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Experimental validation of an electrical and thermal energy demand model for rapid assessment of rural health centers in sub-Saharan Africa

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HIGHLIGHTS

- A gap in current understanding of rural health center energy demand is identified.
- A building energy model (BEM) is parameterized for rural African health centers.
- The BEM is coupled with electrical demand data and validated using a case study.
- A method for creating synthetic demand forecasts using measured data is proposed.
- Energy demand prediction via the above can enable health center energy system design.

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ABSTRACT

Rapid deployment of health service infrastructure is underway to meet the growing needs of populations in sub-Saharan Africa, however the energy infrastructure needed to support high quality services has tended to lag. Understanding the electrical and thermal energy needs of health centers constructed with local building methods and materials and operating outside of the jurisdiction of heating, ventilation and air conditioning (HVAC) codes is complicated by a lack of appropriately scaled and configured energy system design frameworks and validation data for dynamic simulations. In this work we address this gap by linking the thermal envelope performance of health center buildings under heating and cooling loads with measured indoor air temperature, meteorological conditions, and operational electricity demand. A resistance-capacitive type energy balance model is parameterized using typical health center architectural data for sub-Saharan Africa (floor plans from Uganda and Lesotho) and heat transfer characteristics; to achieve this energy flows between HVAC equipment, internal loads, and ambient conditions are simulated on an hourly time step with indoor temperature thresholds representative of thermostat settings. A typical meteorological year dataset for Lesotho is used as a case study, validated with indoor temperature measurements and power metering at four health center sites spanning a daily patient load ranging from 15 to 450 per day over rural and urban communities. High resolution electricity measurements from smart meters installed at the clinics are used to close the energy balance and form the basis of a probabilistic method for forecasting long term hourly electricity demand in African health centers. These data and the corresponding method have relevance to energy system design for health clinics across sub-Saharan Africa, especially those featuring intermittent renewable generation. The integration of these two modeling approaches constitutes a novel tool for sizing and costing energy infrastructure to meet operational demand at health centers in both urban and rural areas of developing countries.

1. Introduction: Powering health infrastructure

In sub-Saharan Africa energy for health centers is increasingly prioritized by planners pursuing a general strategy of increased energy access for the approximately 600 million people who lack electricity services [1–3] This stems from the expectation that electrification contributes to positively impacting health outcomes through improved service delivery, i.e., use of modern equipment and procedures, electronic medical records (EMR), etc. Meanwhile market forces have contributed to lowering the cost of energy equipment, e.g., solar panels,

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Nomenclature

α	absorbance
A	area
I_b	beam irradiance
k	thermal conductivity
$\dot{Q}$	heat flow
τ	time
U	overall heat transfer coefficient
$\dot{V}$	velocity

therein expanding the budgetary ability to provide electricity at remote clinics. While new health centers being built in unelectrified areas may include such energy systems in the design, including updated architecture for energy efficiency, the far more extensive portfolio of existing facilities operating without power could also benefit from retrofitting and upgrading. The sizing, configuration, and costing of these retrofit energy systems depend critically on understanding the dynamics of energy demand in a representative setting, something which to date has simply been impossible due to a dearth of relevant data to underpin the evaluation of energy (electricity or heating cooling) demands at these facilities.

1.1. Health center demand dynamics

The energy demand, and time-dependence of demand, correlate with a number of factors such as size of the facility (footprint and patient load), building construction and thermal performance, types of equipment and services deployed, and the meteorological conditions driving heating ventilation and air-conditioning (HVAC) loads - as well as the extent to which the latter are sourced from electricity or (as is more common for heating applications) fuels such as LPG, coal, or biomass. A health clinic energy generation system design tool, such as those developed by [4,5] or the authors previously in [6,7], must therefore perform a simulation of energy system yield over time, matching generation capacity (as a function of resource, e.g., solar, availability) to a (calculated, inferred, assumed, or measured) demand dataset. To do so most accurately requires knowledge of diurnal, weekly, and seasonal variation in demand, data which are typically unavailable. The synthetic construction of a demand dataset is most often pursued using inventory based assessment methods, such as [8], that generally fail to capture actual observed usage patterns [6]. This work proposes an alternative, measurement-based approach to generation of the demand datasets required to drive the annual supply/demand simulations necessary to optimize sizing of energy infrastructure.

1.2. Measurement-based demand forecasting: Background, standard methods, and energy access applications

The development of accurate load forecasts is a challenge as old as industrial scale electricity production, however in recent decades - as computation has become cheaper - research efforts have broadened to include high resolution data-driven and methodological innovations. The literature contains numerous highly complete reviews of load forecasting research across scales and applications (e.g., [9]), so many so that the most recent [10] in fact proposes specific criteria for evaluating novelty of contributions within this dense landscape. Included in this list are new (1) problems, (2) methodologies, (3) techniques, (4) datasets, and (5) findings, though the authors are careful to highlight that *significance* must be judged relative to industry or commercially-relevant challenges [10]. The follow paragraphs outline state-of-the art from these perspectives in order to situate the current manuscript within the field.

Forecasting has been most frequently applied for large scale grid applications on short time frames (hour, day, and week ahead) and specifically in developed economies, scenarios where aggregation provides some level of smoothing and economic motivators for forecasting accuracy are large (hundreds of thousands of dollars [11]). Allocation and sizing of generation capacity (for base, peak, and intermediate loads) was historically approached through the use of load duration curves (LDCs) derived from daily peak demand data on an electric grid [12], with capacity investments determined through medium term (months to years) estimation of the evolution of LDC shapes. Accurate, long-term high resolution forecasting of load profiles corresponding to the hourly-annual (8760) simulation format found in widely used typical meteorological year datasets [13] and in models for building energy performance [14] and renewable generation applications [15] is today usually of interest for any application with highly constrained economics or poorly constrained demand/generation characteristics. Small islanded power systems (the focus of this work) fall squarely into both of these categories, particularly renewable energy systems which on one hand suffer significant economic penalties when forced to run backup generators and on the other face high capital costs related to battery storage and high variability and uncertainty in demand characteristics (e.g., as tackled for wind systems by Dutta et al. [16]). For such applications, where dynamics of both demand and generation are sub-hourly, LDCs prove inadequate for engineering design and therefore high-resolution demand data and simulations are needed.

Analysis of smart meter data has provided significant insight into some industry specific load behaviors [17,18], but development of probabilistic load prediction models for electricity applications (needed especially for cases where historical data are lacking) has lagged significantly relative to other fields [19]. Several novel, more generalizable approaches have been evaluated for creating probabilistic demand models, ranging from probabilistic behavior modeling [20,21] to representative load curves [22] to Bayesian approaches [23], based on numerous different techniques (hidden Markov models [17,20], time-varying splines [24], ARMA models [23,25], and machine learning algorithms [22,23]) and generating some successes and cross-cutting lessons (e.g., temperature dependence of demand curves [20,26]). Transferability of methods to new applications is, however, in many cases limited by (1) a necessity for large volumes of application-specific ground-truth data (e.g., for behavior modeling), (2) loss of information in statistical representation (e.g., representative load curves), (3) loss of information in time structure (e.g., time-invariant Bayesian approaches), or (4) computational constraints. Identification of the appropriate method for a particular application therefore requires navigating trade-offs that are dependent on the ease (and cost) of data collection, volatility of actual demand, strength of demand auto-covariance, etc.

In particular, research related to load forecasting for small rural energy systems (micro- or mini-grids) in developing nations has lagged due to a paucity of recorded demand data (some exceptions include [21,27]). This remains true in spite of increasing interest in the potential for achieving significant energy access in, e.g., Africa and India via renewable energy based minigrids, as well as the recognition that essential services in the health sector critically depend on access to both electricity and thermal energy for indoor climate control [2,4].

To help bridge this gap, this manuscript presents a long time-frame (years) probabilistic electricity load forecasting tool for use in optimized design and sizing of islanded energy systems for off-grid health care facilities, a challenge which to date has primarily been (with very limited success) using inventory methods for demand prediction [4]. The tool is calibrated with a novel multi-year dataset collected from sub-Saharan health clinics (electricity demand, indoor and outdoor temperature, solar insolation) for the specific purpose of load forecasting. Probabilistic demand forecasting is accomplished using a Bayesian approach (the underlying probability distribution function is estimated using collected high-re solution data) wherein auto-