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ORIGINAL ARTICLE

Evaluation of IoT-based remote monitoring systems for stand-alone solar PV installations in Kenya

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Abstract

The deployment of remote monitoring systems based on Internet of Things (IoT) presents an opportunity to curtail operational and maintenance (O&M) costs associated with stand-alone PV systems. This study evaluates the characteristics of the commonly employed IoT platforms, their capabilities and associated O&M cost savings. Analysis of avoided field visit costs based on three remotely monitored solar PV sites is conducted through clustering of system faults and filtering out major ones that would warrant actual site visits. The obtained results are verified with information gathered from four other PV installer companies based in Nairobi, Kenya. Results obtained from the study show that majority of system faults can be monitored and often corrected remotely. Annual site-specific cost savings associated with IoT platforms range from \$2040 to \$3096. In comparison to ordinarily locally monitored systems, annual operation and maintenance costs can be reduced by 47–95%. This implies that it is now possible to adequately maintain healthy solar PV systems located in remote locations ensuring their longevity and convenience.

Keywords Real-time monitoring · IoT platform · Solar off-grid systems · O&M

1 Introduction

Solar photovoltaics (PV) technology is increasingly gaining grounds in most developing countries. Most of these countries, however, do not have sufficient grid networks to bring most of these new technologies and installations onto the mainstream electricity supply platform. Thus, most of the PV systems remain off-grid, independently providing power to a single or a number of consumers. Due to the nature of such off-grid installations; their sizes, remote locations, logistics, maintenance costs, etc., most installers find it difficult to adequately maintain them even within the specified warranty period [1]. Owners of such systems are also not adequately trained or prepared to manage the systems and failure cannot be ruled out despite proper design and installation [2].

Most grid-tied PV systems are designed with financial returns in mind and come with a structured, O&M arrangements and budget. However, off-grid systems usually have little or no such arrangements due to the associated costs and the individualized nature of the installer–client relation. In the past years, off-grid systems were solely the responsibility of owners after the departure of donors and/or installers from the individual projects. The greatest challenge with this arrangement is that most users or local technical personnel are not adequately trained to manage those systems. Most users have little or no idea about electrical systems. Moreover, retaining local personnel (usually casual or contract employees) who sometimes acquire some form of training during the commissioning process is very difficult due to the nature of their terms of service. Installation technicians also find it difficult and/or uneconomical to make long-term follow-ups due to the location of those systems [3]. The deficiency in technical understanding and lack of technical support leads to abandonment of most of off-grid systems in sub-Sahara Africa even due to very minor faults. Hence, users tend to revert to their former sources of energy such as diesel generators or even push for the more expensive grid power, making the

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solar investments redundant. Furthermore, majority of off-grid systems are either funded by donors or the government and hence the operational structure is rather weak. Replacement of components when they reach their end-of-life is rarely considered while very little funds are raised through such projects. This situation has made off-grid solar PV systems unsustainable, slowing the sustainable growth of the PV industry.

In recent years, novel business models such as Free-for-Service, Vendor sub-contracting (by governments) have rekindled interests and demand for off-grid installations although this places more burden on installers. Technical maintenance personnel have to visit installation sites more regularly to ensure that faults are kept at minimum. To maintain such a structured routine support mechanism, the cost of power becomes more expensive compared to the mainstream supply alternatives. This puts more financial pressure on the rural consumers making it unaffordable to most of them altogether without external support or some form of indirect subsidies. As a result, such programs have often failed because they are not economically sustainable [4]. In Kenya, for instance, the government plans to roll out more than 1100 off-grid installations under the Kenya Off-grid Solar Access Project (KOSAP) to provide power in communal facilities [5]. These installations will be installed and operated by local installer companies and hence structures must be put in place for long-term sustainability.

Kenya has a dynamic and robustly growing PV industry which presents some interesting opportunities for critically scrutinizing current trends in the PV industry. Due to the high costs of maintaining off-grid systems, the local PV industry seeks solutions that aim to reduce the costs rather than transfer this burden to the consumers. With the observed trends of system O&M shifting from the consumer to the service providers and the need to bring down running costs, remote monitoring systems are being explored. Several privately owned PV systems are remotely managed by installation companies. Application of IoT platforms is widely known to mitigate costs and losses in many fields [6] and further enables advantages of ‘Big Data’ [7]. This study seeks to assess the technical capabilities and benefits associated with the modern remote monitoring based Internet of Things (IoT) to manage off-grid PV installations. It is worth noting that several studies have previously been conducted on grid-tied systems as reported by Mukai et al. [8] but few or no such studies, to the best of our knowledge, focus on off-grid systems. The present study takes a case study approach based on existing and thoroughly investigated systems in different parts of the country to bring out the features and scope of management. This is verified via surveys of local installer companies. It further attempts to analyze technical cost reductions to the installers arising from incorporation of the IoT systems.

2 Study background

2.1 Significance of solar off-grid systems

In most Sub-Saharan countries and other countries alike in Asia Pacific, the Caribbean, for example, off-grid systems play a critical role in providing reliable power to users living very far from the grid network. Solar off-grid systems are attractive due to the general abundance of the solar resource in most locations. Besides, the cost of grid installations in remote, less populated rural settings in most parts of those regions is considerably expensive. Moreover, power supply from most grids is usually unstable [9] and even those connected to the grid usually, must have alternative sources of power supply to complement the grid. As such, off-grid systems have the potential to offer a more reliable, clean, and independent source of power. The off-grid PV industry has in the recent years also witnessed new entrants in the solar energy storage platform where, for example, Lead-free batteries, fuel cells and compressed air energy storage (CAES) have also curved a considerable niche in the market. With the increased variety of energy storage options, off-grid solar PV systems are bound to become more sustainable and even more popular for remote applications.

In the Kenyan context and as earlier mentioned, the PV market is further driven by the private sector and over the years, PV technology has generally gained considerable trust from users. This, supported by the global trend in embracing renewable and greener sources of energy has led to the growth of a very robust and dynamic regime of installer/end-user engagements. This relationship puts more responsibilities on the installer/contractor and assures quality energy service delivery to the end-user. This trend in conjunction with other discussed aspects is likely to give off-grid systems an upper hand in rural energy supply making it one of the most competitive option.

2.2 Architectural characteristics of common off-grid systems

In general, off-grid solar PV systems consist of solar PV arrays, a charge controller, a battery bank and an inverter as shown in Fig. 1. The DC system voltage usually ranges from as low as 12 V to 250 V depending on the size of the system. As pointed out by Tejwani et al. [1], the battery bank presents the weakest point of an off-grid system. The life of the battery is dependent on the available input energy (solar insolation) as well as consumption (user behavioral patterns). These two parameters experience natural mismatches and do also, individually fluctuate quite considerably. Aligning consumption to the available solar irradiance can help extend battery life.

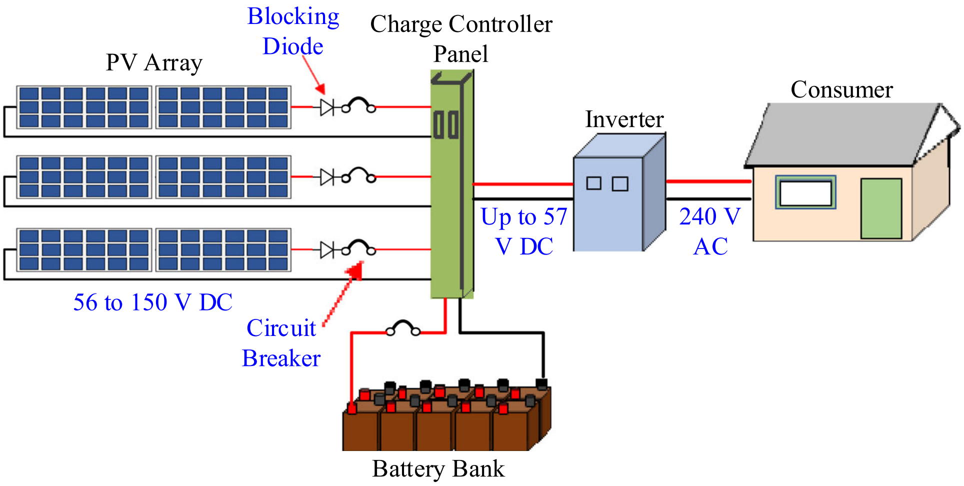


Fig. 1 General configuration of an off-grid system based on a maximum 48 V system

2.3 PV system monitoring and IoT systems

PV system monitoring is crucial for various reasons [10] and the concept of PV monitoring is common even in non-energy applications [11]. Monitoring regimes vary in frequency, i.e. periodic inspections (PIs) or continuous monitoring (CM) and also in the level of detail i.e., global or analytical monitoring. The choice is usually dictated by the type and size of system. Earlier commercial systems employed actual site monitoring (analytical) as demonstrated in Blaesser [12] to ensure that the quality of generated power was in accordance with the desired requirements. Later, combinations of computer-based analysis tools [13] and satellite-based irradiance estimation coupled with simulations were developed to remotely monitor the performance of solar PV systems [14, 15].

The IoT platform is an information sharing environment capable of coordinating analogous things with solitary identifiers, objects, mechanical machines, computing devices and digital machines [2] with minimal human interactions. It is applied in a wide range of sectors including healthcare, industry, automotive and home automation, home energy management, renewable energy systems, traffic maintenance, smart grids, micro-grids, intelligent systems and others [2, 16]. The IoT system architecture for PV system monitoring generally has three layers as presented in Fig. 2. The sensing layer contains the actual physical PV system components, data acquisition (sensors) and processing (microcontroller). The gateway link or network layer initiates data acquisition (communicates) from the first layer and transmits it to the third layer. The control or application layer provides for the human interface allowing them to observe, diagnose, analyze, and sometimes revert corrective actions via reverse communication. Commonly used microcontrollers, transceivers and IoT platforms have been reported by Priharti et al. [17].

Several research groups have developed varied IoT monitoring systems based on wired or wireless platforms. Wired systems and those based on Zigbee wireless communication modules are limited in spatial scope [18]. Wider scope is achieved using, for example, GSM- or Wi-Fi-enabled modules and internet or cloud platforms. A real-time PV performance monitoring and communication module that relays information using the system's DC wiring (power line communication—PLC) was developed by Sanchez-Pacheco et al. [19] while Madeti and Singh [20] coupled a similar data acquisition system to a Wi-Fi module transmission link. Ye Jihua and Wang [3] designed an IoT system with supervisory capabilities based on TinyOS. Wired and wireless PV panel monitoring algorithm have also been developed by several other research groups [10]. Low-cost performance monitoring and data acquisition systems for off-grid applications based on data logging [21], Arduino [22] and Visual Basic [23] have also been developed. Microcontroller-based and LabVIEW or MATLab combinations remote PV monitoring and fault detection softwares have been developed by several researchers [11, 20, 24, 25]. Mukai et al. [8] conducted a comparative study on the technical benefits of CM over PI based on roof-top grid-tied systems. Tejwani et al. [1] highlighted the pros and cons of computer-to-computer communication (Ethernet), embedded system to computer (GSM) and embedded system to embedded system (GSM, GPRS) and introduced an analog signal based GSM voice channel for communication of data between transmitter and receiver. An open-source IoT cloud platform based on Thingspeak has also been developed by several groups [17, 26]. Periera et al. [27] also developed an embedded IoT remote monitoring system based on Wi-Fi and cloud server for grid-connected

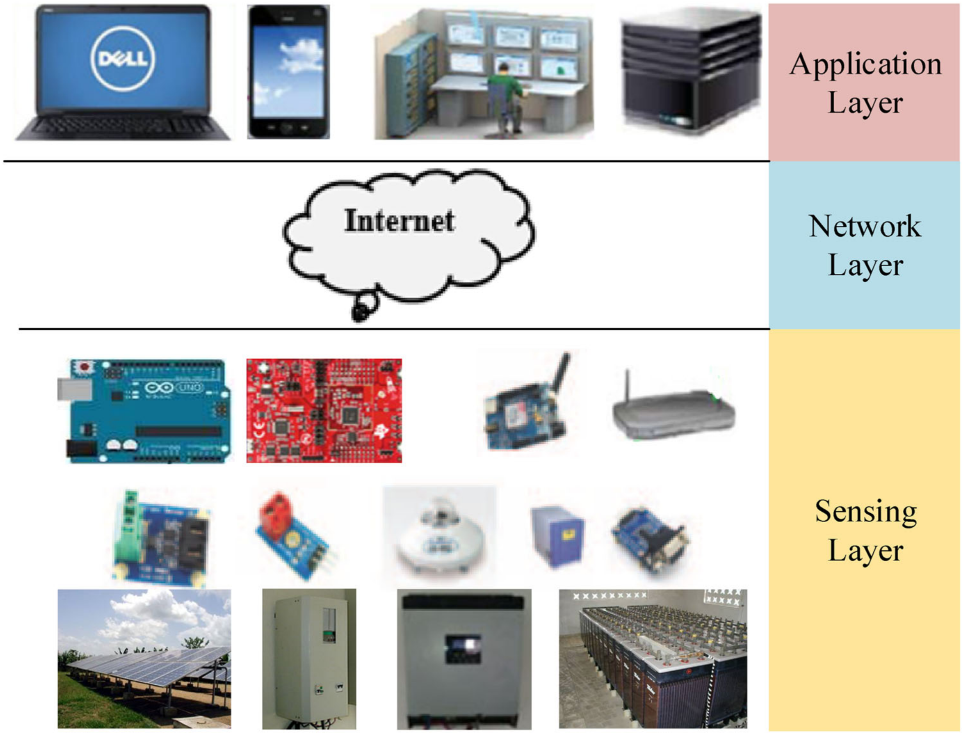


Fig. 2 Structure of IoT-based solar PV monitoring system

micro and mini PV systems. IoT has also been used for remote solar energy forecasting and management [28].

Modern remote web-based monitoring platforms are able to relay PV array voltages and currents, array tilt angles, PV and ambient temperatures, irradiance, wind speeds, dust, rain and/or snow levels [11, 24]. Details of remote solution algorithms currently employed in most applications have been expounded at length by several authors [1, 11]. Most modern commercial systems, however, still allow for performance visualization and analysis of transient phenomena only and key suppliers of these systems include; SMA Solar Technologies, Fronius International GmbH, InAccess Networks, Fat Spaniel Technologies, MorningStar Corporation, SolarMax, [29] Victron Energy, among others. Hence, it is now possible to provide the operator with key services such as control, monitoring, notification, reporting and data export via the internet platform [30]. The exploitation of Internet of Things (IoT) for remote monitoring and diagnostics has therefore become a common practice in recent years [31] and may become a prerequisite for systems situated in remote locations. An interesting study by Bisaga et al. [32] revealed usage of the IoT platform in customer billing and system monitoring for remote solar home systems (SHS) in Kenya and Rwanda. The use of IoT is rather extensive in the East African region where several SHS service providers depend on it to effectively manage the pay-as-you-go (PAY-GO) systems (ibid.)

3 Field study analysis methodology

3.1 System configurations

Over the years and with technological advancements, quite a number of off-grid configurations have evolved giving the installer and end-user some technical and economic advantages, respectively. In general, the load characteristics dictates the choice of the system to be adopted. Both single- and three-phase systems can be designed to suit individual customer's needs. Common off-grid systems serve both residential and commercial applications with distinct operation regimes and hence systems may further be optimized based on when peak load is expected.

3.1.1 Nighttime peak-load optimized systems

The most common designs are the charge controller + inverter configurations. These are generally designed for normal night-load scenarios. In this case, the demand and the solar radiation (supply) timings are generally out-of-phase such that energy is basically generated and stored for use during the night. The design and size are hence governed by the size of the load. This design is similar to that presented in Fig. 1. It is, however, possible to increase the capacities of the array, charge controllers and/or even add another inverter in parallel to the original one should the original one be smaller or in case of additional loads.

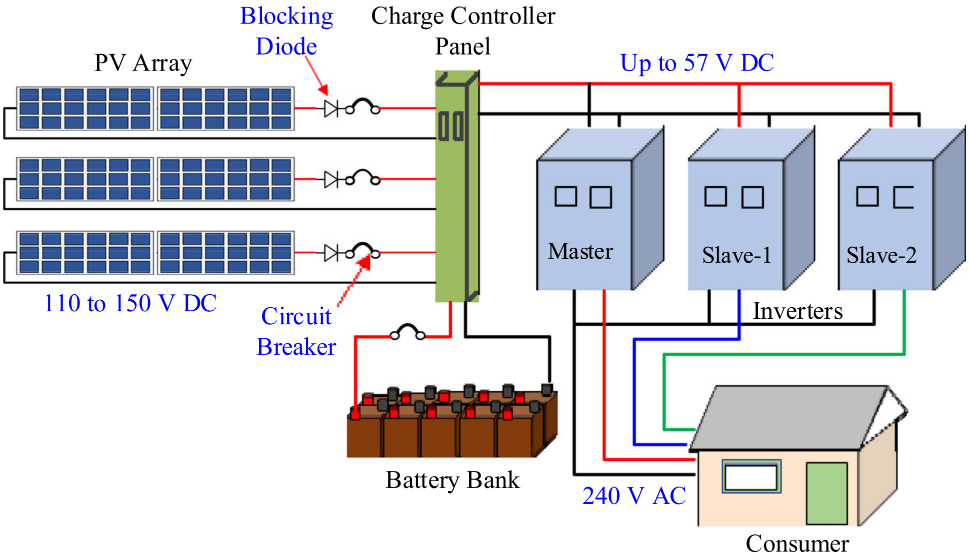


Fig. 3 Night-time optimized 3-Phase off-grid system

Figure 3 shows a more advanced three-phase configuration. The master–slave configuration is basically meant to provide three-phase AC power to the end-user. Inverters are configured where the first inverter or the main inverter is designated as the master and the other two automatically become slaves. As such, a minimum set of three inverters is used to make up this configuration.

3.1.2 Day-time peak-load optimized systems

The day-time optimized system or the grid-tie/inverter-charger design is quite suitable where the load is characterized by regular or sudden peaks during the day due to switching on of special daily-use appliances. To avoid use of a relatively large controller/inverter-charger setup, a grid-tie inverter is used instead as shown in Fig. 4. Whenever there is need to switch on the special and/or additional equipment, the second inverter (inverter-charger) switches to inverting mode drawing energy from the battery bank. When the load is switched off, the inverter-charger reverts to the charging mode. In this case, the peak load may be even twice the size of either of the inverters (grid-tie or inverter/charger).

Irrespective of the optimization type, O&M implications are similar in single- and three-phase cases. Three systems; one (1) that was single phase, and two (2) which were three-phase, formed the basis for the technical study aspects. Whereas the discussion is drawn from all configurations, the three chosen systems were optimized for night usage (Figs. 1, 3, respectively).

3.2 Parameter setting and monitoring

The three systems chosen for the study were arrived at based on their similarities in monitoring systems as well as the availability of comparable systems without the remote monitoring platform. Insights into their capabilities are demonstrated to orient the reader on common visual and analytical capabilities. In the management of off-grid systems, it is critical to promptly report any violations of the most sensitive aspects of the system. Due to the nature and role of the battery in off-grid systems, the battery voltage is crucial to monitor. A minimum allowable voltage is set, and any violations are remotely communicated. Other key aspects automatically reported on daily basis include solar irradiance, PV and ambient temperature, currents, battery terminal voltage, frequency, daily charging and discharged energy. The installer is also at liberty to remotely perform several corrective actions to stabilize the system. It is also possible to observe supply and consumption statistics and take necessary actions to manage the energy service delivery.

3.3 Cost of O&M

To realistically estimate savings on system O&M costs, expenditures incurred on conventional system maintenance are used as a reference. This is done to isolate, and then consolidate costs associated with individual technical personnel. A record of fault detection frequency, nature and time spent to resolve each problem is compiled. System faults are further clustered into three categories; (1) critical and urgent problems that would have warranted a technical personnel to visit the site, (2) critical and non-urgent problems that would have required the technical personnel to interrogate and guide the consumer in resolving them or leave them pending for future visits but would be injurious to the system, and (3) non-critical problems that the system would have survived for longer periods until a planned site visit. Serious problems

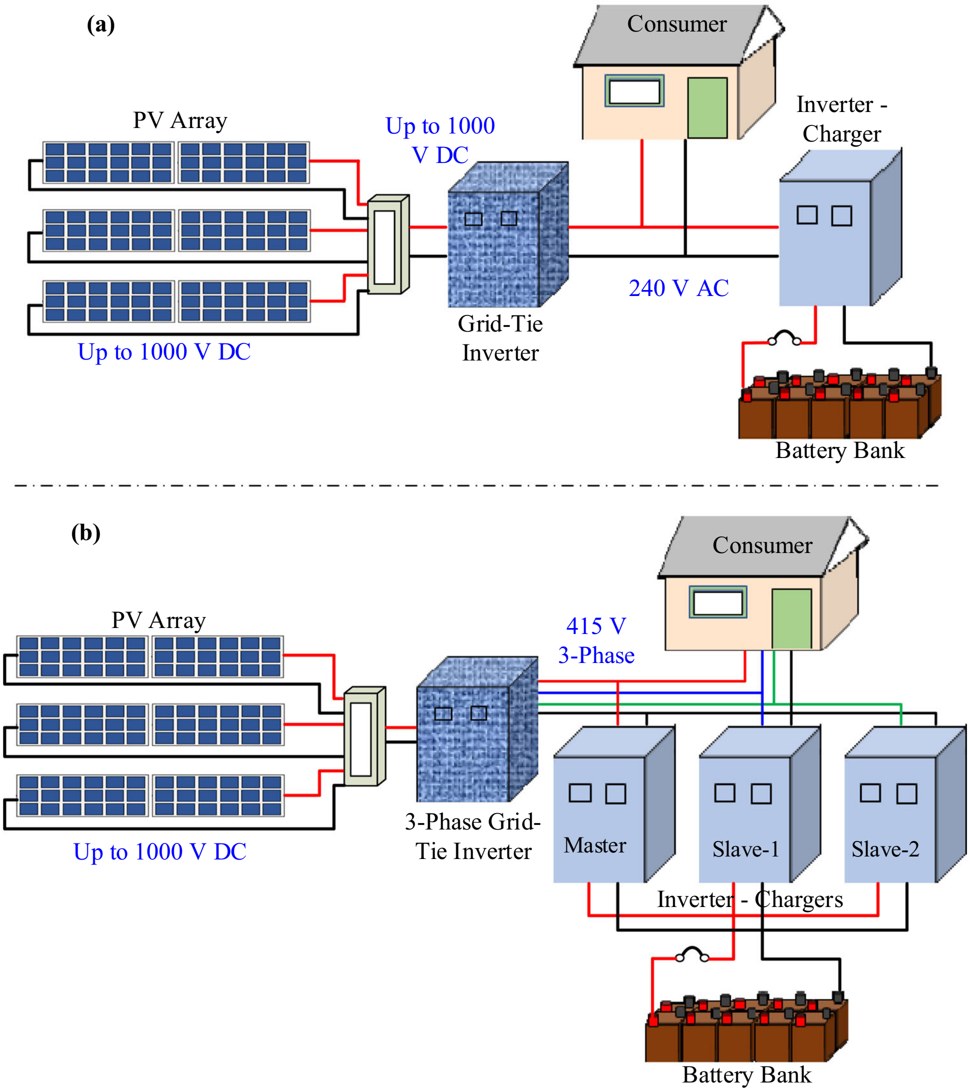


Fig. 4 Day-time optimized configurations; **a** single-phase design, **b** three-phase design

are equated to the costs incurred by the company sending at least two technicians to the site, normal problems are equated and/or compensate for the time spent by technicians in resolving issues remotely, while the minor problems are excluded in the analysis.

The three chosen sites and coded P (17.5 kWp), Q (6 kWp), and R (15 kWp), are located far from Nairobi at distances of 310 km, 320 km and 285 km, respectively. They are installed on two lodges and a research facility (not in any order). Technicians are ordinarily given some mileage and subsistence under normal site visits. The respective rates for the two are \$0.6 to \$0.8/km (two way) and \$150/day to \$200/day per technician. Due to the distance and nature of off-grid sites, a minimum of three (3) days is required for a technical site visit and involves a minimum of two (2) technicians. Remote monitoring on the other hand requires access to internet on a daily basis. For remote monitoring, it is assumed that during working days the extra usage of internet facilities by technicians is equivalent to what they would otherwise have used to make long telephone calls to the same clients. However, technicians incur some extra mobile data costs over the weekends at a rate of 500 Mbs/week which is equivalent to \$1.5–2.0/week and/or \$4.0/month. Those IoT running costs are indeed quite similar to those reported in Bisaga et al. [32] despite the systems being of different capacity ranges. Further, independent interviews with proprietors of four (4) off-grid PV companies are conducted to get their perspectives on the savings associated with the remote monitoring systems. Data and information gathered from the analysis of the three sites and the four installer companies is then used to estimate the cost savings associated with the remote platforms.

4 Results and discussions

This chapter gives a detailed analysis of the capabilities of deployed IoT platforms for remote monitoring of PV systems and the cost savings associated with their deployment. First, the chapter discusses the nature of common faults observed and/or reported to the monitoring platform, then based on this discussion and experiences, a fault classification model is described to later aid in the clustering and/or determination of cost implications.

4.1 System status, faults, and corrective actions

The installed remote platforms in the three sites provide for evaluation of system status, fault detection and reporting as well as implementing corrective actions to resolve system faults.

4.1.1 System status

System status reports present the transient phenomena of the entire system performance. They also provide for long-term information storage for purposes of historical data review on individual projects. They, however, play a key role in helping maintenance personnel to adequately prepare for the next course of action. Problems in PV systems rarely occur abruptly without an observed trend over a specified period. This trend may arise from changes in weather conditions and/or consumer behavior. Figure 5 shows typical information window that technicians are able to observe and monitor daily. It gives an opportunity for a quick scan of individual systems to either prompt further review and/or confirm how things are on the ground. A further scrutiny may be conducted to historically evaluate the actual daily performance on hourly basis as presented in Fig. 6.

Figure 6 shows the hourly generation, consumption and the status of storage. The generation lasts from 6.00 am to 5.00 pm. In Fig. 6b, it is possible to highlight the variables at any particular hour as shown at 14.00 h on the legend.

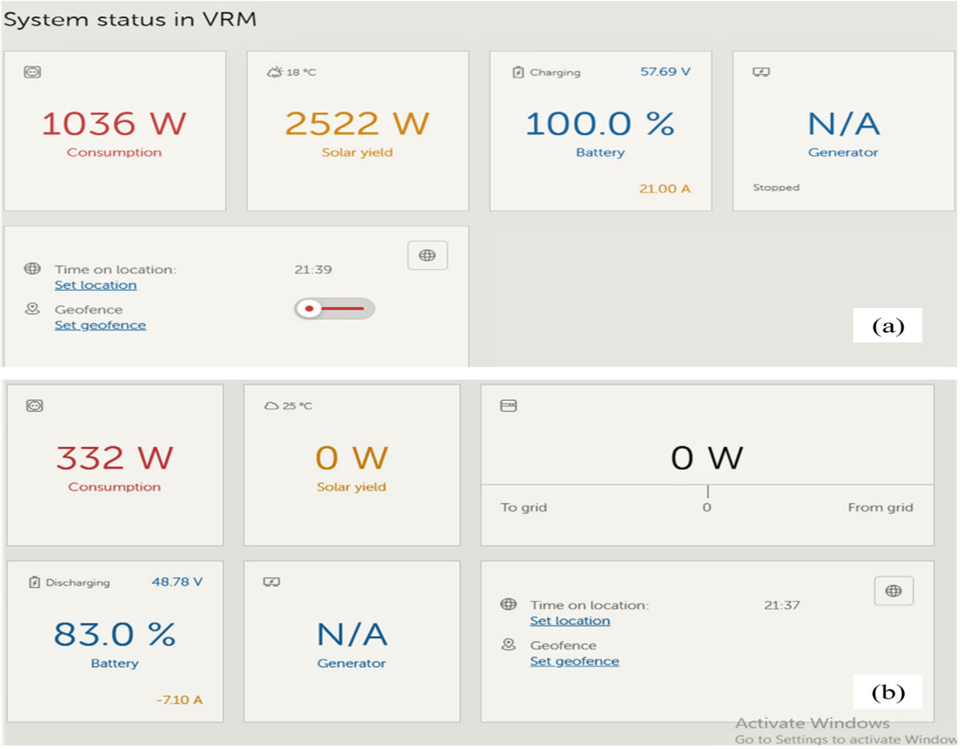
For 3-phase systems, it is possible to re-evaluate load allocations and observe changes in consumer behavior and plan for future amendments. This requires evaluation of a rather longer period data as presented in Fig. 7. In Fig. 7a, the system frequency looks stable with few periodic spikes. An interesting observation is shown in Fig. 7b where energy consumption changes are observed on 21st and 24th March for lines 1 and 2, respectively. Line 1 seems to run appliances continuously as from 21st of March while line 2 appears to have been relieved of some loads with a gradual reduction in loads attached to it. In this particular case, line 1 was attached to the kitchen while line 2 was connected to the guest houses. The decline in the latter was a result of guests' departure. The lack of data between 10 and 14th March was a result of internet failures at the client end and insufficient memory storage capacity. Hence the reliance on the cloud platform may present some challenges at times.

4.1.2 System visualization and fault detection

Under the application IoT platform, it is possible to observe the firmware updates of individual system component and its status as shown in Fig. 8. Technical issues that can be resolved remotely include, but are not limited to; firmware update, adjustment of system configurations i.e. AC voltage range and frequency modulation (internal or external source e.g. generator), parameters at which external sources should operate, charging currents (for external sources), float and absorption voltage for external sources, cut-off voltage, pre-alarm and pre-set voltage, and remotely shutting down the system. Parameters such as overload, system temperature, solar array and battery overvoltage, battery overcharging, individual string performance, battery charging cycles and load imbalances are observable issues that require quick action and/or can be resolved at a later date.

The frequency of change in charge controller status is recorded as shown in Fig. 9a. From the charge controller, one can tell when and how long the battery bank is under float, absorbing, bulk, faulty or stopped. This can be verified further by evaluating the frequency of battery faults in form of high temperature, low battery voltage and overload reports as shown in Fig. 9b–d. Figure 9b shows a battery bank that is working well with only one incident of low battery voltage while (c) shows a bank that is repeatedly experiencing problems. The last figure or Fig. 9d shows even more frequent low battery voltage and overload cases between November and February an indication of overuse during that season.

During rainy seasons, there is a likelihood of batteries not getting fully charged due to reduced solar insolation. This results in low battery status triggers. Thus, monitoring the charging cycle on a daily basis is done remotely and the client is advised on load shedding options. One of the sites is a tourist lodge that exhibits some special characteristics. Most tourist camps and lodges sometimes get 100% guest occupancy at peak seasons such as during wilder beast migrations in the Maasai Mara. Guests bring in cameras and other plug loads which might not have been factored in the design. Abnormal energy demand is experienced in guest rooms, the kitchen as well as in laundry areas leading to overloads and low batteries alarms, warnings and eventually premature system shutdown occurs before sunrise. In such situations, the battery bank's cut-off voltage may be adjusted remotely with allowable margins for that particular period to avoid power cuts and/or interference. Alternately or as a combination thereof, load shedding and external sources kick-in parameters can too be configured and/or adjusted remotely. The IoT platform hence gives the technical team humble



System status in VRM

1036 W
Consumption

18 °C
2522 W
Solar yield

Charging 57.69 V
100.0 %
Battery
21.00 A

N/A
Generator
Stopped

Time on location: 21:39
Set location
Geofence
Set geofence

(a)

332 W
Consumption

25 °C
0 W
Solar yield

0 W
To grid 0 From grid

Discharging 48.78 V
83.0 %
Battery
-7.10 A

N/A
Generator

Time on location: 21:37
Set location
Geofence
Set geofence

(b)

Fig. 5 Daily overview of energy yields; **a** system working very well, and **b** low energy due to poor insolation, but still working well at night

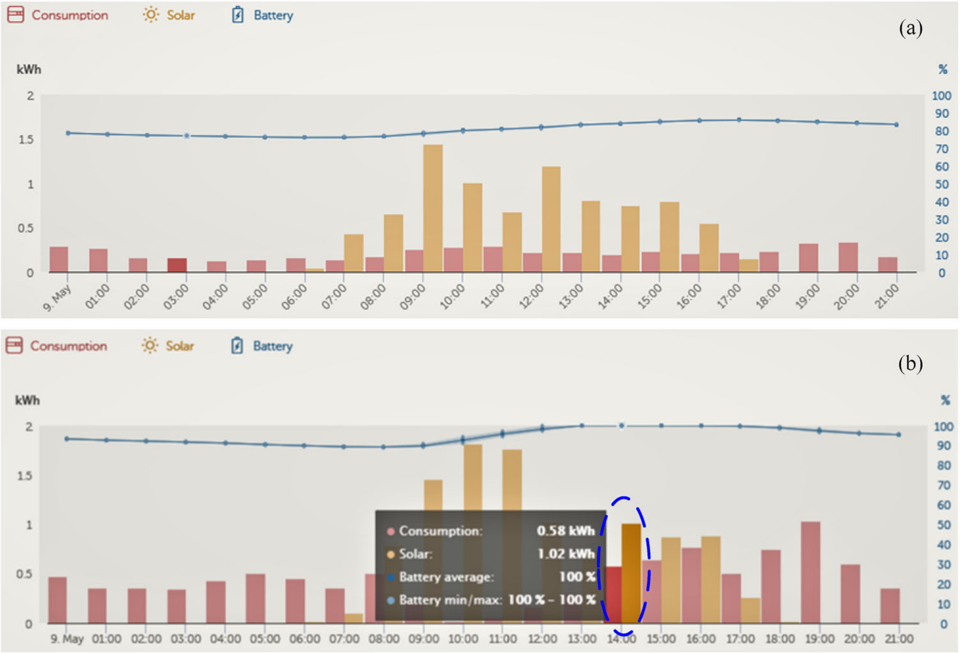


Fig. 6 Hourly energy generation and consumption summary for a day. **b** Also shows the capability of displaying the actual values

time to interrogate a developing problem and prepare way in advance for the necessary course of action.

4.2 Classification of system faults and scheduled maintenance

The analysis of the three sites revealed that alarm triggers due to, for example, high inverter temperatures, system fre-

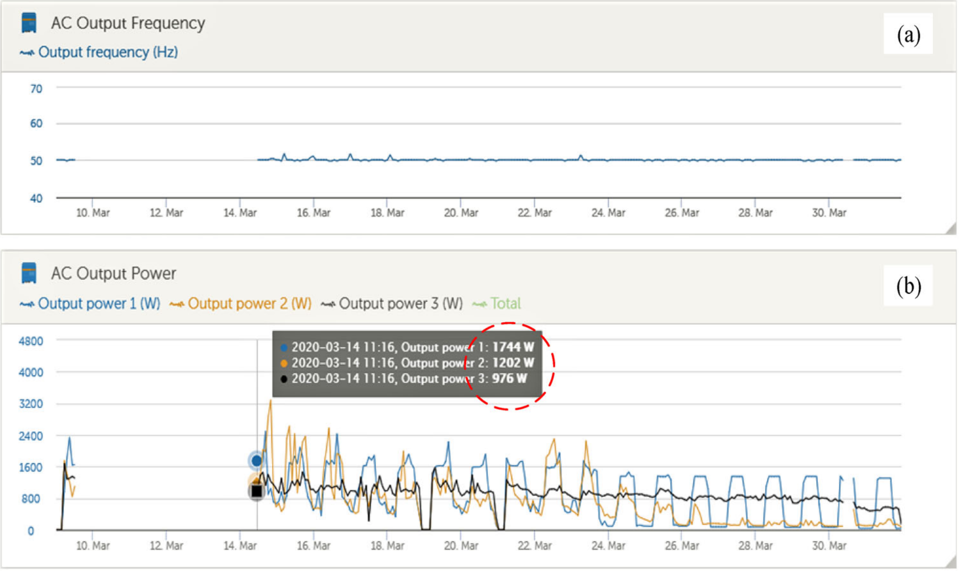
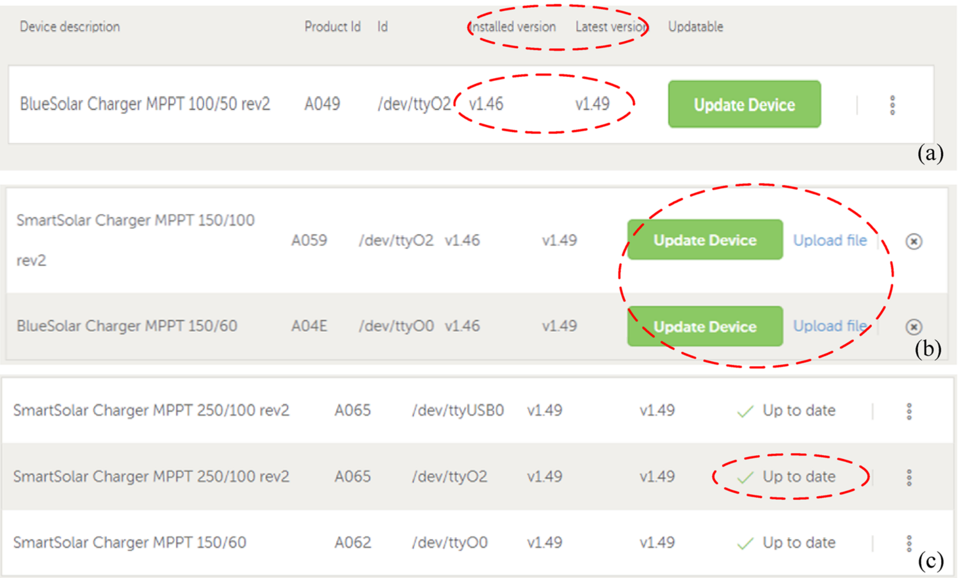


Fig. 7 Periodic performance results; **a** report on AC output frequency, and **b** individual line AC output power trend in a 3-phase system



Device description	Product Id	Id	Installed version	Latest version	Updatable
BlueSolar Charger MPPT 100/50 rev2	A049	/dev/ttyO2	v1.46	v1.49	Update Device
SmartSolar Charger MPPT 150/100 rev2	A059	/dev/ttyO2	v1.46	v1.49	Update Device Upload file
BlueSolar Charger MPPT 150/60	A04E	/dev/ttyO0	v1.46	v1.49	Update Device Upload file
SmartSolar Charger MPPT 250/100 rev2	A065	/dev/ttyUSB0	v1.49	v1.49	✓ Up to date
SmartSolar Charger MPPT 250/100 rev2	A065	/dev/ttyO2	v1.49	v1.49	✓ Up to date
SmartSolar Charger MPPT 150/60	A062	/dev/ttyO0	v1.49	v1.49	✓ Up to date

Fig. 8 Firmware status of individual components; **a** shows installed firmware versions and update prompt, **b** update request and **c** an updated status

quencies, battery under voltage during the day, battery high voltage beyond set point voltages, and abnormal system shutdown are some of the critical aspects of maintenance. Poor system frequencies can cause failure of the entire system. Under- and over-voltage problems are very common and can be quite detrimental to the system if left unchecked. Where systems are connected in a hybrid setup, auxiliary supply frequencies may also disfranchise the system. Those may be considered as the major concerns of autonomous off-grid solar PV systems. Other aspects that need monitoring though not major include low battery voltage and charging currents in overcast months, battery temperatures, system shutdown due to low battery voltage, as well as load management. Those aspects can be periodically monitored. Given the fact that energy derived from off-grid systems is of high value, any aspect that denies the user maximum benefits requires attention.

Major O&M problems have to be resolved within the shortest time possible and require the technical team to plan for a visit. Other problems can be delayed and/or instructions given to the user on ways or resolving them. As such, most unplanned maintenance site visits are triggered by major causes and when reported. The levels of convenience to the user depend on how fast the installer company is able to respond to those issues. Minor issue on the other hand are usually lumped up together with regular scheduled mainte-

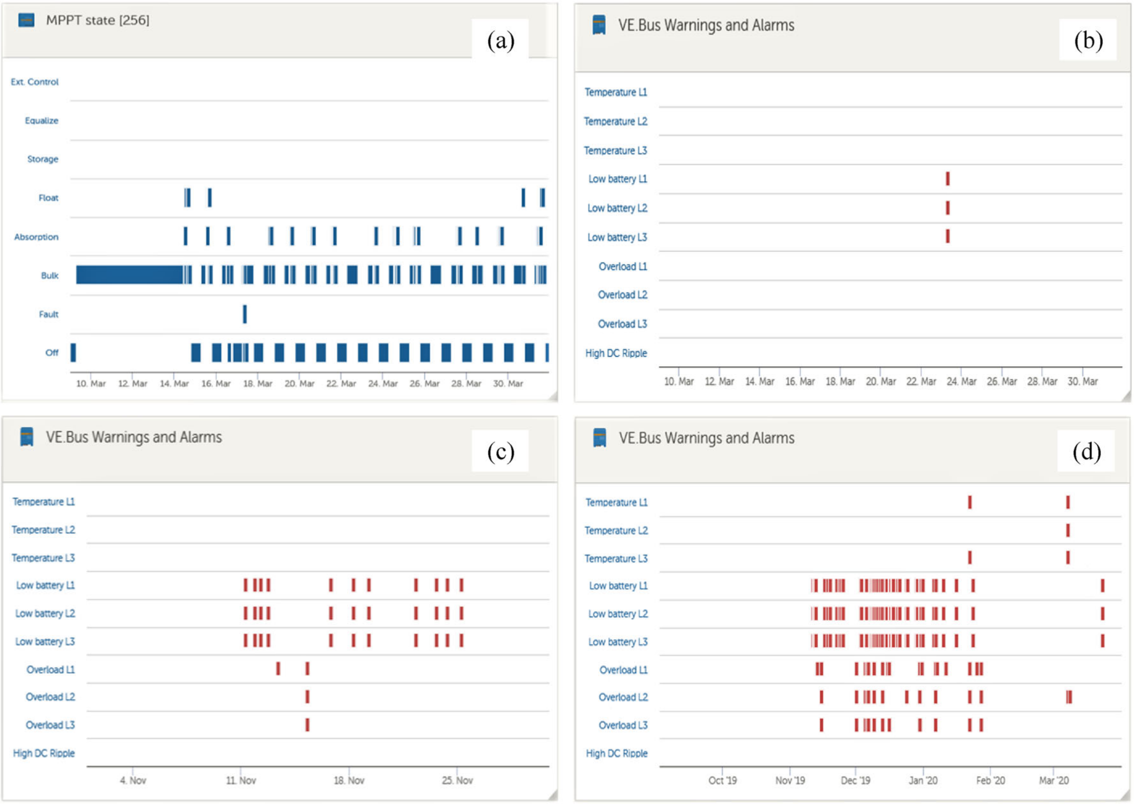


Fig. 9 Fault record and reporting on charge controller and batteries; **a** shows the distributed time-scales of charge controller status, **b–d** show frequency of problems in different batteries mainly reported in form of high temperature, low voltage and/or overload

nance. Based on the three sites and with the reference to the major O&M issues that warrant visitations on conventional sites, a minimum of three visitations were avoided per site per year.

Figure 10 further shows typical characteristics of systems managed by four installer companies that use IoT-based remote monitoring. All the companies are based in Nairobi. Figure 10a gives an indication the capacities that range from 5 to 30 kWp with majority of systems being over 10 kWp in capacity. From Fig. 10b, company A and C have over 50% of their installations remotely managed while company B and D have 30% and 40%, respectively, of their systems under remote monitoring. The installed remote platforms also exhibit similar performance characteristics in terms of scope as shown in Fig. 10c. Most of the specified capability tasks can be monitored and remotely corrected. However, remote load management and battery temperature monitoring are uncommon.

The observed results show that advanced IoT systems have taken root in the country. Most of the major O&M problems can be detected and resolved remotely. This also implies that most of the local installer companies focusing on 5–30 kWp capacity clientele have largely adopted remote monitoring systems to reduce physical site visits. This may also apply to larger capacities. On the contrary, smaller systems which are likely to fall into domestic category may have challenges sustaining the IoT platform. This is attributable to IoT costs, maintenance costs as well as access to reliable internet services.

4.3 Maintenance cost savings derived from use of IoT

Based on the interrogation of maintenance aspects, evaluation of historical maintenance schedules of the three sites and using the average costs, a single site visit costs from \$180 to \$240 on transport and from \$900 to \$1200 on subsistence considering deployment of two technicians to the site. With a conservative average of three visits per year, the costs of maintenance ranges between \$3240 and \$4320 per year. These costs are significant, given that the primary goal of an off-grid system is to reduce, if not eliminate energy expenditures. This also establishes a minimum limit on system capacity as well as institutional capability (size) that can afford a properly maintained solar PV system. In other words, individuals for example requiring less than 5 kWp may not afford the maintenance services for off-grid PV systems.

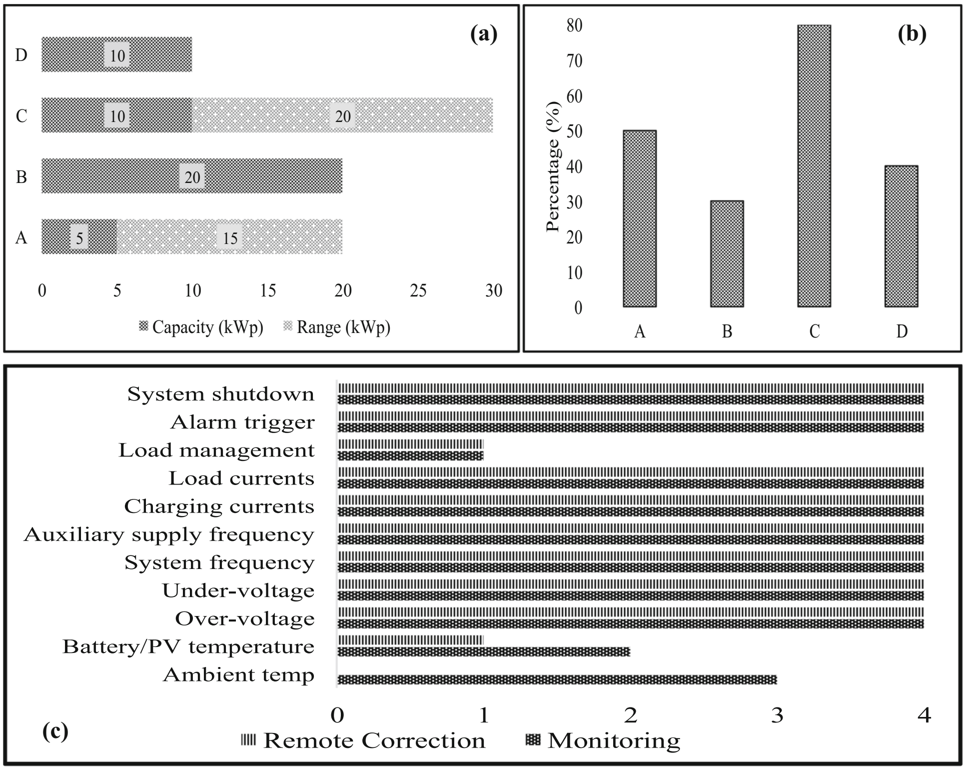


Fig. 10 Characteristics of installed systems: **a** capacity of installed systems, **b** percentage of systems under IoT, and **c** capabilities of installed IoT systems

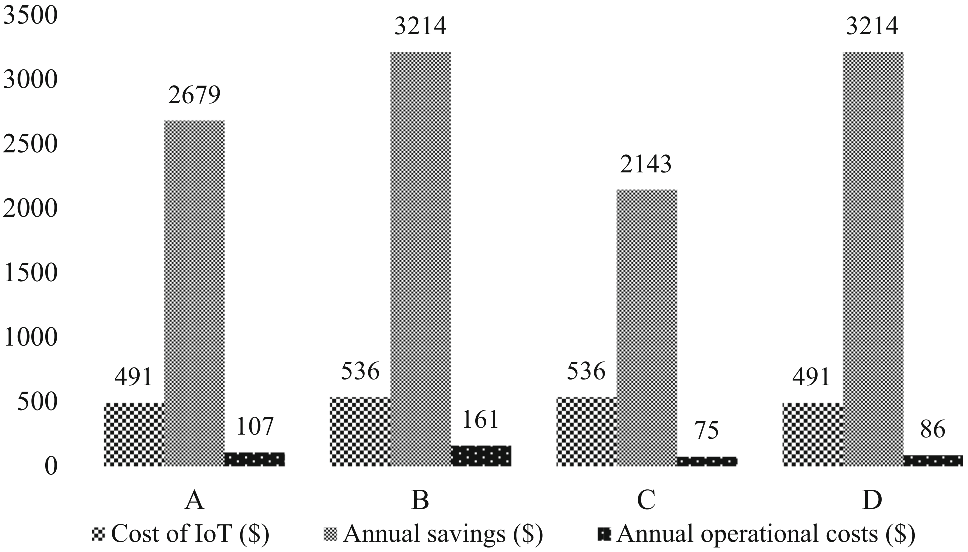


Fig. 11 Costs and savings associated with IoT systems

Information gathered from the installer companies employing IoT in Nairobi also revealed that despite remote platforms having gained popularity in the management of off-grid systems, they also come at a premium that may not favor smaller systems. From Fig. 11, the initial costs of installed IoT systems are over $510 on average. Monthly savings associated with the remote platforms range from $180 to $268 with expenditures on their operation being less than $10. This translates to annual savings of $2040 to $3096.

From the analysis of the three sites and the information gathered from the four installer companies, annual savings from remote monitoring systems may range from 47 to 95% depending on the location, components quality and the age of the system, operation, and design characteristics of individual installations. A similar study by Broering and Bajlekov showed that advanced remote monitoring systems have a combined labor and logistic cost savings of around 64% [33] which tallies well with the present results. In the best case, IoT platforms present a possibility of eliminating physical site visits on all but rare occasions. Besides increased monetary savings, the component longevity and project observability greatly improves. Consumers further enjoy increase levels of convenience. The minimum response time for a physical technical support is usually 8 h and subject to availability of technical personnel. As such, the benefits of IoT go beyond financially quantifiable terms.

5 Conclusion

Internet failure notwithstanding, remote monitoring platforms present human capital, time, and monetary savings of over 47–95% on the O&M of PV systems. Spatial and portfolio coverage by operators has been widened, reaching out to extremely remote locations at reduced costs of maintenance. Beyond corporate level clientele, individual client-based systems can now enjoy almost real-time monitoring from technical personnel with troubleshooting accomplished within less than 24 h. Solar PV investments do not necessarily have to be left in the hands of clients like it has always been for most off-grid systems in sub-Sahara Africa. Unmanned establishments such as radio and telecommunication masts, community water pumping points, holiday homes, etc. can be managed at very low costs. This development is indeed crucial in this era of pandemics such as the recent COVID-19 pandemic.

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Declarations

Conflict of interest The authors declare no competing interests, financial or otherwise.

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