Post-installation Analysis of Locally Manufactured Small Wind Turbines: Case Studies in Peru

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***Abstract*- In wind-based rural electrification projects, installing a small wind turbine is only the first step in providing energy access to a remote community. Locally manufactured technology is particularly susceptible to failures and as a result, an effective socio-technical system must be put in place to ensure that it continues in operation for many years to come. The systems created by two non-governmental organisations operating in the Andean region of Northern Peru were investigated and correlated to the post-installation performance of their wind turbines. Whilst both organisations appointed members of the community to operate and maintain the wind power systems, the level of training given to them was very different. The availability of each set of wind turbines was directly related to the amount of maintenance that community members were able to perform on them. Thus, clearly showing the wind power systems' critical dependence on the quality of the socio-technical system constructed around them to ensure its smooth operation after installation.**

I. INTRODUCTION

Electricity is a vital element for human development, yet 1.4 billion people have no access to it at all [3]. In Peru, over 67% of the country's rural population lacks access [3]. Fig. 1 shows that in some regions, there are sufficient wind resources for small wind turbines to provide electricity to remote communities.

Small wind turbines can be manufactured locally and doing so has the potential to boost the local economy, build local capacity and provide a flexible solution that can be adapted to the local context [4]. In addition to this, it is also possible to transfer knowledge and provide a sense of ownership of the technology to the end-users through their involvement with the construction and installation process [5]. When combined with printed manuals, formal training and other conventional methods of knowledge transfer, the end-users can be empowered to make productive use of the energy and carry out the necessary operation and maintenance procedures to keep the system functioning properly [5].

Locally manufactured technology is inherently less reliable than its imported counterpart that will have been manufactured from expensive materials with precision equipment. In a recent study of the Kenyan small wind sector, where many locally produced machines are also employed, it was found that "lack of government incentives and out-of-order turbines are the main factors that inhibit confidence in small wind turbines" [6]. In order to address this issue, an effective socio-technical system needs to be established around the wind turbine to:

- Increase reliability by conducting preventative maintenance, such as sanding down and repainting corroded metal parts.
- Further increase reliability through condition monitoring. Well trained end-users can spot when their wind turbine is operating irregularly and perform preventative maintenance before a major failure occurs.
- Increase resilience (the speed at which the system can recover from a failure) by having the necessary skills, tools and spare parts available to perform corrective maintenance when failures inevitably do occur.

Whilst corrective maintenance is obviously necessary to ensure the continued operation of the wind power system, predictive maintenance and condition monitoring are widely used by wind energy utilities due to their ability to "reduce maintenance costs and breakdown frequency, increase machine life and productivity, and reduce spare parts inventories" [7].

With the above criteria in mind, this paper aims to investigate the effectiveness of the socio-technical systems put in place by two separate non-governmental organisations (NGOs) working on wind-based rural electrification projects using locally manufactured technology in Peru: Soluciones Prácticas and WindAid.

A. *Soluciones Prácticas*

Soluciones Prácticas is the Latin American branch of the International NGO, Practical Action. In Peru, it employs over 100 people, the vast majority of whom are Peruvian. They develop small-scale appropriate technology solutions for poverty alleviation across a diverse range of fields, from irrigation to access to markets. Within the field of renewable

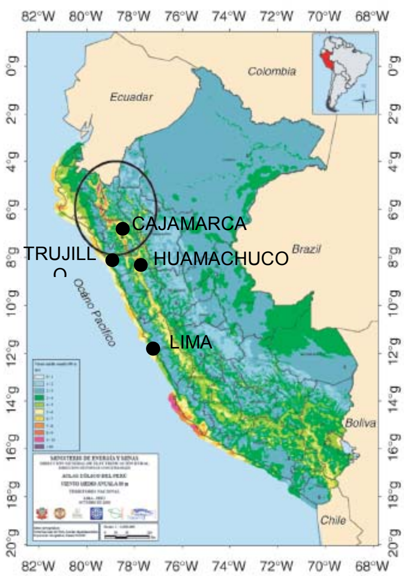

Fig. 1 Wind resource map of Peru showing the key locations in which WindAid and Soluciones Prácticas operate (image adapted from [1], original data from [2])

energy, Soluciones Prácticas was one of the first to employ micro-hydro power generation technology for rural electrification in the 1980s. They pioneered the local manufacture approach by using off-the-shelf components, such as a pump as a turbine and a motor as a generator. Their commitment to putting people first, not technology, means that they invest a significant amount of time and effort into training community members to operate and maintain the technological systems that they design.

Following in the footsteps of their micro-hydro technology development programme, Soluciones Prácticas (with the aid of Scottish small wind expert Hugh Piggott) developed a small wind turbine during the late 1990s that could be built in Peru. The resulting IT-PE-100 [8] is a small, domestic machine with a 1.7m diameter rotor, capable of producing 300W at 11m/s and a rated annual energy yield[1] of 548kWh/yr. Shortly afterwards, the larger SP-500 [9] with a 4m diameter rotor that produces 1,000W at 11m/s and a rated annual energy yield of 1,807kWh/yr was also developed.

Following the production of a number of prototype models, El Alumbre in the mountainous region of Cajamarca was selected as the first community for Soluciones Prácticas' wind-based rural electrification programme. Wind turbines have subsequently also been installed as part of hybrid renewable energy systems in two further communities, Campo Alegre and Alto Perú. However, only the data from El Alumbre is analysed in this paper as this is where the most complete post-installation record exists.

1. Geography

The IT-PE-100 and SP-500 were developed in Lima, where the headquarters of Soluciones Prácticas is located. The turbines are manufactured here by a Peruvian private enterprise, Tepersac, who specialise in the production of renewable energy equipment. Soluciones Prácticas have additional regional offices around the country, including Cajamarca, the region in which all three of their wind-powered communities are located (Fig. 2).

2. Technology as Installed

In El Alumbre, 35 individual turbines were installed at each demand point in two phases. In January 2008, 21 households received IT-PE-100s and a single SP-500 was installed at the secondary school. In January 2009, 12 domestic IT-PE-100s and another SP-500 for the health post were installed in the second phase.

3. Socio-technical System for Operation and Maintenance

Knowledge Transfer and Management Structure

Prior to the installation of the wind power systems, all members of the community received basic training on the limitations of the system, how to take care of it and how to make best use of the energy it provides. Printed manuals were also produced as a reference guide for community members.

The next stage in the training process involves the nomination of members of the community in an open meeting for the position of the operator/administrator of the wind

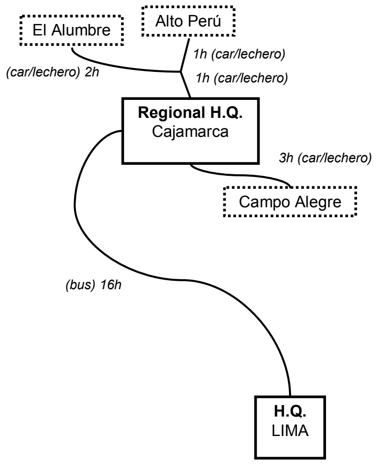

Fig. 2 Network diagram showing the travelling times (by the usual mode of transport) between the headquarters (H.Q.), regional H.Q. and communities where Soluciones Prácticas have installed wind turbines.

power system. The nominees attend a comprehensive training programme at CEDECAP[2] on the operation and maintenance of a wind power system, covering both technical and business skills and ending in a written exam to check for comprehension.

The next stage involves election of the operator/administrator by a panel of community members and project organisers based on the test scores and reputation within the community. The top candidate becomes the operator/administrator, whilst the second acts as an assistant.

After selection, the operator/administrator runs the wind energy system as a micro-enterprise: each family pays a small fee for the electricity they receive, which goes towards a reserve fund to pay for maintenance costs and a wage for the operator/administrator.

During installation of the systems, community members are encouraged to actively participate in the labour intensive tasks such as the raising of the tower and digging of the anchors.

Maintenance Plan

The roles of the operator/administrator are as follows:

- Perform monthly condition monitoring and, when necessary, preventative maintenance (lowering the tower and checking the integrity of all major components) on each turbine.
- Perform corrective maintenance when failures occur and keep a logbook to record any such incidents.
- Collect a monthly fee from community members for the provision of electricity.

Supply Chain

In the event of a failure, components are replaced from a stock of spare parts kept in a store room within the community consisting of three complete systems (blades, generator, tail, controller, inverter, and dump load), ten rectifiers, a selection of nuts and bolts and electrical cabling with terminals. The operator/administrator has the following tools available within the community to perform both

[1] The rated annual energy yield is the estimated annual energy yield of a turbine with 100% availability in a standard atmosphere with 5m/s annual mean wind speed and a standard (Raleigh) wind speed distribution.

[2] CEDECAP (Centre for Demonstration and Training) was established in Cajamarca by Soluciones Prácticas in 1997 for the demonstration of appropriate renewable energy technologies to students, policy makers, engineers and community members, as well as providing training on the installation, operation and maintenance of these technologies.

preventative and basic corrective maintenance operations: a toolbox containing spanners, pliers, screwdrivers, Allen keys, a hammer and electrical tape; cleaning equipment; a multimeter; and sandpaper, paintbrushes and rustproof paint.

If a repair cannot be made within the community, the failed part will be sent back to Cajamarca on the lechero's truck[3], where it is received by the regional headquarters in Cajamarca for inspection. If it is possible to repair the part, it is sent back to the Lima office by bus and finally to the original manufacturer, Tepersac. Batteries and towers are also supplied from Lima.

B. WindAid

WindAid is a social enterprise founded by the American entrepreneur Michael VerKamp in 2006 with the aim of exploiting the country's wind resources to improve the inadequate levels of electrification. VerKamp adapted the open-source design of Hugh Piggott [10] to create WindAid's 2.5kW wind turbine for production in Peru. The turbine has a 4m diameter rotor that is capable of producing 1.9kW at 11m/s and a rated annual energy yield of 2,541kWh/yr.

WindAid began as a purely commercial operation, selling its turbines to businesses operating in remote areas, such as chicken farms or hotels. In 2009, WindAid's volunteer programme was established to address the difficulty faced by rural communities in finding sufficient capital to purchase a wind turbine. The volunteer programme invites international participants to travel to Peru and build a wind turbine with WindAid. The construction process lasts around 4 weeks and culminates in the installation of the wind turbine in a remote Andean community during the final week. The materials and overheads for the construction of the wind turbine are paid for by the volunteers, who pay around US$2,000 for the 5 week programme. The volunteers receive what is essentially a practical wind energy training course, along with the experience of living in a remote Andean community and providing them with a renewable energy system. The community is therefore able to receive this system free of charge.

1. Geography

WindAid are based in Trujillo, where they also manufacture their own wind turbines. Fig. 3 shows two Andean regions in which they have installed wind turbines: Cajamarca and Huamachuco.

2. Technology as Installed

WindAid typically install a single larger turbine at a community building, such as a health post or school. Whilst the community building receives electricity directly, domestic users must bring their batteries there to charge them.

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[3] A lechero is truck that collects milk from the communities, where the main form of income is often dairy farming. The truck also transports goods and passengers during its normal service for a fee.

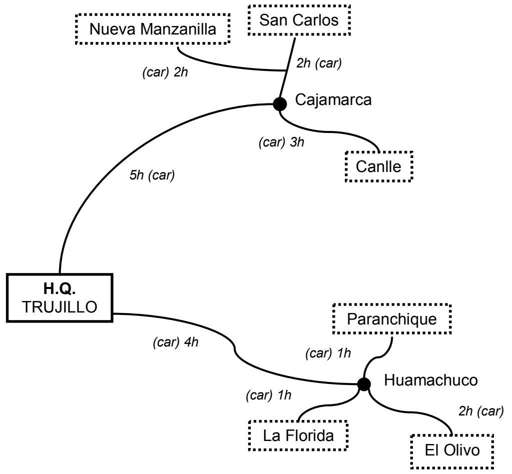

Fig. 3 Network diagram showing the travelling times (by the usual mode of transport) between the headquarters (H.Q.), regional H.Q. and communities that WindAid work with.

3. Socio-technical System for Operation and Maintenance

Knowledge Transfer and Management Structure

All members of the community are invited to participate in the installation of their new turbine, however little technical training is given. The community are encouraged to form a wind committee to look after the operation and maintenance of the turbine, but the way in which this is done is left up each individual community.

Maintenance Plan

Almost all maintenance is performed by WindAid staff, who operate from Trujillo and travel to the communities in the event of a failure. For safety reasons, WindAid do not allow the communities to lower the tower by themselves. Funds are collected by the wind committee for the battery charging services that the wind turbine offers, however they are rarely enough to cover the maintenance costs and the balance is paid by WindAid.

Supply Chain

All spare parts are supplied from Trujillo and few tools are kept in the community. Basic repairs can be made by some wind committees with telephone instructions from WindAid.

II. METHODOLOGY

A database was created of the incidents that have occurred with each turbine following its installation. Each entry included the date of the incident, the subsequent system downtime, the failed part/s, details of the specific fault, the root cause of the fault and where a spare part was supplied from. The database was constructed and managed using Visual Basic for Applications (VBA) in Microsoft Excel.

A. Data Sources

1. Soluciones Prácticas

The maintenance log kept by the operator/administrator in El Alumbre records any failures that have occurred with the wind power systems in the village. This historical data was used as an input for the model, with estimations made for any incomplete entries. Data was available from the day the turbines were installed in January 2008/09 until October 2010 and covered a total of 28,206 days of turbine operation.

2. WindAid

The data for WindAid was generated retrospectively by the relevant members of the organisation's technical team who performed each of the maintenance operations. The data begins when each turbine was installed and finishes in December 2011, covering a total of 1,848 days of turbine operation.

B. Scope

The post-installation performance of a wind power system at any one point in time is governed by the following three key factors:

1. Technical availability – whether the system is operating correctly without any technical failures.
2. Meteorological availability – the amount of wind available at that moment in time or that has been available recently and stored in batteries.
3. Utilization – how much power the user requires at any one time.

It is only when these three factors coincide that the wind power system can be said to be fulfilling its function, i.e. delivering the required amount of energy to the end-user when desired. This paper aims to investigate purely the technical availability of the studied wind turbines, but it should be noted that even when a wind power system is technically available, it does not necessarily mean that it is operating successfully.

III. Results and Analysis

Fig. 4 is a graphical representation of the complete database for both Soluciones Prácticas and WindAid, whilst Fig. 5 shows three key indicators of the post-installation technical performance of the two organisation's wind power systems. Reliability is measured by the Mean Time Between Failures (MTBF), i.e. how often failures occur. Resilience is measured by the Mean Time To Return (MTTR), i.e. how quickly the system can be put back into operation when a failure does occur. The technical availability is a combination of both reliability and resilience, and represents the amount of time that the system is technically able to provide power to the end user.

A. Reliability

WindAid's MTBF of 115 days is less than half that of Soluciones Prácticas' 291 days. This can be partly explained by the fact that the operator/administrator in El Alumbre is able to perform sufficient preventative maintenance and therefore greatly reduce the probability of technical failure. In addition to this, WindAid developed their first wind turbine 10 years after Soluciones Prácticas and have produced around 10 times fewer turbines in total. As a result, Soluciones Prácticas' increased manufacturing experience has greatly reduced the number of design flaws present in their machines. What is more, their turbines are produced by a specialist company, who has manufactured renewable energy technology since the 1980s. This is in contrast to WindAid's turbines, which are produced by international volunteers with little or no prior experience of manufacturing. Although they are overseen by permanent technical members of staff, the potential for introducing errors in the manufacturing process is clearly greater. In addition to this, the basic training and printed manuals given to the end-users by Soluciones Prácticas has allowed for swift identification of any irregularities in system operation by the end-users. When reported to the operator/administrator, appropriate preventative maintenance has then been performed before a major failure has occurred.

B. Resilience

With regards to resilience, WindAid's MTTR is almost double that of Soluciones Prácticas, at 31 and 13 days respectively.

For Soluciones Prácticas, the presence of the fully trained operator/administrator in the community means that whenever a technical failure does occur, they are able to perform a repair as soon as possible. The fact that many potential operator/administrators were trained means that there is always somebody on hand to provide technical assistance, even if the appointed operator/administrator is unavailable. The stock of spare parts and tools kept in the community is also vital to getting the wind power systems up and running again as soon as possible. For example, Fig. 6 shows that rectifiers are one of the most problematic components for Soluciones Prácticas; however replacing a rectifier is cheap and very simple. With the spare parts and tools on hand, as well as the knowledge of how to do so, the majority of the failed rectifiers were replaced within 24 hours.

Unfortunately the system created by Soluciones Prácticas is not perfect. This was illustrated when high winds in April 2009 caused the failure of 9 turbines. Once all the spare parts

Fig. 4 Timeline plots showing the uptime (green) and downtime (red) of each turbine in the database for a) Soluciones Prácticas and b) WindAid.

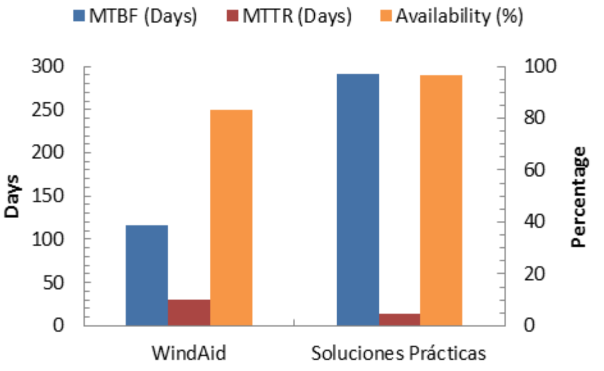

Fig. 5 Comparison of three key performance indicators: Mean Time Between Failures (MTBF), Mean Time To Return (MTTR) and technical availability.

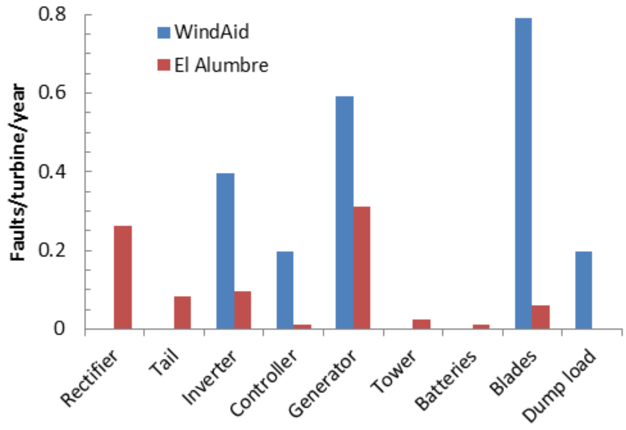

Fig. 6 Normalised comparison of the breakdown of faults per component experienced by both WindAid and Soluciones Prácticas.

in the community had been used, the long, slow supply chain all the way to Lima and back caused several households to spend months without power. In much the same way, when all of WindAid's turbines suffered technical failures in November 2011, they were left without power for over a month, until the technical team were able to find time to travel up to each of the communities in the mountains. Extended periods without power significantly inhibit the utility of the energy system to the community as any vaccines stored in fridges will have deteriorated and any businesses based on its operation may well have gone bankrupt. This is turn further reduces the amount of effort that the members of the community are willing to put into maintaining the system in the future. In fact, this was one of the major contributing factors to the decision of the Nicaraguan NGO, blueEnergy, to put a halt to its wind power programme [5, 11].

C. Root Cause Analysis

A root-cause analysis allows the identification of serial defects in major components. Design modifications can then be made, operation and maintenance procedures can be adjusted or the supply chain strengthened to ensure the availability of spare parts when failures do occur. Fig. 6 shows the breakdown of the average number of failures per turbine per year by component.

Both the major problems for Soluciones Prácticas have been caused by the failure of the over-speed protection system in high winds. This has led to the burning out of generators and rectifiers and has been the root cause of 46% of their failures. The tails are also often broken in high winds (10% of failures), but would not have been protected by the over-speed protection system. The twisting up of the power transmission cables inside the tower has often resulted in the cable ripping out of the back of the generator and is responsible for 13% of failures.

Safety is critical with wind turbines, as the machines spin at high speed on top of a tower and can easily harm a bystander if a part were to fall. In El Alumbre, poor quality welding has led to two towers collapsing and three turbines falling from the top of the tower, whilst 30% of WindAid's failures have been from blades flying off. Fortunately nobody was hurt during any of these incidents, but it is of critical importance to address these modes of failure, especially when considering that many of the turbines are installed at homes or schools where children will be present.

Corrosion of the permanent magnets in the generator have caused problems for both WindAid (10% failures) and Soluciones Prácticas (6% failures). When water gets into the magnets, they swell and cause the stator to rub on the rotor, preventing the turbine from rotating.

Finally, WindAid experienced an inverter failure caused by a user plugging in a large television and drawing too much current.

IV. Recommendations

As a result of the above analysis, the following recommendations are made to Soluciones Prácticas and WindAid to improve the technical availability of their wind power systems:

A. Soluciones Prácticas

Soluciones Prácticas have successfully created an effective socio-technical system that is capable of ensuring high levels of availability for the wind power systems that they have installed. However, there are some persistent supply chain and technical issues that still need to be resolved.

Although the availability of three full wind turbines in the community for spare parts is usually more than enough to make any necessary repairs, incidents of high winds can cause multiple failures and the supply chain to Lima is far too long. It is recommended that as a further two communities in Cajamarca now have similar wind power systems, that a further three spare systems are kept at the regional headquarters here.

To avoid dangerous structural defects, the quality of welding should be checked before leaving the workshop and rechecked regularly for cracks and corrosion.

To address the problems with the over-speed protection system, a wind tunnel has been constructed by Soluciones Prácticas at the Universidad Nacional de Ingeniería in Lima with the aim of characterising and optimising the over-speed protection system. The issues of twisting up of electrical cables inside the tower and the breaking of tails are also being addressed with simple modifications to the design.

During manufacture of the generator, when the permanent magnets are placed on the steel rotor disc, their magnetic attraction causes them to hit the disc with significant force and often chips the brittle protective coating. WindAid have recently modified the design of their generator to include a thin layer of resin directly onto the steel rotor disc to act as a cushion when the magnets are placed on top. This design modification could equally well be applied to Soluciones Prácticas' turbines and would most likely solve their corrosion problem.

B. WindAid

The large distances between WindAid's communities and their headquarters, coupled with the lack of technical training for wind committee members has caused significant downtime and needs to be addressed if the wind power systems are to be considered sustainable.

To improve the technical abilities of the wind committee members, more technical training is needed. Although setting up a new demonstration centre similar to CEDECAP may be impractical, negotiation between the two organisations could allow WindAid to use the facilities already established there. Another possibility is to establish a revolving demonstration and training programme whereby members of the latest community to receive a wind turbine visit the previous and is trained by both WindAid staff and members of the previous community. As a comprehensive wind energy training programme is given to the international volunteers when the turbines are produced, this provides the perfect opportunity for members of the newly formed wind committee to learn by participating in the construction alongside volunteers. Added benefits of this approach are an increased sense of ownership of the turbine for members of the wind committee and greater opportunity for the cultural exchange that the international volunteers signed up for. Increased understanding of system capabilities should also prevent problems such as the use of appliances with excessive power ratings, as in the case the large television mentioned previously.

The problem will also be alleviated by the fact that WindAid plan to select future communities in closer proximity to each other within the Huamachuco area, However, with 10 further installations planned for 2012, it is recommended that WindAid also establish a regional headquarters in Huamachuco that will be able to perform corrective maintenance operations without the need for WindAid staff to travel up from Trujillo.

Finally, the issue of flying blades was initially addressed by modifying the design to reduce the weight and appears to have now solved the problem.

V. EVALUATION

Although generally successful in identifying the key issues surrounding the long term sustainability of the socio-technical systems for maintaining high levels of technical availability, the study suffered from the following limitations:

- The logbook used to obtain the data for Soluciones Prácticas may not always have been completed by the operator. It was originally transcribed for a separate project and as a result, it did not always include all of the required information. Consequently, estimations had to be made based on knowledge of the system and previous complete entries.
- The data for WindAid was generated retrospectively and as a result may be incomplete or incorrect as the first turbine was installed two and a half years before the data was collected.
- The datasets are small, especially WindAid's.

VI. CONCLUSION

The socio-technical systems put in place by both WindAid and Soluciones Prácticas were studied and correlated with the post-installation record of the turbines they have installed. It was found that the increased level of training, selection of tools and stock of spare parts given to the operator/administrator by Soluciones Prácticas allowed them to successfully perform condition monitoring and both preventative & corrective maintenance. As a result, the wind turbines they looked after had much higher levels of availability.

Further work is needed to include economic factors and to extend the analysis to further local contexts. This would add further weight to the argument put forward in this paper, i.e. an effective socio-technical system embedded within the community is absolutely essential in ensuring the long-term sustainability of wind-based rural electrification projects.

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