Reliable Electric Power for Developing Countries

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1.0 Introduction: What's Needed

Everywhere in the world, reliable electric power is key to economic development, education, and medical care. In developing countries, electricity is fundamental for many essential services, including those that increase income and benefit rural areas. Major uses for electrical power are:

- **Agricultural:** Electrical energy is important for the enhancement of rural production and food security through land preparation, fertilization, irrigation, agro-processing and conservation. In many rural areas, energy needs are, at present, predominantly supplied in the form of traditional biomass fuels and human and animal labor. This inequitable scenario severely limits many rural people from enhancing their agricultural productivity and quality of life.

- **Water Purification and Distribution**: Energy is required for water collection, distribution, and purification. It is well accepted that drinking unclean water is one of the biggest killers in the developing world. Around 10% of children under five years of age die each year from water-borne diseases such as diarrhea, bilharzia, typhoid and cholera. Applications of electrical energy in this field include both mechanical pumping and filtering of the water supply and its ultraviolet (UV) disinfection.

- **Health care:** Modern energy services are key to improving the health of people in rural areas of many developing countries. In health clinics, access to electricity provides for well-equipped maternity facilities and medical equipment and safe storage for vaccines. Electricity in housing accommodations makes it more likely that doctors, nurses and other skilled staff will be retained.

- **Education:** In rural schools, electricity is needed in order to make use of modern learning technologies. These include computers, lighting to facilitate adult education and literacy classes in the evenings, community access to educational audio and video media, as well as helping to retain teachers.

- **Commercial and Industry Application:** Reliable electricity should be scalable to communities, not just adaptable to individual farms or households. Uses will include small factories and commercial enterprises with power needs up to at least 100 kW.

- **Bidirectional Communications:** The wireless phone is the predominant personal and business two-way communications tool in developing countries. In some areas, hand-held, two-way radios (walkie-talkies) are also used. Charging these portable communications devices requires electrical energy. The desire for communications is so great that people will walk for miles to find a charging station for their phone batteries.

- **Residential and Community Quality-of-Life**: Rural households and communities use electrical power for lighting, television, and radio. Many households without access to electricity routinely use dry cell and lead-acid car batteries for modest power needs. The average household needs on the order of 0.1 to 1 kW.

Effective and sustainable energy-planning policies are needed in developing countries to stimulate investment in power-plant modernization and in rationale energy usage. In this connection, the main critical points to address are that:

- The electric power industries are among the most capital-intensive in an economy and drain scarce financial resources;
- For countries lacking energy resources, importing fuels is a major drain on foreign exchange reserves;
- Environmental issues, such as the fact that higher levels of carbon emissions go along with economic development, further increase the complexity of energy decision making.

All these factors make defining effective and sustainable energy planning policies for developing countries very complex.

Developing nations can count on a variety of potential electrical energy sources, including solar, hydroelectric, people-powered, fossil-fueled, geothermal, and wind. To maintain availability of electricity, backup batteries are often used. Cost remains a major factor in obtaining affordable power sources. But frequently power sources are undersized, battery and charging system are often misused and fail, and there is a lack of standard and convenient interfaces for switching among various power sources based on capacity and demand.

Some power sources are AC, typically 220-volt, 50-Hz, and others are DC, typically solar-powered or backup batteries DC to AC inverters, or devices capable of operating off either type of power, are important and generally lacking. Where electrical energy sources are present, there often is insufficient operations, maintenance and repair capability on the part of the local people. A lack of spare parts and a lack of local knowledge, including illiteracy in some cases, contribute to once-functioning systems languishing in a state of disrepair.

Such challenges can be met successfully by making use of some or all of the following:

- Low power (0.1 to 1 kW) stand-alone power-generation systems
- Low/medium power generation (1-5 kW) with multiple generation and storage capabilities
- Developing new technologies for micro-power generation
- Developing solar kiosks for battery charging
- Identifying technological solutions for load interfaces and system management
- Finding new ways to improve energy efficiency
- Developing local training programs to support and promote initiatives in reliable electricity

We need to develop plans with the intended beneficiaries and with feet-on-the-ground Non-Governmental Organizations (NGOs) that can help set up and manage the initial implementation of any new systems. And we need a sustainable outcome that can be owned by the beneficiaries and, with their help, replicated in other areas. We need to envisage projects that can be multiplied a thousand-fold, and avoid high tech wonder babies that risk dying in their cribs.

2.0 Environmental Description

Roughly 350–400 million households, or 40% of the population of developing countries, have no access to electricity. The proportion of rural populations served by electric power grids range from 98% in Thailand and 85% in Mexico, to only 2% to 5% in much of sub-Saharan Africa. In particular, almost 1.6 billion people in developing countries currently live without electricity. They live in either remote rural areas that have no connection to a power grid, or urban areas with inadequate utility systems. Those who live beyond the electrical networks also lack access to health care, education, communications, and enterprise opportunities that modern energy services can facilitate. The lack of access to modern energy services severely limits socioeconomic development—an integral part of sustainable development.

The demand for energy in these countries is expected to grow with increases in population and living standards. The International Energy Agency (IEA) estimates that by 2020, developing countries will need to double their electrical power output. Demand for energy is growing much more rapidly than the rate of expansion of conventional electricity grids. Also, if we aim to reach the United Nation's Millennium Development Goals, estimates predict that developing counties will have to more than double their energy capacity.

Using guidelines of having one health clinic for every 5,000 people, Africa and India, with populations of more than 900 million and 1 billion people respectively, should have about 400,000 health clinics, each needing some source of power. Other developing nations have about another 500 million of un-served or under-served people. Similarly, using as a guideline one school for every 1,500 people, about 100,000 schools would be needed across the developing countries of the world. Lighting the schools and powering basic learning tools such as PCs require electricity. One estimate puts power currently available in only about half the areas where it is needed.

Another estimate is that the basic, getting-started need for power in un-served villages is 0.1 to 1 kW of generating capacity, or 0.13 to 1.3 HP, with a corresponding battery backup capacity of about 1 to 10 kW-hrs. A typical rural hospital needs 3 to 5 KW, ideally provided from multiple sources for reliability and to accommodate peak usage (for example, being able to turn on a local generator for auxiliary power when the energy-consuming X-ray machine is in use).

Solar systems are used today in some developing areas at relatively high initial cost. Twelve-volt solar panels generally cost US $5 to $6 per watt and generally need a 10- to 15-year payback. Getting the payback period down to five years or less would make them much more attractive.

Backup battery packs for solar systems are typically of the lead-acid type, with a five-year life, if properly maintained. Most do not last that long because of poor maintenance. Some solar and other power generators have inverters to convert DC power to AC. Such converters are generally inefficient and waste energy. DC-powered appliances would result in more effective use of the limited electric power.

Experience shows that once power becomes available, demand often exceeds the capacity to deliver it. For example, people will travel to power sources to charge their cell phones. But as the number of such users grows, less power is available for its originally intended uses. Often, the reduction in power availability because of over-consumption results in insufficient battery charging, so little or no power at all is available when the power source is offline. This is sometimes misdiagnosed as "faulty batteries" when the true problem is that with the additional load, the power demand exceeds the generation capacity.
In some areas where power generators are available, prolonged equipment breakdowns occur because of a lack of spare parts and little knowledge of preventive and corrective maintenance. One estimate is that about half of all new equipment in the field will fail in the first year of service.

Well-intentioned benefactors sometimes provide mid-to-large-sized power generators, but no ongoing budget for fuel or maintenance. Using generators that are oversized for their load, results in expensive and inefficient use of fuel. It is not uncommon for villagers to purchase just a half liter of petrol to run a generator for a limited time for battery charging. The cost of transporting fuel can be a substantial factor in the cost of electricity. Running a 20 kW generator part-time typically costs US $500 per month.

In the field today, small generators generally run on petrol while larger ones of 10-20 kW run on diesel fuel. Diesel generators are usually of simpler engine design and easier to repair.

Switching among power sources is often done manually, by removing a plug from one power source and inserting it into another. It is not unusual to see multiple power strips attached to extension cords fed by different power sources, with the user shifting appliance plugs from one power strip to the next.

Recent technological innovations in Distributed Generation Systems (DGS) and the sensible growth of Information and Communication Technologies (ICT) could play a strategic role in bringing reliable electrical power supplies to developing countries.

DGS are based on small generators compared with typical central station power plants. The distributed systems provide unique benefits not available with centralized electricity generation. Many benefits stem from the fact that the generating units are inherently modular, which makes distributed power very flexible. The generators can provide power where it is needed, when it is needed. And because they typically rely on natural gas or renewable resources, the generators can be quieter and less polluting than large power plants, which make them suitable for installation at user locations.

The integration of ICT-based systems with DGS could improve the latter's efficiency in several ways. The combination could make possible the optimal regulation of generator parameters as a function of environmental variables (using online control), automatic detection of system anomalies (with online diagnostics), remote system management, optimal maintenance scheduling, and more.

The challenge of bringing reliable electrical power to developing countries needs a set of technical, operational, and financial solutions particularly suitable for developing countries. For example, in addition to electrical energy generation and energy management products, training programs for people in charge locally are also needed. Without training, problems with day-to-day maintenance of the technical systems, as well as weak system management, are likely.

Technologies to be considered for solutions should consider nodal as well as networking aspects of powering, spare part availability, system protection, and administrative control. Solution elements should have the following characteristics:

- Low cost
- High reliability
- Low maintenance
- High scalability
- High flexibility
- Be environmentally friendly

We propose that a four-pillar approach be considered when identifying and evaluating applicable technologies:

1. Building a reliable, standard, modular power system suitable for a variety of developing countries. The system should:
   - Accommodate multiple power sources
   - Auto-switch among sources
   - Auto-start auxiliary power sources (e.g., generators)
   - Autosense fuel levels and maintenance status
   - Have a battery or other backup storage
   - Follow standards for open sourcing and interconnectivity of elements from different suppliers, including, most importantly, in-country sourcing
   - Utilizes Smart Grid Internet protocols
   - Provide a communications hub for grid preference, electricity demands, availability, rate information, etc.
   - Foster new energy management applications that provide a set of monitors to respond to disasters
   - An Independent System Operator to manipulate the importation of power and load shedding, Time-of-Use (TOU) switching and other techniques. These actions could be

monitored or controlled by local government agencies, e.g., Ministries of Health for clinic power systems.

2. Encourage intensive conservation
3. Promote and develop stakeholder involvement
4. Apply smart, next generation, energy storage systems
5. Generate electricity through renewable sources, i.e., solar, wind, geothermal, etc.

Identifying the most suitable technological solutions for each site is critical. This comprises gathering and analyzing local data, such as the following:

- **Weather data**: solar radiation, temperature, wind speed, etc., on a medium to long time horizon of 1 to 5 years, are necessary to identify the best generation technologies, the expected producible energy, and maintenance procedures.
- **The existing electrical infrastructure**: data about the generation, transmission and distribution facilities already in place.
- **Energy indicators:** statistical classification of economic activities, number of people in the area, number of families, energy demand, etc.

While it may be tempting to focus on power sources, it is worthwhile also to consider the power consumers. Inefficient refrigerators, incandescent lighting, and old desktop personal computers are significant energy-wasters. Improving the efficiency of such energy consumers could extend the utility of the local power-generating systems planned for installation.

As potential solutions are explored, a few pilot locations should be identified where detailed data can be assembled and analyzed to ensure that what is proposed will truly meet local needs and fit the local environment.

As an example of developing country environments, the following first-hand observations have been provided by one of our major contributors:

> "There are both urban and rural problems with electricity reliability, but perhaps the biggest problem affecting the most people is the near, or complete, lack of electricity. This is certainly true in the few rural areas I have seen personally, such as Guatemala, Mexico and parts of Southern Africa. In rural Guatemala, I lived for several weeks in a small town, working on a project to build new school structures after a huge

earthquake, and this town had basic electricity but most people (farmers) did not seem to have it in their homes. Their houses were made of cornstalks with dirt floors and had typically one cooking vessel. The only electrical machine was one corn grinder that started up at 5 a.m. every morning to serve all the women who needed the day's corn ground into meal. There was an issue with getting children of even five years old to come to school, because their labor was often needed in the fields of the small coffee plantations. Our group of workers owned a gasoline-fired mixer for the concrete and mortar for our project.

"By contrast, in the middle of the huge city of Johannesburg was Soweto with about 7,000 residents crammed into a few square blocks. The tourist showroom house – two small rooms for seven people – had a 12-volt car battery which serviced one light bulb and a very tiny black and white television. For cooking, there was a tiny camp-sized stove, burning paraffin that left soot all over anything above it. A few entrepreneurs provided a community service to charge the batteries and deliver cooking fuel daily. They also delivered water in cans drawn from the two spigots in the area. The sanitation for these 7,000 residents was a row of 10-to-12 porta-potties. This area was relatively well kept and there was a volunteer medical service at a nearby center. We also saw the other Soweto, the upscale part where the Mandelas and Bishop Tutu lived. Later in Capetown, we saw the most upscale beautiful shopping areas and hotels juxtaposed with some of the most deplorable shanty towns of 10,000 to 20,000 on the outskirts toward the airport. It was only a year or so ago that these areas even got a water supply and sufficient electricity to run small appliances, thanks to the high priority given the program by the new government.

"So, one rural setting, and another setting in or near a huge rich city, have very similar problems. In the first case, the local source of electricity is meager and not reliable; in the second case it is close by, but inaccessible because of poverty.

"This is the picture in my mind as I ask, what electrical supply model or models would work in these areas that would (a) immediately benefit the populace; (b) be based on a locally sustainable economic model; (c) be operable and maintainable by people in the community; and (d) have local backup capability to guarantee reliability and high availability?"

3.0 Shorter-term Challenge (about one to two years)

For the short term, we propose four areas for improving the availability and reliability of electrical power:

1. **Low/medium electrical power generation**

- **Low power (0.1 to 1 kW) stand-alone power generation:** A stand-alone power generator able to deliver 1 kilowatt per hour of electrical power. Used primarily where no other sources of electrical power exist, it could also supplement other sources. AC or DC output. Used for lighting, cell phone charging, powering medical instruments and PCs, driving irrigation systems and charging backup batteries and to handle peak usage periods and times of generator outage. The generator would:

  - ✓ Use diesel fuel, at a minimum, with other fuels also considered
  - ✓ Tie into the power grid, if it's available
  - ✓ Have "load-following" capability for efficient operation across a range of load levels
  - ✓ Have reliability suitable to the local application
  - ✓ Operate in dusty conditions that would clog most cooling fans, in an environment of up to 55-60 degrees C
  - ✓ Have controls to limit overloads
  - ✓ Offer efficient power generation at staged operating levels (e.g., at quarter, half, three-quarter and full capacity)
  - ✓ Be locally maintainable:
    - o Self-monitoring and self-diagnostic
    - o Have easy-to-replace parts
    - o Provide auxiliary or integral maintenance training

  In addition to the above requirements, the generator should:

  - ✓ Be capable of being powered by a variety of fuels, including diesel, kerosene, gasoline, LPG, plant oils, waste vegetable oils, and bio-gas.
  - ✓ Be usable for mechanical applications, such as water pumping
  - ✓ Produce little air pollution (measured as PPM of CO_2)
  - ✓ Produce modest noise levels

- **Low/medium power generation (1-5 kW) based on multiple generation and storage technologies:** Hybrid (multi-source) generators able to work in both grid-connected and stand-alone configurations. The generator should include a combustion engine, a DC generator, a storage system and a DC-to-AC inverter. The engine should produce DC power to charge batteries and run an inverter. The Inverter converts the stored DC power to AC electric energy. Having battery storage also helps the engine absorb load spikes. Energy from wind or solar power should be capable of being interconnected with the generator for increased efficiency. To accommodate multiple sources of power, the generator system should use a computerized controller to control operation, usage, and energy production. The controller should also monitor the engine's starting and stopping (i.e., it should shut the engine off when demand is low and start and optimize its operation when the power from the engine is needed). A program to build and maintain this generator with local manpower should be included.

- **A solar kiosk for battery charging**: comprised of a photovoltaic generator, a local storage system and a charge controller. The controller takes the varying power levels from the solar panels and conditions it to safely charge the modules in the storage system. The charge controller should rely on pulse-width modulation (PWM) and a three-stage charging method: bulk, absorption, and float (maintenance) charge. It should also isolate the panels from the batteries after the sun goes down. The components should be sized to assure adequate backup battery charging, considering the irradiance characteristics of the site.

- **Backup battery pack:**
  - ✓ Battery state monitoring to assess degree of charge/discharge, long-term battery wear, and estimated life.
  - ✓ Deep discharge protection to prolong battery life.

- **AC/DC conversion** is also needed as a supplemental capability for complete power plant operation.

2. Technology for load interfaces and system management:

- **An automatic source switcher**: Power electronics should be considered for sensing power sources and loads, and automatically switching sources to accommodate the loads. The system would work in conjunction with one or more stand-alone power generators, solar systems, electricity power grids, batteries, and other power sources. It should be able to switch among power sources, and even connect to multiple sources simultaneously to meet local load demands. Conversion between AC and DC (both rectification and inversion) is desirable. In its simplest form, this is an Uninterruptible Power Supply (UPS) without built-in batteries. Note, however, that most commercial UPS systems for the developed world are not well-suited to harsher environments and more frequent power interruptions.

- **An intelligent charging and load-management system:** An electrical system connected to a generator and batteries should be able to of monitor and report loads, limit power consumption to reduce excessive battery drain and generator overloads, and charge backup batteries to their full potential. Charge controllers today are relatively inefficient, and most reported field failures of batteries result from incorrect or insufficient battery charging and discharging. Failed batteries are often insufficiently charged because other power demands almost match, or exceed, generator capacity, leaving insufficient spare capacity for charging the backup battery. Insufficiently charged batteries are then too frequently deep-discharged, leading to their early demise. Batteries in the field are usually sealed lead-acid.
- **An Intelligent Electronic Unit (IED) for automatic diagnosis and remote management of distributed power resources.** IEDs receive data from DGS sensors and power equipment, and can issue control commands, such as load shedding, if they sense voltage, current, or frequency anomalies. Or they can raise or lower voltage to maintain the desired level. An IED can assure that the DGS functions reliably; it should be equipped with an external bi-directional data-communication unit for connecting the system operator with the electricity user. With this, the system operator could receive basic information and even forecasts of the reserve levels while the electricity user would know when controls and smart-metering actions are expected at the point of use. Data exchange could be supported by mobile Short Message Service (SMS) messaging or a plug-point device, using smart-metering protocols.

3. **New solutions for improving energy efficiency**: Energy efficiency is one of the most effective means of meeting rising energy demands. It can limit the rate of increase of electric power consumption and so reduce the need for capital-intensive investment in generation. For example, a range of technological options is available to achieve energy savings in electric lighting. These include using more efficient lamps and ballasts, and lamps with a high light output ratio. The introduction of innovative light-emitting diode

(LED) light sources and solar lanterns is expected to accelerate energy savings. For irrigation and potable water transportation, e.g., for moving water between cisterns, more efficient DC motors and pumps could reduce electric power requirements, freeing up power for other uses.

4. **Training programs**: Strengthen local expertise in energy technology so as to encourage initiatives in developing reliable electrical energy systems:
   - Develop training courses for students and teachers in high schools, universities and technical institutes;
   - Favor the exchange of information among expert organizations and professionals qualified to work in the field of energy production;
   - Organize regional forums and workshops focused on mature technologies adapted to energy production;
   - Work collaboratively with industry for industry-specific but vendor-neutral certification of people qualified to install and repair smart meters and smart grids;
   - Offer online training courses;
   - Teach local talent to administer, operate, and maintain electrical power equipment.

   These might be efficiently and effectively accomplished by partnering with other groups involved in supporting the local community, especially local universities.

4.0 Longer-term Challenge (about three to five years)

Develop a network of interconnected active energy nodes for supplying electrical energy in larger areas, comprised of one or more of the following:

1. **Village-scale micro-grids:** Village-scale micro-grids can serve tens or hundreds of households in settings where sparse population density does not allow economical interconnection to a large central power generator. Traditionally, mini-grids in remote areas and on islands have been powered by diesel generators or small hydroelectric systems. Generation from solar PV, wind, or biomass, often in hybrid combinations, can replace or supplement diesel power in these grids.

2. **Advanced Energy Management Systems for remote control, monitoring and management of power systems facilities**: An advanced control system for the optimal management and control of DGS should be considered. The wide dispersion of DGS presents an opportunity to organize the control architecture in a set of functional modules connected by a high-speed Local Area Network (LAN), open to both external connection (Wide Area Network, WAN) and field connections by terminal servers and modems. The overall control architecture could be structured in the following functional modules:

   - A front end for field data collection;
   - A server for Supervisory Control and Data Acquisition (SCADA) applications;
   - A server dedicated to the Distribution Management System (DMS), Energy Management System (EMS), and the Data Base Management System (DBMS) for
   - Historical data storing (possibly with an applet server);
   - Telecommunications equipments dedicated to WAN and field connections.

   Monitoring and control functions emerging from this distributed assessment architecture should be developed based on open standards, on an open software platform, possibly JAVA software-based. Such a software platform should integrate a web server for graphical synopsis and report development, a server (possibly Apache Tomcat) to support the software modules, a Data Base Management System (DBMS) for historical data storing, a mathematical solution engine for post-processing activities, and a Virtual Private Network (VPN) to assure connectivity between the remote units and the host servers. The principles and design criteria assumed as reference in developing this architecture should be oriented, in particular, to assure high reliability and robust levels for the entire system by:

   - Hardware redundancy;
   - A high level of modularity and expandability that allows the system to be easily adapted to the control centers;
   - Function sharing on various hardware modules;
   - Adoption of standard software packages for system programming;
   - Employment of open source principles to allow better integration of the software components as well as uniformity in the system administration;

- Structured and controlled access to a double-level database to assure both fast data access and high reliability levels for the stored data.

5.0 Applicable Technologies

- Electrical energy production
  - Photovoltaic
  - Wind
  - Fuel cell
  - Biomass and biodiesel
  - Diesel generators
  - Combined heat and power generators (CHP)
- Electrical energy storage
  - Batteries
  - Flywheel
  - Compressed air
  - Hydrogen
- Management systems
  - Standby power reductions for appliances to 1% (most at 10%)
  - Information and Communication Technologies
  - Sensor networks
  - Power systems communication
  - SCADA

6.0 Financial Considerations

- A basic power generation system should start at US $200-$300
- The target price should include a fair return to the manufacturer to ensure continued product availability and support.
- Foundation funding may be available for product development

- Some generators will likely be purchased by NGOs and government agencies for deployment where most needed. However, economic sustainability could be achieved if some fraction of the generated power is devoted to economic activity that would, in turn, pay for the cost of buying and maintaining the generator, thus leading to more deployments.
- Marketing the generator for other applications simultaneously, e.g., for temporary power needs, portable applications and disaster response could help lower unit cost by raising sales volume.

7.0 Related Humanitarian Needs

Reliable electric power facilitates meeting many other basic humanitarian needs: agriculture, potable water, health care, education, and others. In some cases, the mechanical energy used in systems to generate electric power can also be used to operate machinery that can pump water or perform other manual tasks. Also, some electric power generators can be operated in inverse mode, acting as electric motors fed by stored electrical energy in batteries.

8.0 Relevant Activities Already Underway

- ***Lighting Africa*** is a World Bank Group (WBG) initiative which supports the private sector to develop, accelerate, and sustain the market for modern off-grid lighting technologies tailored to the needs of African consumers.
- Many different humanitarian initiatives focus on distribution of solar cells for powering
- Winrock International initiative on electrification of schools in Brazil
- Low pressure steam engines are under development, which could serve as more efficient drivers for electric generators
- Whispergen Stirling Engine by Whisper Tech Limited is a new technology source of electric power generation

9.0 Non-technical Constraints

- To assure that spare parts are available, most or all of them should be manufactured locally
- Need to understand and appreciate prevailing sociological, political, or religious views that could affect the provision of reliable electricity

10.0 References and Best-Practices

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