Technical Design of Off-Grid Energy Kiosks

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***Abstract*—Rural communities in sub-Saharan Africa are frequently afflicted by energy poverty; as it is typically cost-prohibitive to extend the electricity grid to these locations, off-grid energy kiosks provide a locally sourced alternative for the community. This paper describes the technical design, development and implementation of an energy kiosk in Chalokwa, located in southern Zambia. Predicted load profiles are estimated based on experience from previous projects and are refined for the specific requirements of the Chalokwa community. Computer simulations are performed using publicly available software to size the photovoltaic panels, system batteries, and electronic components in such a way that the kiosk may function reliably in a range of operating conditions. The energy kiosk was installed and commissioned in June of 2016, and was outfitted with a data logger which measures system voltages and temperatures; this makes it possible to close the design loop and validate the assumptions made in the design process. The process outlined in this paper is presented in such a way that it may be used as a template for the technical design of future energy kiosks.**

Keywords - Off-grid energy kiosks, data logger, technical design procedure

I. Introduction

The global electrification rate stands at just 85%, meaning that over one billion people lack access to development-enabling electricity [1]. Although progress is being made at eliminating this form of energy poverty - over 220 million people gained first-time access to electricity from 2010 to 2012 - due to population growth, the number of people without electricity is increasing in several Sub-Saharan Africa countries [1]. Several relevant approaches to electrification include solar lanterns, solar home systems, energy kiosks, micro-grids and mini-grids [2]. This paper focuses on energy kiosks, which are centralized off-grid electrical systems that serve a community using a walk-up retail model in which customers pay to have electronic devices recharged [2], [3], [4]. Energy kiosks often provide a range of energy-intensive services such as refrigeration or rental of battery kits [4], [5], [6]. Nearby houses, businesses and social service centers may be powered via a wired connection, and sundries and mobile phone credit may be sold to encourage a steady flow of customers [4], [6].

Energy kiosks are often custom-designed for their particular location and application. Several design approaches are possible, including the use of IEEE Standards [7], [8], but custom design approaches are more common. There is an abundance of literature detailing the bespoke design of off-grid systems, including energy kiosks [9], [10], [11], [12], [13], [14], [15], [16]. A criticism of these reports is the design approaches are not generally applicable and the suitability of their designs is not verified *ex post*.

This paper contributes to the extant body of work in two unique ways. First, the authors draw upon their experience in designing and implementing energy kiosks in Sub-Saharan Africa [2], [6] to present a general approach for energy kiosk design. The design of an energy kiosk in Chalokwa, Zambia is used as a specific example. Second, data collected from the Chalokwa kiosk is used to compare the design assumptions with actual operating conditions. The "closing of the loop" on energy kiosk design adds insight not found in most literature, making the Chalokwa kiosk a uniquely available case study which can be used as a demonstration of this design process.

The remainder of this paper is arranged as follows. Section II describes the challenges of designing an energy kiosk. Section III outlines the proposed design template and lists the requisite flow of information in the process. Sections IV and V describe the assumptions made in sizing the kiosk and simulation results used to obtain a finalized design. Section VI summarizes the design of a remote data logger, which is developed in parallel to the kiosk design and used for system maintenance and future data. Section VII provides a synopsis of the implementation and a validation of the design process. Conclusions and future work are presented in Section VIII.

II. Energy kiosk design

A. Chalokwa energy kiosk scope

The general design approach will be discussed in the context of a recent collaboration by Kilowatts for Humanity (KWH) and the General Electric (GE) We Share the Power program to implement an energy kiosk in Chalokwa. This rural community is located in Zambia's Southern Province on the bank of the Zambezi River (GPS coordinates: S16.28°, E28.83°); the village has no current source of electricity and is 20 kilometers away from the nearest electrified town. Chalokwa itself has approximately 300 households, although there are five nearby villages that bring the number of homes in the area to around 2000. The most common sources of employment are fishing, farming, and trading. The climate and lack of vegetation provide an ample solar resource, making Chalokwa an ideal candidate for a solar energy kiosk.

B. Design challenges

The primary challenge in designing an energy kiosk for a village similar to Chalokwa is the uncertainty involved with the consumption and production of energy in the community. When introducing electricity into an impoverished community for the first time, it is difficult to estimate the level of investment in the project; as such, the kiosk needs to be designed to appeal to the needs of the community while also being robust enough to provide uninterrupted service, often under a limited development budget. The method used to develop the Chalokwa kiosk is presented in detail in the following sections as a generalized design template; future projects can follow the outlined iterative process within their specific project constraints, permitting a more efficient design of the energy system as more empirical data becomes available.

III. Energy kiosk design protocol

The process diagram used for the Chalokwa energy kiosk design is shown in Fig. 1. A summary of each step is discussed in the following sections.

A. Assessment trip phase

In order to determine the capability of the community to support an energy kiosk, in addition to the available renewable energy resources and local geography of the area, the design team must conduct an assessment trip. Community surveys are conducted to evaluate current expenditures on energy use and the willingness to pay for electricity. The revenue from the community members is critical for the long term sustainability of the kiosk; more detail about the surveys conducted in Chalokwa can be found in [17]. A potential site for the energy kiosk is selected based on proximity to the community and an appropriate renewable energy source, such as a river for hydropower or an open space for photovoltaic (PV) panels. While a number of other important tasks are conducted, such as designing or selecting an appropriate structure, procuring the land deed for the kiosk and developing relationships with the community leaders and a local non-governmental organization (NGO), these are not the focus of this paper and will not be discussed. The renewable energy source and the anticipated electricity consumption of the community members are of primary interest for the technical design; these are dictated by the site determination and the community surveys, respectively.

B. Budget

Ultimately, the selection of the kiosk components is governed by the available budget. While some projects develop a microgrid for a predefined load and arrive at a budget estimate afterwards, the assumption for this scale of project is that the design team has been awarded a grant and is sizing the kiosk in such a way to maximize the available energy with respect to the budget constraints. The available funds govern the selection of kiosk components.

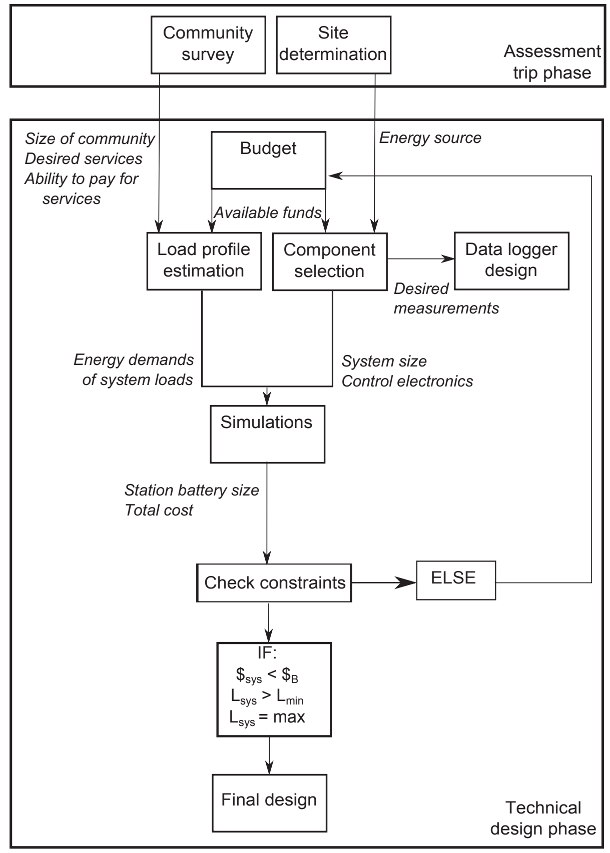

Fig. 1. Iterative process used to develop the technical design for an energy kiosk. Critical information passed out of each step is provided in italics. The design constraints include the system cost ($\$_{\mathrm{sys}}$), the equipment budget ($\$_{\mathrm{B}}$), the system capacity ($\mathrm{L}_{\mathrm{sys}}$), and the minimum required system capacity ($\mathrm{L}_{\mathrm{min}}$).

C. Load profile estimation

The load profile refers to the energy demands on the system; this may involve charging battery kits or cellular phones, powering a freezer, electrifying nearby buildings, or a range of other services. The power draw of these devices will be highly time-dependent, and will vary both hourly (as devices are connected and disconnected from the grid) and seasonally (as the demands for different types of energy change). This variability introduces a substantial level of uncertainty into the system design. For a proposed selection of devices, it is necessary to develop an average load profile with reasonable confidence bounds on the power draw of the devices.

D. Component selection

The components of the solar energy system are selected to maximize the power delivered for the given budget constraints. The renewable energy source is chosen based on the site location, and the available budget dictates the sizing of the system and storage. The component selection typically makes some basic assumptions about the load profile - for example, that an AC power output is desirable, thus requiring the appropriate DC-AC conversion components - but can primarily be developed in parallel with the load profile. As such, it is necessary to determine both the system size and the required control electronics (charge controllers, inverters, etc).

E. Simulations

For the energy kiosk to support the assumed load profile, the station batteries must store a sufficient amount of energy to power a nominal load profile during interrupted electricity generation times. As both the energy consumption of the kiosk and the availability of the energy resource can vary hourly, weekly, and seasonally, computational tools are useful for analyzing the performance of the system over a full year. Publicly available software packages are used to determine the number of panels and batteries required to support the provided load, and the resulting system cost is calculated.

F. Data logger design

The ability to remotely monitor the performance of the energy system is vital for real-time fault detection, long-term system maintenance, and providing load profile data for future projects. Remote data logging systems can be installed to measure electrical (currents, voltages, kilowatt-hours) and physical (temperature, solar irradiance, etc) aspects of the system; furthermore, this data can be transmitted through a local cellular network so that these properties can be monitored remotely [18]. A data logger system can be developed independently from the kiosk itself, although the desired measurements of the system need to be provided for the final design.

G. Final design

A final design is one that fully supports the estimated load profiles, maximizes the available energy that can be delivered by the kiosk, and meets budget constraints. In some cases, this system may be fabricated by the designer; however, in the method outlined in this paper, the final design is used as the basis for a Request For Proposals (RFP) which is sent to energy contractors that are local to the country. Selecting a contractor which is in close proximity to the kiosk location greatly facilitates future maintenance of the kiosk. The RFP process is not discussed in detail in this paper; however, any proposed design submitted by contractors is verified by the design engineers and validated using the simulation tool used to size the original design.

IV. Load profile estimation

The challenge with specifying a load profile for a community that has no previous experience with electricity use is the inability to establish potential market trends. Surveying the community during the assessment trip phase provides some data, although it can be incomplete or inaccurate [17]. The best solution is to establish clear expectations based on empirical data from the power use of similar villages and to scale these results to the population of the new community. Typical services that have been popular in previous installations include cell phone charging, lighting, radios, TVs and cooling/ice production [4], [5], [6]. The job of the designer is to estimate a reasonable load for each of these (or other) services; in the case of KWH, as an emphasis is placed on the communal improvement of the village, a local community center such as a church or school is often electrified for a reduced rate.

It is helpful to categorize the load profiles into groups based upon what, where and when they will be used; the categories defined for the Chalokwa kiosk are listed in Table I. Portable Battery Kits (PBKs) are not used in Chalokwa, but are included in the table due to their increasing prevalence in off grid energy projects [6]. This load assumes that the battery kits are charged at the energy kiosk, not at home with a separate solar panel. Distribution loads, or power supplied to a building adjacent to the kiosk, can be advantageous from a community development standpoint but are difficult to predict and subject to significant transmission losses. The category with the highest level of uncertainty is the freezer, as little data exists which characterizes the actual load profile of off-grid freezers. Variables such as volume of ice, frequency of opening and rate of material exchange all affect efficiency and therefore power consumption; furthermore, the freezer will run overnight when the station batteries can not be replenished by the solar panels, results in a higher effective energy cost.

The selected categories can be scaled to fit assumed need and budget restrictions; typically, all capacities should be estimated conservatively by assuming a maximum power consumption of the devices. As the energy requirements of the community will likely shift as the market develops, it is important to retain circuit flexibility and to continually add to an empirical data library that can be used for future microgrid installations. Overestimating the consumption of the kiosk loads provides an energy margin that can be reallocated when new electricity enterprises are introduced.

The daily load profiles developed using these assumptions are plotted in Fig. 2. The ‘flat day’ load profile, shown in Fig. 2a, assumes all modeled devices have a binary on/off characteristic. This provides a baseline representation of the kiosk power consumption and establishes maximum circuit capacities, although it is somewhat unrealistic; for example, it is improbable that the same number of cellular phones are always being charged. In order to provide a better estimate of how the loads will vary during an average day, the total load of the flat day profile is scaled to match empirical data from a previous energy kiosk [5]. Individual load profiles (freezer, lighting, cellular phones and distribution) are scaled to fit this new value of the daily profile. The results, shown in Fig. 2b, indicate that the peak load will occur near 21:00 as the distribution loads increase in the second half of the day.

This approach to load sizing requires some basic experience with energy kiosk use. The flat day profile will serve as a useful first approximation for kiosk design; however, given the availability of empirical data, this model should always be refined if possible. As a result, the adjusted load profile in Fig. 2b was used to simulate the Chalokwa energy kiosk. The designed system capacity is still much greater than the

TABLE I
LOADING ASSUMPTIONS FOR VARIOUS KIOSK SERVICES.

Load type	Duration assumptions
Kiosk	• Estimate number of 10 W interior LED bulbs during operating hours • Estimate number of 10 W exterior (security) LED bulbs used during night hours • Chalokwa kiosk: 2 interior bulbs, 4 security bulbs (total of 20 W and 40 W)
Cellular phones	• Estimate the number of phones to be charged per hour • Assume 1.5 W phones that take 6 hours to charge • Chalokwa kiosk: Maximum of 35 phones draw 52.5 W • Chalokwa kiosk: Over an 8 hour day, results in an average consumption of 40 W
PBKs	• Assume that a PBK needs to be recharged every two days • Assume that system capacity is not sufficient for inrush charge surge of all PBKs • Design a charging schedule so that no more than 25% of the PBKs are charged at a time
Distribution	• Determine the use of the circuit, ie, lighting or laptop power • Chalokwa kiosk: A daily lighting load of 250 W
Freezer	• Determine minimum and maximum power draw • Assume number of times per day ice is made • Assume the frequency of freezer cycling • Chalokwa kiosk: Min/max power of 150 W and 400 W • Chalokwa kiosk: One ice cycle per day • Chalokwa kiosk: Assume nominal draw of 150 W

maximum values of 410 W or 370 W shown in the figures, permitting future kiosk expansion.

V. SIMULATIONS

A. Available software tools

There are a wide variety of software solutions for sizing an off-grid solar system. The most basic are targeted at Western homeowners curious about adding solar to their property [19]. At the other end of the spectrum are professional grade solar design tools, ranging from stand-alone applications [20] to plugins for architectural software [21]. These tend to promise more accurate models in exchange for more information from the user, and can present a significant learning curve; they can also cost hundreds of dollars per year in licence fees.

The preferred software solution of KWH is the Hybrid Optimization of Multiple Energy Resources (HOMER) code. Originally developed by the National Renewable Energy Laboratory (NREL), HOMER is now a commercial product, but legacy versions are available for non-profit and educational use [22]. HOMER simulates an entire year in one-hour increments. The user may supply a full year's worth of solar irradiance and electrical load, or monthly averages, to which HOMER applies a probability distribution. HOMER then searches a user-defined solution space for the cheapest system that satisfies the load. The strength of a HOMER model depends directly on the quality of the solar and load data. Under default settings, HOMER will interpret load input as mean values, with considerably higher peak loads. When the input

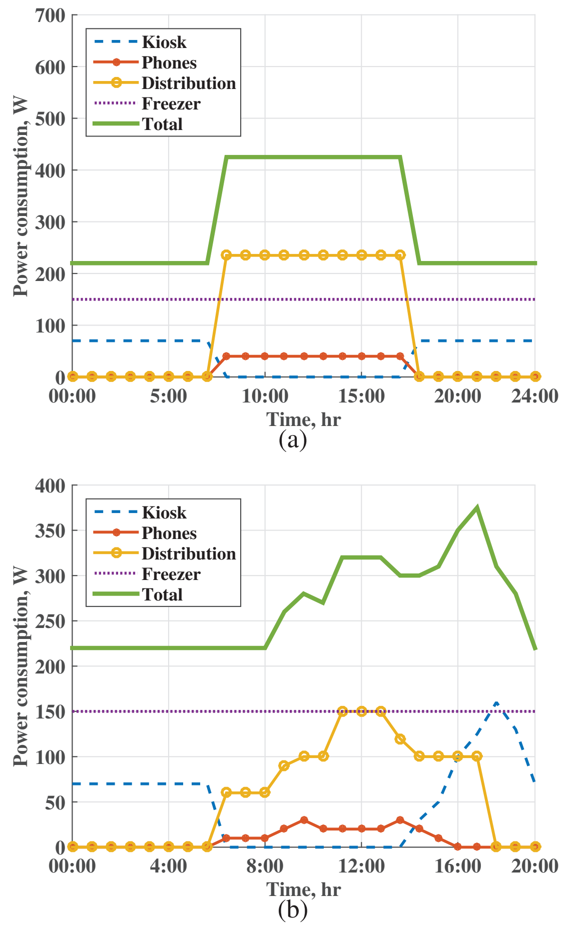

Fig. 2. Estimated load profiles for the Chalokwa energy kiosk, assuming (a) flat daily profile and (b) adjusted profile based on empirical data assumptions.

is instead a maximum guaranteed load, HOMER will oversize the system. Additionally, the solution space must be carefully chosen so that HOMER can find an appropriate system.

B. Simulation results

The legacy versions of HOMER search through combinations of electrical components (in the case of the Chalokwa kiosk, this includes PV modules, batteries and inverters, hereby referred to as the "HOMER items"). Systems that can not meet the prescribed load for the duration of the entire year are eliminated. It is not uncommon for an initial run to have no feasible solutions, requiring the user to expand the solution space. HOMER then ranks the remaining feasible solutions by cost, and outputs the cost and specifications of the cheapest system. Additional costs, such as wiring and installation fees, need to be estimated by the user. The parameters of the HOMER model are then varied and the simulation is run repeatedly until a database of acceptable design solutions has been developed. The HOMER costs and additional costs are compared with the project budget; if the costs are considerably higher than allowed for in the budget, the scale of the load profiles and/or the scope of the project may have to be reduced.

A representative set of HOMER outputs are shown in Fig. 3; while much more data is available from the simulation, these results are of significant importance for determining if a system is appropriate for a specified load. Fig. 3a shows a representative result for a week of system operation, including the power generated by the photovoltaic panels, the power flowing into and out of the system batteries, and the prescribed load profile. Note that the load profile is shown as a negative value to match the sign convention of the system batteries, where negative power represents current flowing out of the batteries. Fig. 3b shows a histogram of the state of charge of the battery over the year-long simulation; the critical result is that the battery reaches a depleted state of 50% charge for only 371 hours. This indicates that the system should not experience a power outage more than 5% of the year. Therefore, this proposed system represents a good solution for the prescribed load profile shown in Fig. 2b and again in Fig. 3b.

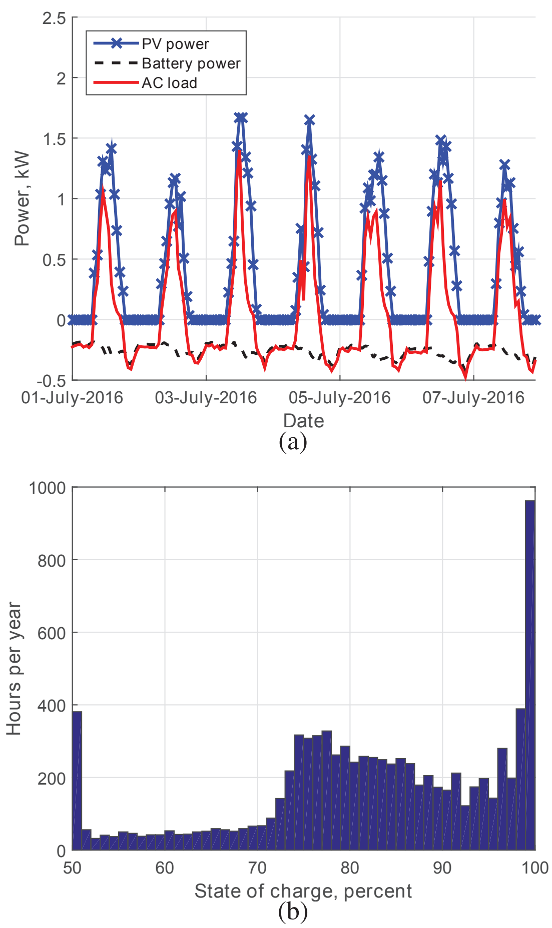

Fig. 3. HOMER outputs for Chalokwa variable profile depicting (a) representative daily values for the collected photovoltaic (PV) power, power flow in and out of the station batteries, and the prescribed AC load, and (b) histogram of the predicted number of hours per year the battery will experience a given state of charge.

VI. Data logging and transmission

A. Communication

The data collected is most useful if it is transmitted regularly to a server, where it can be stored and scanned in real-time for important information. Even in off-grid locations in less economically developed countries, reliable cellular networks are frequently available and can be used to transmit data packets to the server. Data can be transmitted via SMS (short message service, commonly referred to as text messaging) or via TCP (Transmission Control Protocol) or UDP (User Datagram Protocol) internet protocols. For the Chalokwa kiosk, TCP/IP was selected because it transmits persistently until it receives confirmation of data receipt. This feature of TCP/IP makes the data stream much more consistent through time, where UDP/IP and SMS would only make one transmission attempt and would not receive any return information about the transmissions receipt.

B. Data

The data desired for transmission is highly system dependent; however, several points in the system can be strategically selected to provide critical information regarding system health. The system battery temperature and voltage should be monitored to mitigate the chances of damage, fire or explosion. DC power from the solar panels or charge controller provides a measurement of the power generated by the system, whereas the DC power through the inverter provides an estimate of the power consumption of the kiosk loads. Power is calculated by measuring the DC current using a current transducer (CT) and multiplying this value by the battery voltage. The data points and sensors for the Chalokwa kiosk are listed in Table II.

C. Data reduction

The measurements of the solar power, DC power draw, and AC power consumption of the system make it possible to record and analyze daily energy consumption as well as the time histories of power consumption on daily, monthly, and yearly time scales. These measured load profiles can be compared with the estimated load profiles discussed in Section IV and used to refine the assumptions that go into the design process. Furthermore, KWH provides free access to their kiosk data, providing real world baseline data that can be used by other groups designing energy kiosks [23]. Finally, by configuring simple server side scripts to compare incoming data to acceptable values, it is possible to autonomously notify kiosk operators of potential problems so that they can be quickly addressed. For instance, applying Kirchhoffs current law and subtracting the solar current from the inverter current provides the current that flows into and out of the station batteries. The product of this battery current and the battery voltage defines the total power that has flown into and out of the batteries, which provides valuable information about the battery's life, as well as providing data to guide future predictions about maintenance schedules.

TABLE II
SENSORS AND DEVICESUSED IN THE CHALOKWA ENERGY KIOSK DATA ACQUISITION SYSTEM

System measurement	Sensor/Device	Purpose
Station battery temperature	DS18B20 digital thermometer	Ensure batteries do not overheat
Station battery voltage	Voltage divider circuit	Ensure batteries retain appropriate charge; voltage divider steps battery voltage down to an appropriate voltage for the data logger
Solar/inverter current (charge controller to DC bus)	HST21 direct current transducer	Calculate power draw and generation
Inverter output, kiosk/distribution/freezer circuits	Huabang DDM30SC AC pulse energy meters	Measure total energy consumption

VII. SYSTEM IMPLEMENTATION: CLOSING THE DESIGN LOOP

A. System architecture

Following the design process described in Sections III - VI, a final design for the Chalokwa energy kiosk was obtained. For a given budget in the order of US$10,000, the expected loading profile required a 2.4 kW array of solar panels, a 1600 VA/24 VDC inverter and two strings of 2×12 V, 220 Ah station batteries, giving the station a storage capacity of 10 kWh. The primary loads expected to be supported by the kiosk were a freezer, lighting for the kiosk and an adjacent schoolhouse, and cellular phone charging. This design left substantial available power for new electricity enterprises to be developed by the local community over time. The proposed system architecture is summarized in the diagram in Fig. 4.

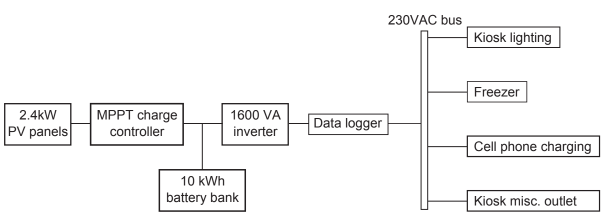

Fig. 4. Proposed system architecture of the Chalokwa energy kiosk.

B. Implementation

The installation of the Chalokwa kiosk took place over the course of a week in the end of June, 2016; an image of the completed energy kiosk is shown in Fig. 5. Following the commissioning of the system, kiosk services were made available to the community and data acquisition was begun to monitor the energy loads and system performance. The loads of the various kiosk components are of primary interest, which can be compared with the expected loads used in the design and used to validate the design process. One modification to the proposed architecture shown in Fig. 4 is that during the implementation trip, it was determined that the local school building did not have a strong enough need for electrification to justify the monetary and energy costs of running a 200 meter distribution wire; as a result, no distribution loads were connected.

Fig. 5. South face of Chalokwa energy kiosk.

C. Comparison with predicted results

The data transmitted from the Chalokwa kiosk was separated into daily records and an ensemble average was computed to estimate the nominal daily load profile measured by the DAS; the relative error associated with this averaging was also computed, and a selection of these results are plotted in Figs. 6 - 10. The nominal profile was computed using data from July 16, 2016 through August 4, 2016; this limited set was selected as it was observed that it took nearly two weeks for the freezer to reach its operating internal temperature, likely because it is located on the warmer north-facing side of the kiosk and is not rejecting heat efficiently. Currently the freezer is holding a nominally constant value of $T = -18.7°$C, and the measured power through the inverter clearly shows the duty cycles of the compressor (although these are diminished on the averaged load profile as the cycle does not always begin at the same time each day). Real time data is available for viewing at [23].

The data in Figs. 6 - 10 indicates that the power consumption of the kiosk follows a repeatable daily pattern, as indicated by percent errors in the order of 10% of the average values (with the exception of the numerical artifact in Fig. 6, where the nighttime solar power is near zero and the relative error is not of interest). Freezer operations have contributed the majority of business for the kiosk, such as selling ice and frozen meat; correspondingly, the power consumption of the

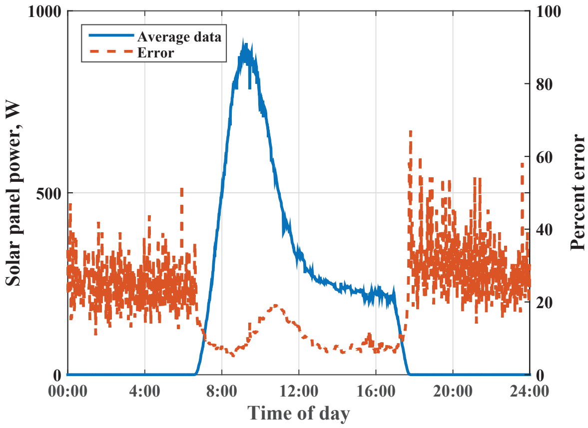

Fig. 6. Measured solar power from PV panels.

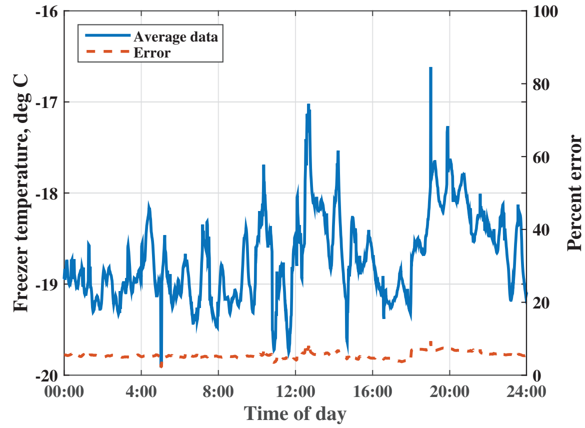

Fig. 9. Measured internal freezer temperature.

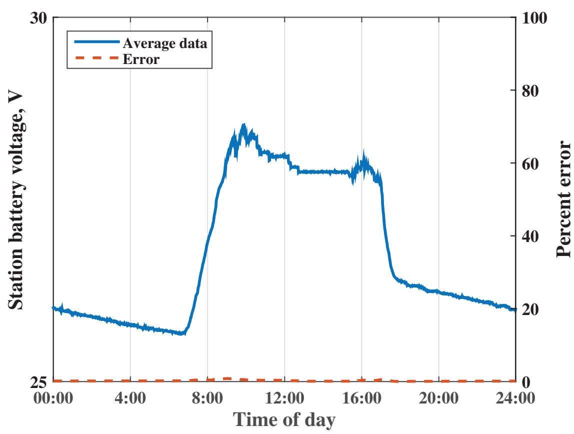

Fig. 7. Measured station battery voltage.

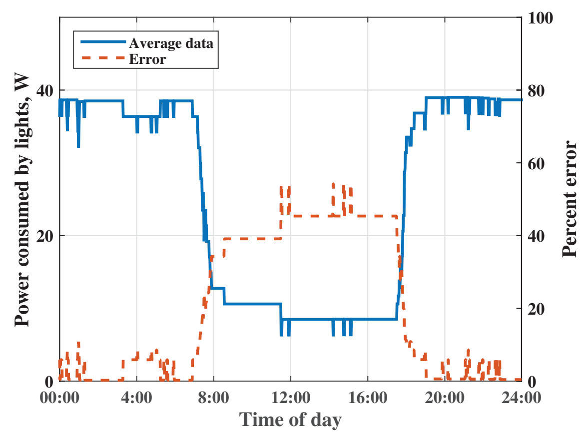

Fig. 10. Measured power consumption of security lighting.

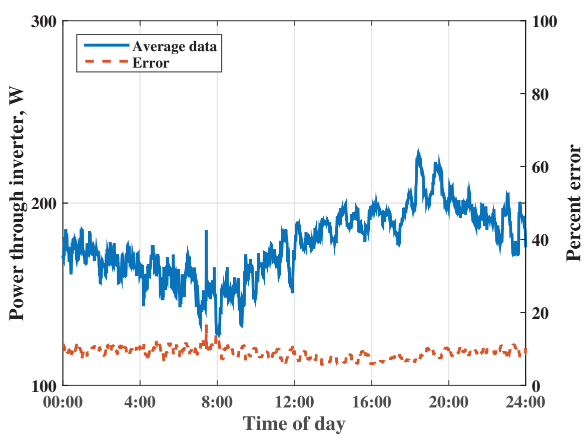

Fig. 8. Measured power draw through the inverter.

freezer comprises the majority of the nominal load. The other significant source of power consumption is the security lights for the kiosk, which are left on overnight and consume a total of 40 W. The temperature inside the freezer is maintained at a nominal value of $T = -18.7°\mathrm{C}$, with the most significant amount of variation of all the data. This is partially due to the unsteady nature of the freezer compressor as well as the variability of the demand placed on the freezer, as it is frequently opened and closed to be loaded or unloaded during the day. As the temperature inside the kiosk rises in the afternoon, more power is required to maintain this nominal temperature; this is evident in the increased power drawn through the inverter in the afternoon, as depicted in Fig. 8.

In Fig. 11 the measured load profile is plotted against the adjusted load profile from Fig. 2b with the distribution loads subtracted out. An order of magnitude agreement is clear, as is the predicted trend of peak power consumption in the early evening; the primary difference between the two cases is that the freezer power consumption was overpredicted in the design phase by approximately 50 W. This conservative estimate means that the annual battery performance will be even more robust than the predicted state of charge; rerunning the HOMER simulation with the updated load profile gives a state of charge histogram that shows the station battery will spend only 47 hours per year in a 50% state of charge, or only 0.5% of the time instead of the 4% frequency computed using the predicted load profile. This result indicates that not only was the predicted model accurate enough to provide a basis for the kiosk design, but the estimates were conservative enough that approximately 90% of the system power remains available for future expansion of the kiosk business.

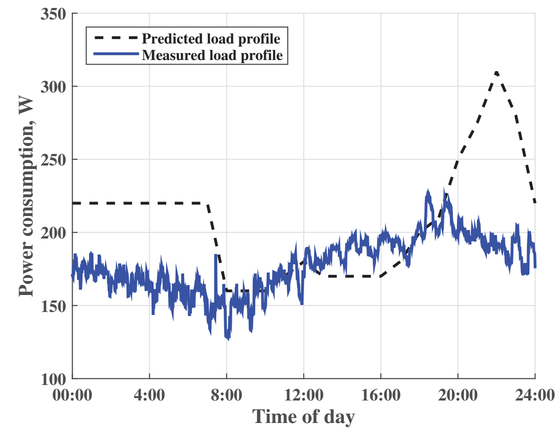

Fig. 11. Comparison of predicted and measured daily load profiles.

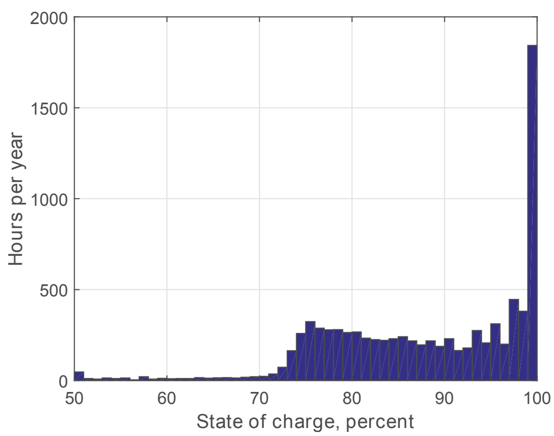

Fig. 12. Updated state of charge histogram using measured daily load profile.

VIII. Conclusions and Future Work

This paper has described a generalized design methodology for off-grid energy kiosks, using the development of a kiosk in Chalokwa, Zambia as a representative case study. The uncertainty of how electricity will be used, lack of available power consumption data and solar resource variability make it inherently difficult to estimate system load profiles. An iterative design process is used to compare a series of kiosk systems to ensure that they can provide uninterrupted coverage while remaining under an allotted budget. The flow of information between different design subsystems is a critical component of this iterative process, and is outlined in detail in this paper. Ultimately, a final system design may be obtained and implemented with a reasonable degree of confidence. Measured results from the Chalokwa kiosk validate the assumptions made in the developed load profile and suggest that the procedure outlined in this paper is a viable strategy for future kiosk development.

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