Eternal Light

By Henry Louie, Peter Dauenhauer, Michael Wilson, Adriaan Zomers, and Joseph Mutale

SUSTAINABILITY HAS BEEN FAMOUSLY defined as "the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs." While elegant in its conceptual simplicity, this definition is often not the most useful one to practitioners, especially those working in the area of energy deployment in developing communities. The sustainability of small-scale, off-grid energy systems—systems that appear to fit this definition neatly—cannot, in fact, be taken for granted. And sustainability is key: it can mean the difference between prolonged poverty and transformational prosperity for the 1.2 billion people around the world who lack electricity, some 85% of them in rural areas.

The introduction of small-scale, off-grid energy systems—also known as community microgrids—to power-impoverished rural areas has become a favorite program for governmental and nongovernmental organizations (NGOs) alike. It has been estimated that the market for these systems is between 70 and 100 MW per year in Africa alone, as they serve a need currently unmet by the established grid. Extension of the grid to serve the needs of the rural poor has proven to be agonizingly sluggish and is so far unable to keep up with increasing demand. In Mozambique,

Digital Object Identifier 10.1109/MPE.2014.2317093
Date of publication: 17 June 2014

 1540-7977/14©2014IEEE

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Ingredients for Sustainable Off-Grid Energy Development

an additional 10,000 households are connected to the grid each year, but over the same time a growing population adds 90,000 new households. Even if the requisite electrical infrastructure is present, up-front connection fees can be equivalent to several months' income, and energy costs can be as steep as US$0.50/kWh. Obtaining a grid connection is not the only hurdle. In more than half of African countries there are generation resource adequacy deficiencies and chronic reliability issues that lead to disruptive scheduled or impromptu blackouts.

Small-scale, off-grid systems, which typically offer between 0.1 and 100 kW of peak capacity, require less up-front capital, have shorter implementation time frames, and can be strategically located. Medical clinics, schools, and community centers may have solar photovoltaic (PV) panels, petrol generators, microhydro, wind turbines, and associated components installed by generous organizations (see Figures 1 and 2). But whereas many organizations expend a great deal of effort on fundraising, technical design work, and the implementation of a system, only a few thoughtfully plan for a project's long-term viability. For one reason or another, one or more aspects of sustainability are overlooked, resulting in the chronic underperformance, underutilization, or even outright failure of the system. The consequences of failure are steep because so much is at stake.

Based on their experience in small-scale, off-grid energy development projects, the authors have concluded that a "sustainability first'' mindset is needed at the inception of any project. This article relates firsthand experiences that have inspired this mindset. The intention is to leave the reader with an appreciation for a holistic design approach that takes into consideration the technical, environmental, economic, social, and organizational aspects of sustainability that must be weighed and planned for.

Sustainability in Off-Grid Development

What does it mean for a small-scale off-grid energy development project to be sustainable? Here is one answer:

Sustainability is the perceived potential for a system or project to endure, build a self-perpetuating capacity within a community, and ultimately reach the end of its predefined life span or evolve into another beneficial form.

Framing sustainability in this manner is useful and indeed practical because it is forward-looking. Sustainability can be judged *ex post*, rather than *ex ante*. Importantly, it also allows an assessment of sustainability to occur at any time—and hopefully many times—within the project's life span. It acknowledges that the sustainability of a system may vary over time, potentially in response to changes in exogenous conditions.

This definition recognizes the importance of the local community in sustainability. Development projects introduce a short impulse of physical and human capital into the local community. The impulse will quickly decay unless the community directly acts to prolong, perpetuate, or even grow from it.

Finally, the definition offers an exit clause. Technologies, processes, and systems are never permanent. Some are intentionally designed to bridge a gap until a future time when exogenous conditions are expected to change—for example, installing an off-grid system meant to last until a known date of grid expansion. Others become obsolete naturally: the telegraph's being replaced by the telephone, for example.

table 1. Typical component life spans and associated costs.					
Typical Life Span	<1 year	3–5 years	5–10 years	>10 years	>20 years
Components	Lightbulbs (incandescent)	Lead-acid batteries	Inverter	Charge controller	PV panels

figure 1. PV panels at the Sabongari CCS in Cameroon (photo courtesy of Michael Wilson).

The sustainability of a system is not a simple univariate, time-independent binary condition. Rather, it is a continuous, multidimensional dynamic state variable. Technical, environmental, economic, social, and organizational aspects all influence the sustainability of a project. These key ingredients are all important and interrelated. Careful attention to each at the planning stages of project can maximize the potential for sustainability.

Technical Sustainability

Technical sustainability refers to the ability of a system to meet technical specifications and service expectations throughout its life span. At the outset of a project, a designer makes several key decisions and assumptions that either encourage or jeopardize the prospects for sustainability.

figure 2. Installation of the CCS in Thiou, South Sudan (photo courtesy of Mou Riiny).

One assumption that must be made but is subject to wide uncertainty is how the system will be used postinstallation. Once electricity is available, people often begin climbing the "energy ladder"—purchasing additional lighting and moving on to luxury items such as televisions and portable DVD players that drive up their energy usage. Initial expectations of energy use, therefore, may no longer hold.

The authors once worked on a project to add a micro wind turbine to a farmer's small PV system. The extra energy would have allowed the farmer to earn additional income for his family by recharging his neighbors' mobile phones. The next morning it was discovered that the charge controller had disconnected the loads due to low battery voltage. The battery was drained. After some investigation, it was found that in anticipation of increased energy, the farmer had purchased additional lighting. He purchased less efficient and less expensive incandescent bulbs (approximately US$1 each) rather than the compact fluorescent bulbs (approximately US$4.50) he had previously used. In a single day, his demand increased by a factor of four.

This natural appetite for electricity can and should be planned for. Educating the end user in understandable terms about basic concepts of efficiency and the system's limitations, as well as designing for future expansion and scalability, can guard against failure due to overconsumption.

Another important design consideration is the replacement or repair and maintenance of the system. Components will inevitably fail (see Table 1), and the system designer should plan for this. There are two philosophies about how this should be done. The first is to select high-end, highly durable and ruggedized components that offer superior performance in terms of reliability and thus reduce replacement and repair as well as maintenance frequency. The disadvantages of this approach are that components of this quality are usually expensive and not easily obtained or supported locally. The logistics of importing equipment are not trivial. It is an endeavor potentially rife with corruption and long delays, and steep duties make already expensive equipment even more so. The added expense may not be a barrier during implementation, but postinstallation—unless the project has continuing donor support or, better, is financially self-supporting—a failed component may never be replaced.

The second approach is to use locally available and less expensive components whenever possible. These may be of inferior quality but can be less burdensome to replace and repair. The disadvantages of this approach include more frequent and sometimes more complex maintenance. Flooded lead-acid batteries are less expensive than their sealed counterparts, but they require routine maintenance and care. Developing countries are also awash with low-quality knockoffs that have uncertain and inconsistent quality and specifications (see Figure 3). Whichever approach to component selection is ultimately taken, the designer should be keenly aware of the consequences.

Broad actions are needed to improve the technical sustainability of off-grid systems at large. First, engineers—locally and abroad—can be better educated on how to design for sustainability in developing community applications. Few universities offer courses or programs in this area, yet there is an opportunity to tap the interest and enthusiasm of today's more socially conscious and globally aware generation of students. Second, development and broader acceptance of standards for rural off-grid systems, including standardized connectors for lightbulbs, PV panels, and portable battery kits can make for easier system design and component sourcing. Organizations such as Lighting Africa are already making progress on this front. Third, the development and adoption of a sustainable energy reference architecture, which provides a template for off-grid systems, could be a catalyst for their rapid proliferation.

Environmental Sustainability

The environmental effects of off-grid systems can be roughly classified as being global or local. The focus hereafter is on local effects as these are more relevant to the practitioner, but the topic of electrification and global CO_2 emissions deserves at least a brief discussion. The electricity demand at the lowest rungs of the energy ladder is modest, often less than a few hundred kWh/year per household. The global effect of upgrading the energy-impoverished (approximately 20% of the world) to this standard would add less than 1% to current cumulative worldwide CO_2 emissions, even accounting for increased fossil fuel–powered generation. Therefore, incipient electrification of the energy-impoverished carries little weight in the context of the internationally agreed-on objective of reducing CO_2 emissions. Of course, as the energy ladder is climbed, the global effects of electrification increase concomitantly.

The local environmental effects of electrification consider the indoor home environment and external impacts. The provision of electricity services to people in rural and remote areas can displace dry cell batteries, dangerous kerosene (paraffin) lamps, candles, and other devices such as automotive batteries. This results in improvements in indoor air quality and reductions in spillage of effluents and waste from batteries in the physical and biological environment. Indoor air pollution caused by particulates emitted by inefficient cooking facilities, kerosene lamps, and candles causes some 1.5 million premature deaths each year due to respiratory diseases. In principle, electricity could also replace the wood fuel used for cooking and heating, but experience shows that electricity is largely not used for cooking in rural areas, often for cultural reasons. Nevertheless, the collection and use of wood as fuel for cooking by the local population is generally not the cause of local deforestation. The large-scale production of charcoal often has a larger impact on the local environment.

It is important to evaluate the environmental impact of the whole chain of processes involved in producing, storing, distributing, and using electricity. For example, a number of battery types are available, such as lead-acid, nickel-metal hydride, and lithium-ion, but their overall environmental effects differ substantially and also depend on any additional losses incurred due to turnaround efficiency and battery mass, as well as the way the batteries are used. Many problems associated with the transport, charging, and recycling of batteries, including leakage and the use of unsuitable fluids, have already been reported.

There are also indirect environmental consequences of electricity access. Electric water pumps at times are used for mining groundwater. Their overuse can lower the local

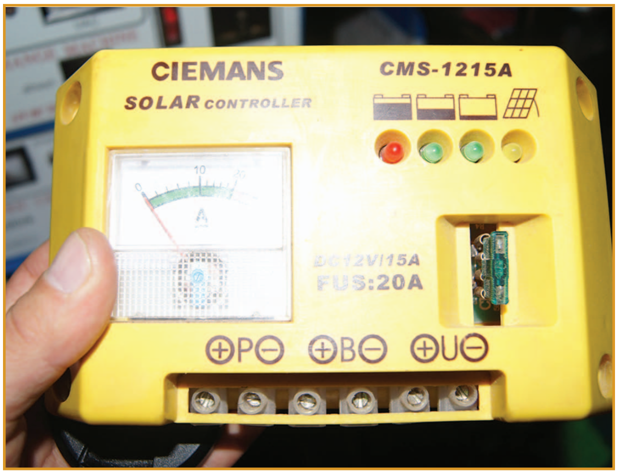

figure 3. Products such as this "CIEMANS" PV charge controller can create brand identity confusion (photo courtesy of Peter Dauenhauer).

figure 4. Mobile phone recharging provides an income stream—usually US$0.25 to US$0.50 per recharge—that can help make off-grid systems economically sustainable (photo courtesy of Peter Dauenhauer).

> Small-scale, off-grid systems require less up-front capital, have shorter implementation time frames, and can be strategically located.

water table to such a degree that water is inaccessible to people without electricity. The ensuing water scarcity further exacerbates the vulnerability of the poor.

Economic Sustainability

With off-grid systems, the term *economic sustainability* concerns primarily the financial underpinnings of a system. Unsurprisingly, off-grid systems require an income to be economically sustainable. Even systems that are originally gifted to beneficiaries should plan to charge for services (see Figure 4) to be able to replace components and to (potentially) scale up services or at the very least build up a fund to operate and service the system.

Important activities for ensuring economic sustainability include training, employing market surveys prior to implementation, understanding the short- and long-term system costs, and reducing uncertainty from external conditions as much as possible. Ideally, systems can be self-financed and self-sustaining. In some places, this hope is becoming viable. For most, the level of subsidy needed to establish and maintain operation hinges on diversified income streams, curbing non-project-related expenditures, and avoiding negative external influences.

table 2. Market survey data and use in off-grid system planning.

Market Survey Data	Use in Planning
Current energy use and expenditure	Initial system sizing, pricing model, mix of products and services
Aspirational use	Initial system sizing, future investment planning, compatibility with future electricity products and services
Competition	Risk to future income stream

table 3. Selected results from a 2013 market survey in Kenya.

Average kerosene expenditure per month	329 KES (US$3.87)
Average battery expenditure per month	404 KES (US$4.75)
Average mobile phone recharging expenditure per month	260 KES (US$3.06)
Average current distance to travel to charge mobile phone	2.26 km

Basic financial management training is needed to instill a longer-term economic outlook for the project. Developing a transparent savings mechanism is critical in establishing plans for reinvestment when the system's components inevitably fail. An NGO in Malawi typically began the conversation about long-term economics with the new community rather dramatically: "This system is going to fail. How are you going raise enough money to keep it sustainable?"

The prospects for economic sustainability can be greatly improved if a market survey is conducted prior to the installation of equipment. Surveys provide insight into several important areas, as seen in Table 2. With reliable data, an acceptable market price for the planned service can be estimated and used in a forecast of future income streams. An example of collected data for a planned project in Kenya is given in Table 3.

A model of asset failure and the associated costs should be provided for each project, along with its implications for replacement and higher-than-expected failure rates. A typical small PV system at a school in Malawi using a ten-year window and typical component life spans (see Table 1) has associated hardware replacement costs as follows: US$1,296 (lightbulbs) + US$1,440 (lead-acid batteries) + US$160 (inverter) = US$2,896. These costs must be planned for in both the short and long term. As projects grow into regional deployments or minigrids, these costs will scale accordingly, and a more substantial model is required. Other costs relating to labor, security, losses associated with distribution, and inconsistent tariff collection will put further pressure on system finances.

Financial discipline throughout the system life span can erode; careful management and oversight of project finances are extremely important (see Figure 5). For example, in several PV projects at off-grid schools in Gambia, income from providing electricity services was diverted away from the project and used instead to fund school operations, such as purchasing classroom supplies and pupil uniforms and supporting community vegetable plots. From the perspective of the teaching committees running these systems, the expenditures were reasonable since they benefited the students. Over a longer-term horizon, however, when station batteries, inverters, and lightbulbs inevitably fail, the schools will be unable to cope with the significant expenses of replacement if no reserve funds have been built up.

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Despite reliable market data and the subsequent expectation of a steady income stream, economic sustainability can be threatened for a variety of reasons, even some that are external to the project. The Mikolongo primary school in Malawi had a PV system installed in 2009. In 2012, the main grid was extended to less than 1 km away. The school's mobile phone-charging business, which had previously generated roughly 12,000 MWK (US$75) per month, could not compete with the businesses that popped up using less-expensive main grid power.

Economic sustainability can differ greatly from project to project. In the best of circumstances, rural off-grid projects walk a narrow line to cover operating and asset replacement costs with a modest income source. Threats to system finances due to, for example, top-line income reductions (extension of the main-grid connection nearby) or bottom-line expense increases (higher system failure than forecast or nonsystem expenses) can nudge the whole project toward unsustainability. Further complications include the changing external macroeconomic and supply chain issues that many developing countries face. The target customers for off-grid systems may be more vulnerable to these conditions than other people.

Social Sustainability

Although access to electricity correlates well with various indices of human development, it is also disruptive to the sociocultural norm, with consequences that are difficult to anticipate and appreciate fully. It is easy for unforeseen changes in sociocultural dynamics to tilt a project into unsustainability. Prospects for sustainability can be improved, however, if at the inception of a project the key stakeholders are identified and consulted and community buy-in is obtained.

An important stakeholder is often the local village chief or council, even if the system will be owned and operated by an independent organization or someone else in the community. A reason for this is that the incumbent local social hierarchy can be threatened. The supplier of electrical services has an asymmetric relationship with its customers and a great amount of control. The individual or organization in charge of the off-grid system, which may previously have had little authority in the community, may now find itself with considerable leverage and sway in local affairs. At the same time, the chief or council members may view all activities in their area as being under their purview and may feel that only with their approval should a project proceed. There are, of course, many other stakeholders that may need to be engaged depending on the project type, including community members, religious organizations, competing businesses, and local government. Unfortunately, the linkages between the stakeholders and the project are not always transparent.

Development projects should strive for community buy-in. That is, the community should both desire the project and act as a partner in the decision-making and resource allocation process. This partnering is crucial because issues of fairness and equity can be subtle but are important to take into account. Very rarely does a project provide electricity to *all* people in a community. Instead, a divide is placed between the "haves" and the "have-nots," and the potential for jealousy and criminal hostility directed toward the project can increase. In one case, a community charging station (CCS) was a target of arson in a dispute

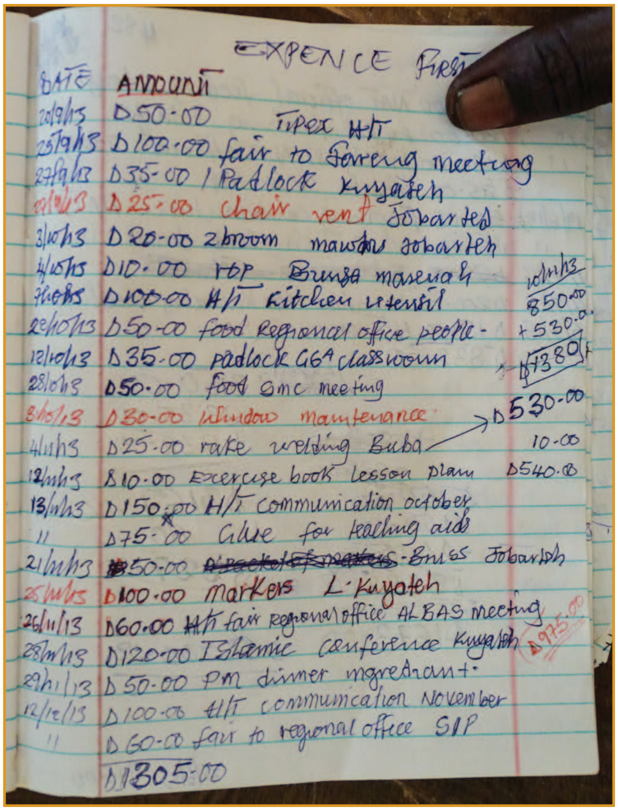

figure 5. Thorough bookkeeping promotes economic sustainability (photo courtesy of Peter Dauenhauer).

> It is evident that the degrees of success in electrification of rural communities vary from country to country.

between two communities. While the feud was not directly caused by the charging station, it was nonetheless a casualty of the conflict.

Engaging the community early will help determine if the project supporter's goals are in alignment with the community's desires. For example, a project might be financially supported by an organization on humanitarian grounds, based on the belief that when people are provided access to electricity they will use it to power lights, sensibly replacing the use of noxious, dangerous, and expensive kerosene. It has been observed in some cases, however, that the energy is instead used for televisions, portable DVD players, and other luxury and entertainment goods, while kerosene is still used for lighting. This "electricity repurposing" may be disappointing for the project's benefactor, but it does have social value. A year after installing one system, its owner was interviewed. When asked if he had purchased additional appliances, he responded that he now owns a color television and he invites his neighbors over to watch soccer matches. In this example, community and familial bonds have been reinforced by electricity repurposing.

The anthropological effects of electrification are broad and often surprising: changes have been reported in sleeping patterns, the number of meals consumed per day, and even the frequency of sexual activity on the part of married couples, along with other documented effects. The nuances, subtlety, and unpredictability of the sociocultural effects of electrification are difficult to plan for, especially for organizations from abroad. For this reason, organizations such as the IEEE Power & Energy Society's Community Solutions Initiative (CSI) require local NGO involvement for all of their projects to anticipate issues that may occur and deftly handle them when they do.

figure 6. Employee training in Bamenda, Cameroon (photo courtesy of Michael Wilson).

Organizational Sustainability

Organizational sustainability touches on the human and organizational capital required to set up and continuously run off-grid energy service organizations. Indeed, successfully addressing the global energy poverty problem more broadly requires identifying and growing systems that produce these important inputs.

CSI currently has off-grid initiatives in Cameroon, Haiti, Nigeria, and South Sudan, each of which utilizes a CCS model. In this model, rechargeable portable battery kits of approximately 17 Ah are available to the community for a monthly subscription fee. Each 1.5 kW of PV capacity per CCS translates into electricity access for about 450 people. CSI's mission is to scale these systems so as to provide modest amounts of electricity for a significant portion of the world's rural poor. For 1 million people, this will require more than 2,000 such systems. To achieve such scale will take not only a production line to manufacture robust hardware but also a business model with a substantial degree of organizational oversight.

Creating an organizational structure not unlike those adopted by the large, successful corporate franchise operations, in which technical and local operational training, customer relations, maintenance, financial transparency, and accountability are all highly codified, holds great promise. But imbuing the proper corporate culture across the cadre of indigenous local operators, who are functioning in an environment where favoritism and corruption is more the norm than the exception, brings with it additional training and operational challenges.

To adequately prepare and operate such a distribution of microutilities requires the establishment of a set of standard operating procedures implemented by a cadre of educated, motivated, and dedicated operators. From experience, observation, and the existing literature, it is clear that this is best achieved when the business at hand is managed by owner-operators.

To establish local skills, CSI's Haiti projects implemented an intensive training program with indigenous microutility entrepreneurs. Predeployment education in the areas of site selection (field survey and community qualifications); operation, maintenance and troubleshooting; system protection and security (dealing with weather, lightning, vandalism, and so on); customer service, relations, and expectations; bookkeeping, tariff collection, and banking; and ethics, transparency, documentation, and

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reporting are all critical to the success of such a wide-scale program (see Figure 6).

Providing the proper franchise model for a microutility operation, where all the benefits of larger corporate oversight can come into play to assure the maintenance of a set of operational standards and accountability while also affording the local operator remuneration that bears a direct relationship to the quality of its operation, has proven to be one business model with significant promise in terms of both sustainability and scalability.

Crossover of Sustainability Ingredients

Teasing apart the various factors that contribute to the sustainability successes and failures of off-grid projects reveals a web of interaction among ingredients that makes the analysis less than straightforward. A weakness in one area can snowball and affect other areas over time. Below, one classic (if stylized) scenario is constructed to highlight the challenge of factor interaction. The sustainability ingredient related to the action contributing to the failure of the project is provided in parentheses.

A rural, off-grid PV project is set up by an NGO benefactor at a school to provide basic lighting for pupils studying at night. To support it, the school staff charges a fee to recharge mobile phones in the surrounding community. Mobile phone charging grows from several per day to ten—the design limit—and then to 20 and sometimes more (technical and organizational). The lights begin to switch off nightly after only an hour of study as it becomes typical for the low-voltage disconnect on the charge controller to protect the battery. The operator attaches a spliced power strip directly to the battery terminal because this allows more phones to be charged despite the lights' going out (organizational).

Meanwhile, the station battery never gets an opportunity to become fully charged and over time is damaged to the point where it cannot hold a charge at all. Revenues dry up from mobile phone charging as customers get their phones back with incomplete charges (economic), and the community, learning that its children can no longer study at night, begins to suspect the operator is siphoning off a personal profit at the expense of the pupils (social).

The NGO arrives later to find a failed system. Any one of the sustainability factors can be pointed to as the cause of the breakdown. During sustainability assessments, it is difficult to disentangle cause from effect, as the events unfold over time and can be interpreted in different ways. In truth, only a holistic view of the situation and its evolution will truly capture the problems, and any solution will depend on the progression of events.

Creating an Enabling Environment for Off-Grid Sustainability

It is evident that the degrees of success in electrification of rural communities vary from country to country. A critical assessment of successful and less successful programs indicates that a sound and robust institutional framework underpinning the electrification effort is critical in creating an environment that maximizes the prospects for the sustainability of off-grid systems. Drawing on experience from several developing countries in Asia and Africa, an attempt has been made to synthesize the key institutional elements that encourage sustainability.

Off-grid systems can be local monopolies. Those that serve substantial numbers of customers must be regulated with regard to the price and delivery of services. This requires a strong and well-resourced regulatory regime that is both robust and transparent.

The existence of a national electrification management and policy implementation agent enables sustainable development. It is helpful to provide a one-stop shop under, for example, a ministry of rural development, where all aspects of rural electrification can be dealt with and where a clear and transparent approach for nongovernmental electric service providers to set up and operate their business at various size classes can be established.

Financing is perhaps the single most important aspect of such projects, as without it no project can take place. Incentives for financing rural projects by, for example, exempting key components from import duties and value added taxes (VATs) can stimulate investment. The ministry of finance or the analogous government arm has a key role to play here. In the near term, many projects will require subsidies to be attractive to the private sector. It is important that once the subsidies are withdrawn a pathway to sustainability be clearly articulated and monitored through regulatory oversight or other suitable mechanisms.

Another key area that is often ignored in initial project planning is the safe disposal and recycling of certain potentially toxic components of off-grid systems. It is important to provide institutional support and policing to ensure that disposal processes are developed and adhered to.

Sustainable off-grid systems require local expertise in the technical and commercial aspects of the project. It is vital that training institutions be created or expanded so as to build up the proficiency of indigenous peoples in these areas.

Finally, for efficient and effective administration, off-grid rural electrification must be undertaken within the broader context of integrated rural development. Electrification should be considered together with the provision of other essential services such as clean water, health care, education, and waste disposal.

Building Local Capacity

Projects supported from abroad often rely on pro bono volunteer labor during the design and implementation phases. An opportunity for local capacity building is thus missed. Countries such as Kenya may have a small yet vibrant and growing ecosystem of companies in the small-scale, off-grid energy system space. Forced to compete with free labor from abroad, a "reverse outsourcing" effect occurs in which paid workers in Kenya are replaced by volunteers from abroad.

Supporting indigenous companies builds local capacity, which in turn improves project sustainability. Maintenance and repair costs can decrease, as they can be locally sourced, and the community may view a project more favorably having participated in its installation. Only through building local capacity will the need for foreign involvement end.

The Need for a Framework

This quick dive into the sustainability of rural, off-grid electrical energy projects in developing communities has revealed the breadth and complexity of the issues that can threaten a project. With the combined experience and foresight that engineers and other practitioners currently have, there is no reason that future development should not strive to meet sustainability expectations. Unfortunately, despite the progress made in achieving energy access over the last two decades, sustainability is uncertain, and learning processes are not yet in place to gather and disseminate robust sustainability data. In other words, learning in this area is both ad hoc and fragmented.

The need is clear: with so many sustainability considerations and the high stakes of substantially improving people's lives through development, there is an imperative to develop a systematic framework to assist practitioners in planning for and evaluating the sustainability of off-grid development projects. The IEEE Power & Energy Society's Working Group on Sustainable Energy Systems for Developing Communities is in the advanced stages of developing such a framework.

The IEEE Working Group

Recently, the United Nations set the year 2030 as a target date for universal access to modern and sustainable energy services, including electricity. With a "business-as-usual" approach, however, more than a billion people will still lack access to electricity in 2030. This is why the United Nations has called for the acceleration of the worldwide transfer of best practices. The IEEE Power & Energy Society created its Working Group on Sustainable Energy Systems for Developing Communities—among other initiatives—in response to this call to action.

The aim of the working group is to address the various dimensions and issues associated with provision of electricity services to rural and remote areas and to provide recommendations for decision makers. A key activity in support of this aim is the creation of the aforementioned sustainability framework.

Conclusions

In summary, small-scale, off-grid systems can provide access to modest yet important levels of electrical energy to millions of otherwise energy-impoverished people around the world. Up-front consideration of the key sustainability ingredients described in this article gives these systems the best chance at providing the greatest benefit over the longest time frame.

For Further Reading

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Biographies

Henry Louie is with Seattle University, Washington.

Peter Dauenhauer is with the University of Strathclyde, Glasgow, Scotland.

Michael Wilson is with the Torchbearer Foundation for Missions Reconciliation and Development, Branson, Missouri.

Adriaan Zomers is with Alliander for CIGRÉ activities.

Joseph Mutale is with the University of Manchester, United Kingdom.

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