Remote Monitoring of Off-Grid Renewable Energy

Case Studies in rural Malawi, Zambia, and Gambia

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Abstract **- Increased understanding of off-grid renewable energy technology (RET) performance can assist in improving sustainability of such systems. The technologies for remote monitoring of RET deployments in developing countries are promising with various configurations and usages being tested. Recent applications of remote monitoring technologies in Malawi, Gambia, and Zambia are presented along with their respective strengths and weaknesses. The potential for remote monitoring applications to improve sustainability of off-grid RET is explored along with some theoretical directions of the technologies.**

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

I. INTRODUCTION

International momentum towards the development of renewable energy has been boosted by the launch in 2012 of the UN Secretary General Ban Ki-Moon's Sustainable Energy For All (SE4ALL) initiative which seeks to: 1) ensure universal 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 [1].

For developing countries in Sub-Saharan Africa (SSA) the emphasis of power sector development has been on the strengthening and expansion of the main grid along with installation of additional generating stations to meet growing demand [2]. Despite this emphasis, significant gaps persist. Overall, electrification rates in SSA are 64% and 13% for urban and rural populations [3]. Table I presents the electrification rates of the case study countries [3], [5].

TABLE I
ELECTRICITY ACCESS IN CASE STUDY COUNTRIES

Region	Urban electrification rate %	Rural electrification rate %
Gambia	*60*	*30*
Malawi	*35*	*2*
Zambia	*48*	*2*

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.

II. NEED FOR AN IMPROVED EVIDENCE AND LEARNING OF RURAL ELECTRIFICATION PROJECTS

The IEA predicts a requirement of nearly USD $1 trillion to realize universal electricity access by 2030, however SE4ALL has secured only 3% of this at present [3]. Universal access would be achieved through expansion of main grids supply to power all urban centers and 30% of the rural areas, while the remainder is split between mini-grids (65%) and stand-alone off-grid installations (35%). Practical action projects 55% of additional electricity access will be through off-grid and mini-grid systems [6]. In SSA, national electrification plans have ambitious targets for future access. Zambia's Rural Electrification Master Plan aims to spend USD$1.1 billion by 2030 to achieve 51% electrification [8]. In Malawi, the rural electrification strategy is defined by the Malawi Rural Electrification Programme (MAREP) that has the aim of increasing access to electricity to 30% of the population by the year 2020.

Even successful rural electrification programs can take decades to achieve high access rates [9]. A contributor to this delay is the lack of oversight and subsequent dearth of evidence created on the success of the portfolio of projects (as cited in a recent evaluation in Malawi [10]). Availability of evidence and adequate analysis of the impacts of rural electrification interventions appears also to be limited more generally [4]. Indeed, Bernard [7] reports that while funding for RE programs continues, very little empirical evidence is available to justify their supposed level of impact.

The poor sustainability of off-grid RET projects is discussed in the following section. Clearly, it is vital to generate evidence for learning on what factors of sustainability must be addressed, and their relative importance in different local contexts to avoid repetition of failures and to improve future deployments.

III. REMOTE MONITORING AND SUSTAINABILITY ISSUES

A. *Sustainability Challenges of rural off-grid RE tech*

Off-grid decentralized RET solutions are recognized as technically feasible for delivering energy services to the rural poor with minimal negative impact on climate change [11]. Moreover, off-grid solutions have the advantage of being an interim measure during the wait for the main grid to extend out to their communities, a process which may take many years, if ever [4]. Since grid extension favors the relatively less poor rather than the poorest, off-grid approaches can be argued to be more equitable, reach the poorest most directly.

Off-grid electrical RETs range from Pico sized solar PV lanterns (small LED powered lights that have a small solar cell and rechargeable battery embedded within one unit) to larger scale mini-grids, such as at the Bondo micro-hydro 75kW scheme coming online in 2013 in Malawi. Mid-scale installations are often targeted at homes, schools and health centers using either solar PV or wind generation. A standard system would consist of a solar panel array (or wind turbine), charge controller, 12-volt lead acid battery array, efficient lighting and an inverter for AC power.

Various sources have provided guidelines to improve sustainability of off-grid RETs [12], [13] for the following areas of sustainability: community ownership and engagement, technical, economics, institutional, and social.

Although the focus of RM in this paper concerns primarily technical sustainability issues, the importance of each pillar of sustainability cannot be overstated. Socially, engagement with community stakeholders and the requirement of evidence of community buy-in ensures that the entire community is represented, including vulnerable groups. Institutionally, the government has a role to play to support the private market development of off-grid rural energy solutions – one of the many policy measures supporting the sector as a whole. Weak policies that fail to promote key off-grid RET (i.e. tariffs on solar PV) can prevent projects from even starting, whereas a hands-off tariff policy, such as occurred intermittently in Kenya in the past 30 years, have allowed for comparable solar PV rates of dissemination as in South Africa [14]. Economically, innovative financing techniques are sometimes needed to provide initial access and ongoing service. Examples of this include longer-term repayment schemes with minimal upfront fees, group-based financing, and flexible repayment option for non-regular incomes (see [15] for a detailed study on financing challenges for world's poorest). While further research is needed to explore the role of these issues and their cross-linkages other sustainability pillars, the literature and case studies presented in this paper identify an encouraging role of RM for technical sustainability. The key technical sustainability issues identified are set out below:

- Lack of standardization of technical design, which can lead to systematic failure of a component.
- Scaling of the project should be influenced by a forward-looking needs analysis. As demand grows (especially with a rigid pricing system), systems can be overused when the system reaches its limits.
- Developing a long term maintenance strategy of these systems, deployed in remote areas of developing countries, will require the building of significant technical capacity
- Lead acid station batteries need to be cared for properly and their durability can be overestimated, failing surprisingly sooner than expected.
- The system must be designed with the skill set of the operators and repair technicians available. When failure occurs, it can be impossible to find technicians to repair complicated systems.
- Determination of the system fault cannot be taken for granted as the available data (often elicited from non-technical system users) may not be sufficient to assess the problem without a detailed site survey.

B. *Value of Remote Monitoring for off-grid RE*

When considering RM solutions for off-grid electrical installations in developing countries, cellular networks are the main communications infrastructure available. Cellular networks have experienced huge growth in Africa, estimated at 44% since the year 2000 with the 2011 estimate of mobile phone subscriptions 648.4 million [16][17]. With these cellular networks matching and even surpassing the functionality and coverage of networks in developed countries, data transfer is now feasible in a simple text format via SMS or with varying bandwidth of internet connection via GPRS, 2G and 3G.

A growing body of literature is available on configurations and uses of RM and wireless sensor networks (WSN) for development projects. Some uses include Pathan et al. [18] who propose a system for flood control and warning and Mafuta et al [19], who demonstrate an irrigation management system with WSN. While these examples exist outside of energy projects, the technology is transferrable and demonstrates the application of modern communications technology in developing countries.

The sustainability of off-grid RET systems faces several challenges, as highlighted in earlier sections. Intuitively, RM technology offers functionality that could help address some of these challenges. In particular, technical sustainability relies on a viable operations and maintenance strategy. Faults have to be identified, reported and rectified in a timely and efficient manner. In remote rural communities the amount of input required to achieve the necessary skill sets is a significant, time-consuming exercise that may take many years. In addition, there is a pressing need to address the maintenance issues facing systems built in the interim period until an adequate level and standard of indigenous skill base is established. RM technology can service these immediate maintenance requirements. RM can support RET technicians and engineers in fulfilling a maintenance agreement following the original installation. Time based maintenance with such stretched technical resource is impractical, where the time and cost of attending remote locations represents a significant overhead, which often undermines the longevity of these installations. RM can enable technical support to optimize its effort and resources by targeting those installations in most need. Reliable and current data on system health can be captured and supported by RET technicians as described for rural schools and home SHS systems [20].

RM can allow the designer to remotely manage the systems usage, and also help the end user understand how to maintain and prolong their system's life, and offer them more value. The RM data could feasibly be presented to the end user, albeit distilled to avoid overwhelming them with technical jargon and numbers. This can have the effect of gradually increasing their technical understanding, which can ensure the system is not abused and is used for the purposes and duty cycle it was designed for, and so improving its longevity.

RM would facilitate the management of multiple remote RET installations by one maintenance team located in a central location. Prompt reporting of the RET system performance metrics allows timely preventive and condition based maintenance work to be effectively conducted. Wider area awareness of system technical performance data such as battery health, charging profiles, and usage profiles would facilitate systematic evidence generation and learning. Maintenance processes could be improved by adopting technologies like SIMbaLink [21] which was designed to capture basic data from SHS in Ethiopia on battery health and panel health (voltages). The data would be reviewed then used by a central maintenance entity. Several scenarios were developed to estimate potential savings through the use of SIMbaLink.

Evidence for the viability of large-scale RET deployment is limited in most developing countries. Data sets on the actual performance of deployed RET systems are few and far between with efforts normally focused on deploying systems rather than monitoring performance. RM solutions facilitate data capture of key system performance metrics that would allow analysis and research to support improved system design and standards and feed evidence into national energy policy and strategy development. In addition, using these technologies for the remote capture of non-system data such as economic, societal and environmental data can be used to monitor and evaluate the socio-economic and environmental impact (both positive and negative) that the introduction of these systems have on the local community, their culture and surroundings, which in turn feedbacks to refine the design and deployment phases to meet the needs of the communities that these systems serve.

IV. Case studies in Malawi, Gambia, and Zambia

Three recent and ongoing case studies are selected and presented below in order to contrast various approaches and to provide some evidence of the various roles RM has in off-grid RE projects. The first case study is part of the Malawi Renewable Energy Acceleration Programme [22]. MREAP is funded by the Scottish Government with the objectives of:
1) Improved enabling environment and evidence based policy for RET in Malawi, and 2) Increased poor Malawian communities accessing modern energy services.

The second case study is from the charitable Gambia Solar Project, operated from the University of Strathclyde's Electronic and Electrical Engineering Department, which has electrified eight remote schools and two health clinics. In addition to the Gambia Solar Project the University of Strathclyde has introduced a Vertically Integrated Project (VIP) into the undergraduate student curriculum that focuses on 'Sustainable Energy for Development'. As part of this initiative a RM unit has been designed and a prototype built that is set for deployment on solar installations in the Gambia.

The final case study is based on recent field test in Zambia of a 160Wp micro-wind turbine [23] which implemented an affordable monitoring approach. The project was led by Seattle University, Engineers Without Borders – Seattle Chapter and the IEEE PES Community Solutions Initiative. The wind turbine project objectives were twofold: 1) to evaluate the technical field performance of off-the-shelf wind turbines currently available in U.S. market, and 2) to estimate wind resource at the particular installation location.

A. Malawi - Channeling Remote Monitoring Data to multiple stakeholders

Additional to the delivery of community based RET projects, MREAP includes a work package to deploy and test a RM system. The test sites for this RM system are PV installations deployed in the rural district of Chikwawa. The remote monitoring aspect of MREAP is intended to both gather technical monitoring data to allow assessment of system performance and technical sustainability and also to investigate the viability of technical RM as a key component of the operations and maintenance strategy for any large scale deployment of RET in Malawi. By implementing both research and monitoring and learning frameworks across the programme, MREAP intends to gather data across a set of key learning topics and synthesize and disseminate evidence on 'what works where and for who' regarding RET in Malawi.

In order to report the performance parameters of the PV system, the RM system will use a cellular network as a bridge between Remote Station (RS) and a Central Monitoring Station (CMS). Specifically, the system will capture PV array voltage, charging current, battery voltage, load current, ambient temperature, and solar radiation. These parameters will be gathered at predetermined intervals then stored locally before transmission to the database of the CMS. Accordingly, the system will alert the management personnel in case of any mishaps in the PV system or itself.

Remote Station (RS)

The RS will comprise the PV installation equipped with Wireless Sensor Network (WSN) devices. When compared to proprietary solutions, open source models have relevant advantages in terms of cost, personalization and independence from a single entity. Consequently, the RS will be based on an Open WSN node. In particular, delivery uses the Waspmote node by Libelium [24]. This node can be powered by a lithium battery which can be recharged through a dedicated socket for the solar panel. This option will make the RS independent of the PV system, hence, permitting a seamless operation of the RS in terms of reporting the PV performance parameters to the CMS regardless the healthy status of the PV system.

As shown in Fig. 1, several RSs will be able to communicate with the CMS via the cellular network. Each RS will have at least one main station which will be processing and aggregating data from far-off sub-stations. However, where the distance between individual PV stations exceeds a 100m limit and where a line-of-sight communication mode between sensor nodes is not feasible, 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 terms of SMS charge.

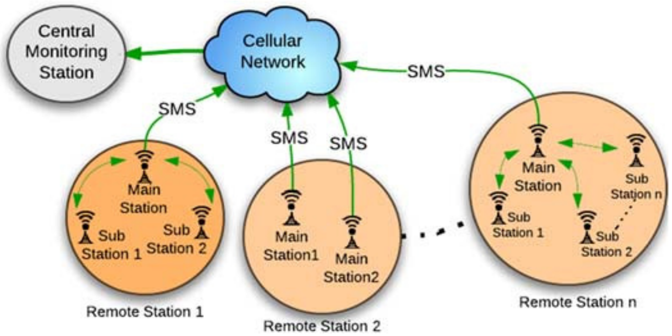

Fig. 1- Remote Monitoring system architecture showing several Remote Stations

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 RScan 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.

B. Gambia - Making Ambassador Projects More Sustainable

Experience from the Gambia Solar Project along with other charitable organizations, NGOs and local communities in the area, has demonstrated that there is a requirement for immediate support of off-grid energy systems in order to ensure that they continue to operate effectively for the duration of the system's lifecycle. Data collated from a RM unit can enable local support for system management, maintenance and operation. Through the University of Strathclyde's Gambia Solar Project and student led VIP on 'Sustainable Energy for Development' a RM unit has been designed and a prototype is set for deployment on solar installations in the Gambia.

This project uses 2G mobile networks to transmit data back to a web server database that can be accessed with a clear and user friendly data interpretation by web applications (including android). While many other projects use a local base station to receive data and update a web application, using the proposed approach simplifies the hardware required in country and the system implementation. RM systems are intended to improve the availability and reliability of the energy system they serve, therefore the complexity of the RM system should not compromise its own reliability. In addition, removing the cost of running and maintaining a local base station means that the overall cost of remote condition monitoring can be lowered, making it more viable to developers and users. This is possible over the 2G networks available, albeit at a lower speed and bandwidth than is used for other applications. The amount of data to be gathered and sent is relatively small compared to media streaming for example, so there is no need for high speed and bandwidth 3G or 4G networks. However, GSM networks are well developed in The Gambia as with most SSA countries, (Fig. 2.) ICT and particularly mobile internet is a major growth area for SSA. 2G networks are widespread and 3G networks have grown rapidly since 2008 [17], [18].

The remote data captured in this project focuses on environmental data and technical data providing an indication of system usage and asset (primarily battery) health. Calculating the batteries' state of health prevents sustained overuse and substantial shortening of battery life. Battery usage can be assessed and managed to allow an even (more affordable) state of wear across the asset base.

For community charging station solutions, as the operator becomes more technically astute in the operation of a PV charging station, more control can be devolved to them.

Fig. 2 - GSM coverage in The Gambia. Purple areas show GSM availability

Integrating asset optimization with remote condition monitoring allows system designers and developers to have more access to the asset deterioration data, meaning they can improve system designs for the future and can assist the operator in the system's operation while not requiring a physical presence at the installation.

The system hardware is capable of receiving data from a remote microcontroller over GSM/GPRS networks, calculating batteries state of health, disabled status, average loads over time, and updating a database of information for multiple charging stations. The Java server is then capable of sending data back to the charging station so that batteries can be updated.

A web application has been developed that can show the information in the database in a user-friendly manner (data presented depends on viewer, with different levels of information available to system users, operators, maintenance technicians and designers), using charts and tables where appropriate (Fig. 3.).

Fig. 3 - Example of System Information Displays

Finally, in anticipation of the future proliferation of android phones in SSA, an android mobile application has been developed and tested to scan a QR code (which would be associated with a unique consumer battery), and display information from the server's database about the battery ID embedded within the code. This can provide the user with an update on their battery's health, state of charge, remaining charge (in terms of time in hours or days) and life. The charging station operator can also remotely disable batteries based on the condition and usage information returned.

It is envisaged that this RM system will offer technical, economic and business information to help manage the lifecycle and asset condition of both individual and regional systems. Different levels of data and remote control (i.e. enable, disable battery assets) will be available depending on the user log on details (e.g. user, operator or designer). By conducting computations on the server from the data received the RM unit can be reduced in terms of specification, power consumption and costs. An additional benefit from this approach is that algorithms can be updated remotely and using a bidirectional communications link control signals can be sent back to particular systems with updates being applied when the asset in next used/charged.

C. Zambia - Shoe-string data gathering and open access technologies

The project in Zambia was not unlike many others with a very limited budget and primarily focused on a narrow research scope. A shoe-string monitoring approach was implemented that would, over the course of the 12 month monitoring period, cost only around USD $150. An SMS phone was chosen over an internet phone based on cost. Initial cost of the phone was around USD $13 with no monthly fee, and international text messages are USD $0.10. Monthly costs of an internet phone would have been prohibitive for the project. The measurement campaign was underway from August 2012 onwards.

The technology consisted of:

- An inexpensive SMS phone
- A simple manual monitoring process using a digital multi-meter
- Operator training
- A simple software service for receiving the SMS messages

The operator (and beneficiary of the wind turbine) was trained to take measurements daily (morning, midday, night) for several metrics (Table II). Each recording would be recorded as a line in a log-book. A small control box was built and installed along with the wind turbine which measured system voltage and charging current with analog meters. To record a measurement the operator would log the time of day and the measurements from the control box. He would then use a multimeter to measure wind speed using a frequency measurement from an installed anemometer. The whole process takes around 5 minutes to complete. When complete, three lines (i.e. one day of measurements) would be sent via SMS to a US phone number.

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:

- An account on twilio.com for sending and receiving SMS messages, including the rental of one phone number
- An Amazon Web Services (AWS) Elastic Compute Cloud (EC2) server. AWS provides very small servers in a free pricing tier, and this "micro" sized server is thus free of charge.
- Support users with SMS phone numbers. Each support user receives a broadcast of any help messages or data errors entered into the system.

The custom software is a very simple program consisting of only 100 lines - yet it provides a responsiveness that no human could produce. At any time of day, it responds within 20 seconds or so that there has been an error in the data recording, at a time when such errors can still be corrected. The program records all data received, valid or not, along with whether the program deemed it to be valid. Future versions of the program could have more advanced error handling. At any time, the data recorded to date can be retrieved by a simple web page. Total operating cost of the software system has been around $40 for a half year. Total development time of the software system was around 8 hours.

Total support time of the software system was around 12 hours. Future work is to create support for the automated system to log the whole conversation between the operator and the support users.

While there the alternatives such as a radio-based system, that would have resulted in superior quality and quantity of data, a data collection system driven by support operator has other advantages. Education, accountability, and engagement are all things money cannot buy, and all were abundant after adopting the lower technology data collection method. Ease of implementation was also very important for a project implementation approach that could not commit to a yearlong on-the-ground support.

This application demonstrates the capabilities to monitor micro-energy projects remotely using free services and at minimal costs. A longer evaluation period is needed to determine whether this approach is more effective in improving sustainability of like projects. The weaknesses experienced to date include a likely lack of accuracy, gaps in the data set, and monitoring system breakdown (anemometer wire). However as a pragmatic solution, there are benefits to the implementing team. First, for a project without dedicated in-country monitor, this allows the project team to gather data from afar. Second, a direct communication line is available for the project team to speak with the operator which improved accountability and engagement. Third, daily data uploads that are transparent and instantaneously available; the project team can react quickly if there is a gap in SMS or for an error (i.e. system failure). Fourth, the monitoring system uses widely available and extremely affordable tools. Fifth, costs for collecting data, around USD $150/year, are much reduced over alternatives; recovering the data in a log book form would require, at minimum, an international post and more likely an international flight.

V. CONCLUSIONS

The ongoing RM deployments in Malawi, Zambia, and Gambia represent variations of a central theme of using appropriate technologies to assist in the monitoring of RET systems in developing countries. The value of accurate and near real time system monitoring of RET deployments offer a promising pathway to greater sustainability. On a technical level, the technology to implement RM is available and is supported by a growing community of engineers and technicians internationally.

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