approach has yet to emerge.

Errors in the estimation of the average daily load propagate through the design phase, resulting in systems perhaps ill-suited to their application. The practical consequences are considerable and are most tangibly presented in the form of increased or decreased cost or reliability. Acute over-estimation of load may yield extraordinarily reliable systems with larger than needed PV arrays and batteries at an exorbitant cost. Managers of often insufficient rural electrification budgets may prefer to install a greater number of off-grid systems with lower—but still acceptable—reliability than fewer at high reliability. On the other hand, under-estimation of load may lead to inexpensive under-sized systems that fail to meet reliability targets.

The reliability of PV systems has been the subject of several research studies going back to at least the 1970's. Early work was focused on component reliability (Stember et al., 1982; Longrigg, 1978). Contemporary research tends to focus on grid-tied rather than off-grid systems. The research often seeks to develop new methods of conceptualizing or calculating reliability, often using probabilistic approaches. A Markov Reward Model was developed in Dhople and Domínguez-García (2012) to incorporate reliability into grid-tied PV performance analysis. In Shimura et al. (2016), the authors present a new method to incorporate reliability into the levelized cost of energy of grid-tied PV systems. Methods for computing the reliability of off-grid systems using the loss of load probability metric are derived in Abouzahr and Ramakumar (1991; Bucciarelli (1984) based on probabilistic models. Off-grid systems are also considered in Maghraby et al. (2002), where the authors combine reliability considerations into the design of such systems. Other existing research considers the reliability of hybrid systems (Paliwal et al., 2014) and clustered microgrids (Nikmehr and Ravadaneg, 2016) using various probabilistic techniques. No existing research directly investigates the impact of load estimation error on reliability or associates system cost with the error.

This article takes a practical, data-driven approach to investigating the implications of average daily load estimation error on small-scale off-grid PV systems. Hourly insolation and load data from seven real-world systems in Malawi were collected over the course of approximately one year. With the actual average daily load known, several intentional over- and under-estimations of the load were made and used as inputs to hypothetically redesign the systems using various design approaches. The corresponding costs are estimated using a model derived from in-country pricing. The reliability of the redesigned systems is evaluated through a deterministic simulation. The simulation uses the collected data to recreate the real-world insolation and load conditions experienced at the Malawian sites. The use of a deterministic approach rather than probabilistic is a unique aspect of this research. Rather than relying on theoretical models of load and insolation, the use of actual data completely captures the potential complex correlation and dependency structures within and among the energy flows.

The main contribution of this research is the quantification of the sensitivity of cost and reliability to average daily load estimation error. In addition, an opportunistic enquiry into the relationship between cost and reliability independent of load estimation error is made. The research demonstrates the value of accurate load estimation. Broader insight is also gained in how following different design approaches affect system cost and reliability. The results highlight an important disadvantage of intuitive design approaches: considering only average daily load and not its distribution or temporal characteristics can result in over- or under-designed systems.

The remainder of this paper is arranged as follows. The Site and data set descriptions section provides information on the Malawian systems and analyzes the characteristics of the collected data. The research methodology is presented in the Methodology overview section. The