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System for Off-Grid Renewable Energy Monitoring

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Abstract - ***Understanding the efficacy of RETs used in off-grid settings can help make these systems more viable. Technology for remote monitoring of RET installations in developing countries is promising, with a wide variety of setups and purposes being explored. We evaluate the pros and cons of recent remote monitoring projects in Malawi, the Gambia, and Zambia. Remote monitoring app's potential to make off-grid RET more sustainable is studied with several theoretical orientations of the technology.***

Keywords—remote monitoring, renewable energy, off-grid, appropriate technology, mini-grid, sustainability, solar PV

INTRODUCTION

Energy for All (SE4ALL), an initiative launched in 2012 by UN Secretary General Ban Ki-moon, has helped to accelerate international momentum toward the development of renewable energy [1]. SE4ALL aims to 1) guarantee that all people have access to modern energy services; 2) double the global rate of improvement in energy efficiency; and 3) double the share of renewable energy in the global energy mix. The emphasis of power sector development for growing states in Sub-Saharan Africa (SSA) [2] has been on strengthening and expanding the main grid and adding additional generating units to meet increased demand.Despite this focus, there are still major discrepancies. The overall rate of electricity in SSA is 64%, with urban and rural populations respectively at 13% and 5% [3]. The rates of electrification in the countries where the case studies were conducted are shown in Table I [3, 5].

This paper argues that applying available communication technologies has the potential to improve the contribution of rural off-grid RETs by providing data on the technical system performance and by opening up potential for remote control. The case studies in this paper present some of the expected and realized benefits of different configurations of remote monitoring systems (RM).

A brief description of the need for improved evidence and learning in rural electrification projects is provided in section II. Sustainability issues common in rural off-grid RET systems are set out in Section III along with a literature review of recent RM deployments in developing countries and a theoretical discussion of the value of RM in addressing sustainability issues. Case studies of recent and ongoing deployments of RM are presented in section IV. The paper concludes with a discussion on how the case studies address sustainability, their strengths and weaknesses, and future directions will be discussed.

IMPROVED EVIDENCE AND KNOWLEDGE FROM RURAL ELECTRICITY PROJECTS IS ESSENTIAL.

While the International Energy Agency estimates that almost $1 trillion would be needed to achieve universal energy access by 2030, SE4ALL has only obtained 3% of this amount so far [3]. All urban areas and 30% of rural areas would be supplied by expanding main grids, with the remaining demand met by mini-grids (65%) and stand-alone off-grid installations (35%). Off-grid and mini-grid technologies are expected to provide 55% of the projected increase in power availability [6].

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National electrification plans in SSA have lofty goals for expanding grid coverage. To get to 51% electrification by 2030 [8,] the Zambian government plans to invest USD$1.1 billion on its Rural Electrification Master Plan. The Malawi Rural Electrification Programme (MAREP) lays out the country's plan to provide power to 70% of the country's rural residents by 2020. High access rates may not be attained for decades, even with the most effective rural electrification projects [9].

A recent study in Malawi [10] noted that insufficient supervision and resulting proof of the successful portfolio of initiatives contributed to the delay. It seems that data and sufficient analysis of the effects of measures to increase electricity in rural areas are few in general [4]. True enough, Bernard [7] notes that despite ongoing financing for RE initiatives, there is little empirical data to back up their claimed degree of effect. Next, we'll look at why RET initiatives that don't connect to the grid tend to fail. It is obvious that preventing failure and enhancing future deployments requires gathering information for learning about which sustainability aspects must be addressed and how important those elements are in various local situations.

Problems with long-term sustainability and remote monitoring

The long-term viability of renewable energy technologies in areas without access to the grid

To provide energy services to the rural poor with little impact on climate change, off-grid decentralized RET solutions are theoretically feasible [11]. Additionally, communities may use off-grid options as a temporary fix until the main grid reaches them, which might take years or never [4]. Because grid expansion benefits the comparatively less impoverished rather than the poorest, off-grid options might be seen as more equitable and reach the poorest more directly. The Bondo micro-hydro 75kW program in Malawi is one example of an off-grid electrical RET. Another example is the use of pico sized solar PV lanterns, which are tiny LED lights with a small solar cell and rechargeable battery combined into one unit. The residential, educational, and healthcare sectors are typical targets for mid-scale solar PV and wind projects.

A typical set-up might include solar panels (or a wind turbine), a charge controller, a bank of 12 V lead acid batteries, energy-efficient light bulbs, and an inverter to convert DC electricity into AC current. Community ownership and involvement, technical, economic, institutional, and social sustainability are all areas where off-grid RETs might benefit from more stringent requirements [12], [13]. The significance of each pillar of sustainability cannot be stressed, even while the emphasis of RM in this work is on technical sustainability challenges. On the social side, the inclusion of community stakeholders and the need to provide proof of community buy-in protects marginalized members of the community. One of the numerous policy initiatives aiding the industry as a whole is the government's institutional responsibility to encourage the private market growth of off-grid rural energy alternatives. While a hands-off tariff policy, as has occurred intermittently in Kenya over the past 30 years, has allowed for comparable solar PV rates of dissemination to those in South Africa [14], weak policies that fail to promote key off-grid RET (i.e. tariffs on solar PV) can prevent projects from even starting. Financially, providing initial access and continued service doesn't always work without creative finance methods. Long-term repayment plans with low initial costs, group-based financing, and repayment options that accommodate irregular revenues are all examples (for a more in-depth look at the difficulties of financing for the world's poor, see [15]). The literature and case studies provided in this article indicate a promising role of RM for technical sustainability; nevertheless, further study is required to understand the relevance of these challenges and their cross-linkages with other sustainability pillars. Here are some of the most pressing concerns in regard to technological sustainability:

- There is a lack of uniformity in technical design, which may cause a component to fail repeatedly.

- A prospective requirements analysis should be used to determine the project's scope. Overuse may occur when demand exceeds supply, which can happen with a tight price structure.

- The establishment of substantial technical capability is essential for the development of a long-term maintenance plan of these systems, which are deployed in inaccessible regions of developing nations.

Lead acid station batteries need special care and may not last as long as anticipated. The system must be developed taking into account the capabilities of the operators and service personnel.

- Determination of the system fault cannot be taken for granted as the available data (often elicited from nontechnical system users) may not be sufficient to assess the problem without a detailed site survey; when failure occurs, it can be impossible to find technicians to repair complex systems.

The Importance of Off-Grid Renewable Energy Monitoring

Cellular networks are the primary means of communications accessible when thinking about RM solutions for off-grid electricity projects in impoverished nations. With an estimated 648.4 million mobile phone subscribers in Africa as of 2011 [16][17], cellular networks have seen tremendous expansion across the continent. These cellular networks are so advanced that they can compete with and sometimes even outperform their developed-world counterparts. This allows for the transport of data in a variety of formats, from the bare-bones SMS to the more complex GPRS, 2G, and 3G internet connections. There is a growing corpus of research on the configurations and applications of RM and wireless sensor networks (WSN) in aid programs. Some examples of applications are the flood control and warning system proposed by Pathan et al. [18] and the irrigation management system shown by Mafuta et al. [19]. These non-energy-related examples nonetheless show how current communications technology may be put to use in underdeveloped regions and prove that the technology is transferable. Several issues have been raised that threaten the long-term viability of off-grid RET systems. It is obvious that RM technology has features that might be used to tackle some of these issues. In particular, a strong operations and maintenance plan is essential for long-term technological viability. It is essential to promptly detect issues, report them, and resolve them. It might take a long time and a lot of effort to acquire the essential skills in rural areas far from urban centers. In addition, until an acceptable level and quality of indigenous talent base is formed, there is an urgent need to solve the maintenance difficulties confronting systems constructed during the interim period. These urgent maintenance needs can be met via RM technology. As part of a maintenance agreement after the first installation, RM might provide a hand to RET's personnel and engineers. Time-based maintenance is problematic when technical resources are already stretched thin, since the time and cost of traveling to distant sites is a considerable added expense that may shorten the lifespan of these systems. Through the use of RM, technical support may better allocate its time and resources to the installations that really need help. For remote and home-based SHSs, RET personnel may collect and maintain accurate data on system health, as detailed in [20].

MALAWI, GAMBIA, AND ZAMBIA: CASE STUDIES

In order to compare and contrast different methods and to offer some proof of the diverse roles RM plays in off-grid RE projects, three recent and continuing case studies are described below. Malawi's Renewable Energy Acceleration Programme [22] is the first case study. The Scottish Government is providing funding for MREAP so that 1) the country of Malawi has a better enabling environment and evidence-based policy for RET, and 2) more low-income areas in Malawi have access to modern energy services. The Electronic and Electrical Engineering Department at the University of Strathclyde runs the altruistic Gambia Solar Project, which has brought electricity to eight outlying schools and two medical facilities. The University of Strathclyde has integrated a Vertically Integrated Project (VIP) on 'Sustainable Energy for Development' into its undergraduate curriculum with the Gambia Solar Project. A RM unit, conceived and prototyped as part of this effort, is now ready for use on solar farms in The Gambia. The last case study is grounded on a practical monitoring strategy and a recent field test of a 160Wp micro-wind turbine in Zambia [23]. Seattle University, the Seattle Chapter of Engineers Without Borders, and the IEEE PES Community Solutions Initiative were the driving forces behind this effort. The goals of the wind turbine project were twofold: The goals of this study are twofold: 1) to assess the technical field performance of commercially available wind turbines in the United

States, and 2) to calculate the potential wind resource at the site of installation.

Distributing Information from Remote Monitoring in Malawi for Use by Many

MREAP incorporates a work package to implement and test an RM system in addition to the delivery of community-based RET initiatives. This RM system is being tested at several PV installations in the rural Chikwawa area. The goal of the MREAP remote monitoring component is twofold: (1) to collect technical monitoring data to allow assessment of system performance and technical sustainability, and (2) to explore the potential of technical RM as a central component of the operations and maintenance strategy for any large-scale deployment of RET in Malawi. MREAP plans to collect data across a range of key learning issues and synthesize and distribute knowledge on 'what works where and for who' in regards to RET in Malawi by establishing research and monitoring and learning frameworks throughout the project. The RM system will use a cellular network as an intermediary between the Remote Station (RS) and the Central Monitoring Station (CMS) in order to report the PV system's performance metrics. The system will record parameters such as solar radiation, ambient temperature, battery voltage, charging current, load current, and battery voltage. These values will be acquired at regular intervals, saved locally, and then uploaded to the CMS's database. In case of any problems with the PV system or the system itself, the system will send an alert to the management team.

RS, or Remote Station

The RS will consist of a PV system outfitted with a Wireless Sensor Network (WSN). When compared to proprietary solutions, open-source methods have several benefits, including lower costs, more flexibility, and independence from a single provider. Therefore, the RS will be built onto an Open WSN node. In particular, the Wasp mote node developed by Labellum [24] is used for transport. A lithium battery, recharged by the node's solar panel's specialized connection, provides power for the node. By selecting this option, the RS will no longer be reliant on the PV system, allowing it to function normally in terms of providing the PV performance metrics to the CMS at all times. Multiple RSs, as seen in Fig. 1, may talk to the CMS across the cell network. Each RS will have a central hub where information from remote nodes may be processed and compiled. Independent RSs will be installed at a single site, as shown in RS 2 in Fig. 1, but at the expense of additional running costs in the form of SMS charge if the distance between individual PV stations exceeds a 100m limit and a line-of-sight communication mode between sensor nodes is not feasible.

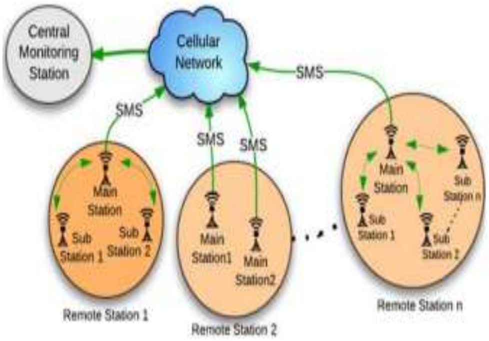


Fig. 1- Remote Monitoring system architecture showing several Remote Stations

In addition to the RM system being scalable in terms of the number of RSs that can be integrated, the RSs themselves are also flexible in terms of the number of sensors that can be added. The architecture of the main station node in the Rescan can be configured to incorporate various sensors including current, voltage, solar radiation, and temperature sensors. A ZigBee module will be used to receive data from sub-stations within its locus. Furthermore, this node will be equipped with a GPRS module for sending SMSs to CMS. The load current sensor will be used to investigate the loading condition of the PV system. Specifically, any system overload will be reported to the monitoring personnel. On the other hand, during the day a low battery voltage and no charging current report will imply that either the charge controller or the PV array is faulty. However, the PV array voltage sensor will indicate if indeed the PV array is faulty; in this case the defective device will obviously be the charge controller. With this arrangement the monitoring personnel will be well informed in real-time of the type of system fault that will have occurred and hence promptly conduct the specific maintenance work.

Central Monitoring Station (CMS)

The CMS is the heart of the RM system. This will aggregate and process data received from all RSs and will have up to three parts. The first part is the monitoring personnel who will receive fault alarms directly onto their mobile phone for prompt reaction to the particular PV system. The alarms may come directly from RSs or from the server housed in the CMS. The second part is the server which is a computer equipped with a broadband dongle. This part will be used to receive, store and display both current and historical performance data of all PV systems. The third section is the internet connectivity which will allow the system performance data to be accessed across the globe.

Gambia - Making Ambassador Projects More Sustainable

The Gambia Solar Project and other local charities, NGOs, and residents have learned the hard way that off-grid energy systems need constant maintenance and upkeep to function properly for the duration of their useful lifespans. Information collected by an RM device may provide regional help with system administration, upkeep, and operation. The University of Strathclyde's Gambia Solar Project and student-led VIP on 'Sustainable Energy for Development' have resulted in the development of an RM unit, with a prototype soon to be installed on solar arrays in the Gambia.

This project use 2G cellular networks to relay information back to a web server database, from which it can be accessed and interpreted clearly and intuitively by web apps (including android). The suggested method streamlines the hardware needed in nation and the system implementation, as opposed to existing efforts that employ a local base station to collect data and update a web application. In order to achieve their goal of increasing the availability and reliability of the energy system they support, RM systems must ensure that the complexity of their own infrastructure does not harm dependability. By eliminating the need for a physical base station, the total price of remote condition monitoring may be reduced, making it more attractive to both developers and end users. The current 2G networks support this, but at a slower rate and with a smaller data allowance than is typical for other uses. As opposed to video streaming, for example, the quantity of data that has to be captured and transferred is very minimal, hence high speed and capacity 3G or 4G networks are unnecessary. The Gambia, like the rest of sub-Saharan Africa, has a robust GSM network (Fig. 2). ICT, and mobile internet in particular, are a rapidly expanding sector in SSA. Since 2008, 3G networks have expanded fast [17], [18], while 2G networks are still widely available. The environmental and technical data that indicates system utilization and asset (mainly battery) health are the primary foci of the remote data gathering in this project. Battery health monitoring may save you money by alerting you to when your batteries are about to die from abuse. It is possible to monitor and control battery use, leading to uniform (and more cost-effective) wear throughout the asset base. As the operator of a community charging station gets more knowledgeable about the technical aspects of running a PV charging station, more authority may be given over to them.

When asset optimization is combined with remote condition monitoring, designers and developers have greater access to information about asset deterioration, allowing them to make design improvements and provide operational support to the operator without being on-site. The hardware can determine the battery health, disabled status, average loads over time, and update a database for numerous charging stations based on information received from a remote microcontroller through GSM/GPRS networks. In order to refresh the batteries, the Java server may transmit data back to the charging station.

System users, operators, maintenance technicians, and designers all have access to different levels of data, so it was important to create a web application that could present this data in a way that was understandable to them

Fig. 2 - Example of System Information Displays

In anticipation of the eventual proliferation of android phones in SSA, a mobile application has been developed and thoroughly tested. It can read a QR code on a consumer battery and display information about that battery based on the battery ID that was retrieved from the server. The user will be able to monitor the health, lifespan, and remaining charge (in hours or days) of their battery. The charging station owner may be able to remotely deactivate batteries based on condition and use data. The hope is that the technical, economic, and commercial data provided by this RM system will aid in the management of system lifecycles and asset conditions on a local and global scale. Depending on the kind of user logging in (e.g. user, operator, or designer), different data and remote control (i.e. activate, disable battery assets) will be made accessible. The RM unit's requirements in terms of specs, power use, and prices may be lowered by processing the incoming data on a server. The advantage of this method is that algorithm modifications may be made during the following use/charge cycle by sending control signals back to specific units over a two-way communications connection.

Open source data collection and low-cost infrastructure in Zambia

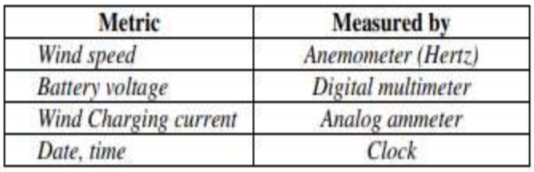
The Zambian project was similar to many others in that it had a small budget and concentrated on a specific area of study. The monitoring strategy used was very cost-effective, costing just around USD $150 for the whole 12-month monitoring period. Due to the lower price, an SMS phone was selected over an internet phone. The phone was first purchased for roughly USD $13, and there is no ongoing expense beyond the USD $0.10 per month for sending international text messages. The project could not afford the high monthly cost of an internet phone. As of August 2012, the measuring campaign has already begun.

The system included: low-cost short message service (SMS) phones, a digital multimeter for manual monitoring, operator education, and a software service to receive SMS messages.

The wind turbine's operator (and ultimate recipient) was taught to track numerous variables (Table II) every morning, lunchtime, and night. A logbook would include a line for each recording. The wind turbine was equipped with a compact control box that had analogous meters for monitoring the voltage and charging current of the system. The time of day and the readings from the control panel would be recorded by the operator. Then, he'd use the anemometer's readings of the wind's frequency to calibrate the mustimeter. The total time required is around 5 minutes. The finished product would be a three-line SMS to a US phone number, representing one day's worth of measurements.

TABLE II

SELECTED REPORTED MEASUREMENTS



Metric	Measured by
Wind speed	*Anemometer (Hertz)*
Battery voltage	*Digital multimeter*
Wind Charging current	*Analog ammeter*
Date, time	*Clock*

A software system was set up to receive, validate, and collect the data submissions.

The software system consists of:

The use of one phone number and the ability to send and receive SMS messages through a twilio.com account.

• A server on the Elastic Compute Cloud (EC2) of Amazon Web Services (AWS). This "micro" sized server is free since Amazon Web Services has a price category for extremely tiny servers.

The usage of SMS phone numbers must be supported. Any time a mistake is made in the system or a message of assistance is typed, a notification is sent to all users. The unique software consists of less than a hundred lines of code, yet it is very responsive. When an issue occurs when capturing data, it alerts the user within 20 seconds, while it's still possible to fix the problem. All data received, genuine or not, is recorded alongside the program's determination of its validity. There may be improved error handling in later versions of the software. The collected information is readily accessible through a web page at any time. For the last six months, the software system has cost around $40 to run. The program took around 8 hours to create in total.

The software system called for assistance for almost 12 hours. The future will include support for the automated system, allowing it to record the whole conversation between the operator and the users of the assistance service. While a radio-based system would have generated more and better data, a support operator-driven data collection system offers its own set of advantages. The three things that money can't buy—education, accountability, and engagement—were readily available after transitioning to a less sophisticated method of data collecting. Ease of implementation was also important for a project implementation approach that couldn't provide a year of on-the-ground assistance. This application highlights the possibilities of remote monitoring of micro-energy plants with no or low expenditures.

Whether or if this method is superior for enhancing the sustainability of similar initiatives requires a more extensive review time. Problems with accuracy, missing data, and a malfunctioning monitoring system (anemometer wire) have all been encountered to far. However, the implementation team may profit from this realistic method. For starters, it facilitates remote data collection for projects without a local monitor. Second, the project team now has a direct line of contact with the operator, resulting in higher levels of both responsibility and participation. Third, daily uploads of data that are both transparent and immediately accessible, allowing the project team to respond immediately to any SMS outages or errors (including system failures). Fourth, the instruments used by the system are cheap and easily accessible. Fifth, the cost of data collection is substantially lower than other options (about USD $150 annually), since obtaining the information from a logbook would need at least an overseas post and more than likely an international trip.

CONCLUSIONS

To monitor RET systems in developing countries, RM is now being implemented in Malawi, Zambia, and The Gambia, with slight variations on a similar concept. Accurate and virtually real-time system monitoring of RET installations is helpful for improving sustainability. The technical infrastructure necessary to put RM into practice already exists, and it is backed by a growing network of engineers and other experts throughout the world.

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