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VILLAGE POWER HYBRID SYSTEMS DEVELOPMENT IN THE UNITED STATES

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INTRODUCTION

The energy demand in developing countries is growing at a rate seven times that of the OECD countries, even though there are still 2 billion people living in developing countries without electricity; most of these people live in remote villages, far from the established grid. Line extension is generally uneconomical; and diesel gensets are expensive to operate and maintain, and have proven to not be environmentally and economically sustainable for remote applications. Renewable energy technologies offer an economical and environmentally sustainable solution for bringing power- and its educational, economic development, health, and quality of life benefits- to remote villages.

Many developing countries have social and economic development programs aimed at stemming the massive migration from the rural communities to the overcrowded, environmentally problematic, unemployment-bound urban centers. It has been estimated that $1 invested in rural communities potentially offsets $6 required to provide support services and mitigate impacts on an urban setting.

To address the issue of providing social, educational, health, and economic benefits to the rural communities of the developing world, a number of government and non-government agencies are sponsoring pilot programs to install and evaluate renewable energy systems as alternatives to line extension, diesels, kerosene, and batteries. These programs are underway in Mexico, Brazil, Indonesia, Bolivia, Guatemala, Mauritania, the Caribbean, the Philippines, and India. These programs are aimed at generating the experience and performance data required to develop large loan requests to the financial community for multiple village-power applications. Several of these loan requests are on the order of $100 million. An official of the World Bank's Environmentally Sustainable Development Department recently stated that the World Bank and multilateral institutions should strive to incorporate renewable energy options into ongoing and pending projects in the developing world.

The use of renewables in remote international villages has yielded mixed results over the last 20 years. However, recently, photovoltaics, small wind turbines, and micro-hydro systems have gained increasing recognition as reliable, cost-effective alternatives to grid extension and diesel gensets for village-electricity applications. At the same time, hybrid systems based on combinations of PV/wind/batteries/diesel gensets have proven reliable and economic for remote international telecommunications markets. With the growing emphasis on environmentally and economically sustainable development of international rural communities, the U.S. hybrid industry is responding with the development and demonstration of hybrid systems and architectures that will directly compete with conventional alternatives for village electrification. Assisting the US industry in this development, the National Renewable Energy Laboratory (NREL) has embarked on a program of collaborative technology development and technical assistance in the area of hybrid systems for village power.

Following a brief review of village-power hybrid systems application and design issues, this paper will present the present industry development activities of three U.S. suppliers and the National Renewable Energy Laboratory.

APPLICATION ISSUES

Off-grid applications in developing countries typically fall into three broad categories that differ in level of energy demand and system configuration: (1) individual home or dwelling power systems for lighting and small appliances; (2) dedicated productive use or rural community facilities applications such as communications, commercial enterprises, health clinics, and water pumping; and (3) general-purpose electrification of rural communities. The systems options for these applications fit into two basic configurations: (1) distributed stand-alone systems that are each dedicated to physically localized load use, and (2) centralized generation systems with a local "minigrid" that distributes power to a number of physically separated loads.

The mini-grid category represents multipurpose electrical power service to communities with populations of several hundred to several thousand (perhaps 50 to 500 households or more), with overall energy demand ranging from several tens to several hundred kWh per day. Depending on the physical layout of the community and load density, the appropriate technical options can range from the distributed individual stand-alone systems to centralized wind hybrid system generation with a local distribution network, to an appropriate mix of the two that is tailored to the local needs and load distribution of the community. The higher overall energy demands for the centralized community power system options discussed here will typically require the use of multiple wind generators of 5-50 kW capacity.

The appropriate technical options for off-grid power needs depends on the available energy resources; the end-use energy requirements and anticipated demand for power, and social, economic, and cultural factors that impact the practicality, acceptance, and sustainability of the various possible technical approaches. There will always be trade-offs between achieving optimum technical performance in any given system and providing a practical solution for meeting an energy need that is both acceptable and sustainable under local conditions and constraints. There are three practical guidelines to follow when considering appropriate technical options: (1) ensuring a good match between the available energy resources, the end-use needs, and the end-user culture; (2) reducing energy requirements where possible through conservation and efficiency measures; and (3) designing and implementing systems and support services with long-term sustainability in mind.

DESIGN ISSUES

The design of a village power system begins with a definition of the current, anticipated, and long-term electrical loads. The loads definition process should include average power levels, start-up surge power levels, and a diurnal distribution, which is usually based on hourly averages. If the village currently has a diesel generator, this definition is best accomplished using manual or automatic load monitoring. If no power generation exists, then an analysis must be performed to calculate the anticipated loads and their time profile. This analysis is usually based on assumptions of specific appliance use (e.g., homes will have four 10-W fluorescent lights operating 4 hours per day, etc.). Projections on future load growth are also made, and systems are typically sized for anticipated needs two to ten years after commissioning. System capacity requirements are normally expressed in terms of energy (kWh/day) and peak power (kW).

The next step, and often the most challenging, is to define the resources (the wind and solar resources). As a first cut, the 1980 U.S. Department of Energy "World Wind Energy Resource Map" provides reasonable estimates of yearly average wind speeds. (However, it should be noted that wind resources can be very site-specific). The wind resource information available from local meteorological sources in developing countries is notoriously inaccurate, usually underestimating available resources by a wide margin. The problem is that wind data are often taken from sheltered urban or airport sites. Higher quality data are available from military, upper air, and maritime sources, but collecting and processing these data can be time consuming and expensive. For large-scale projects, either in size or scope, site resource monitoring is prudent, even if only for a few months to verify the resource. On very small, single-system projects, site monitoring may not be justified economically.

From the loads information and wind/solar resource estimates, the designer can explore various component-sizing options. In almost all situations, the system includes a battery bank for short-term energy storage, an inverter to supply the AC power, and a system controller, switchgear, and back-up diesel generator to cover the loads during periods of low wind. From a hardware perspective, wind turbines have a cost advantage over PV and often an advantage over diesel systems; so, wind is often chosen as the dominant supply option when an adequate wind resource is available.

Least-cost (life-cycle) design is normally the major goal, but other customer-driven factors like the renewable energy contribution ratio, environmental benefits, maintainability/ support, and initial capital costs can significantly influence the process. Design tools are limited and are largely proprietary. Least-cost designs arrive at relative energy contributions of 50%-75% from renewables and the remainder from the diesel genset, depending on a number of local economic and site-specific resource factors. Currently, system integration is not a prescriptive science, yet a number of firms have gained wide experience in village system design. U.S. industry can now install complete systems that provide a quality of service and reliability levels approaching grid-based utility service.

INDUSTRY DEVELOPMENT ACTIVITIES

While the market for hybrid village power systems is still in its infancy, several companies in the United States have invested in system and market development activities that will generate the experience and equipment that are necessary to open this potentially large remote electricity market. The current systems offered by these companies have resulted from their experience in the related telecommunications and small, stand-alone wind and photovoltaic remote applications in international markets. Each of the three hybrid systems suppliers discussed in this paper have selected system designs based on what they believe will meet the multiple needs of the international village marketplace.

BERGEY WINDPOWER COMPANY (BWC)

Bergey Windpower Company is a manufacturer of small wind turbines in the size range of 0.85-10 kW. BWC turbines utilize passive controls, fiberglass blades, direct-drive permanent magnet alternators, and integrated structures to provide for mechanical simplicity that results in high reliability turbines and low maintenance costs. Approximately 1400 BWC turbines have been installed in more than 60 countries. These systems are primarily used for rural electrification, water supply, and remote telecommunications. In addition to supplying wind turbine and balance-of-system equipment, BWC also serves as a system integrator, installer, trainer, and after-sales service contractor.

BWC is pursuing village power systems in the size range from 1.5 to 80 kW. Village power systems utilizing BWC wind turbines have been installed in twelve countries, including India, Indonesia, Australia, Russia, and Mexico. Pilot installations are underway in the Philippines, Uruguay, and Brazil. These systems typically include one to ten turbines, a DC bus, batteries, a bidirectional inverter/charger, a back-up diesel generator, and on smaller systems, photovoltaics. The wind turbines and PV arrays are connected to the DC bus through separate, non-communicating voltage regulators. Battery banks are typically configured for 120, 220, or 240 VDC and are sized at 18-48 hours of load support. Static inverters usually include a reverse-mode battery charging capability and have a sinusoidal output waveform. Most systems operate automatically with the back-up generator start and other control functions being activated based upon battery bank voltage. On an annual basis the typical system derives 60-90 % of its energy from renewables and the balance from the back-up source.

Several of the village power systems are instrumented to monitor system performance; the system in Xcalac, Mexico, was heavily instrumented to evaluate system and subsystem performance. The Xcalac system was installed in August, 1992, and is comprised of six 10-kW turbines, an 11.2-kW PV array, a 400-kWh battery, and a 40-kVA inverter. It is monitored by a 40-channel data acquisition system which telemeters the data records to the Instituto de Investigaciones Electricas (IIE) in Cuernavaca, Mexico. The analysis of the data from this site has provided useful insights into the design and operation of DC bus-based village power systems, including subsystem interactions.

From a development perspective, BWC is working on both advanced equipment and new applications to improve its products and expand its markets. BWC, under contract to NREL, is developing a 15-kW IGBT high-frequency link, full-digital-control inverter to provide high reliability at low cost for its stand-alone AC systems. Also, BWC is developing, collaboratively with NREL, wind-electric ice-making systems for fishing and agriculture-based villages.

INTEGRATED POWER CORPORATION (IPC)

Integrated Power Corporation, a subsidiary of Westinghouse Electric Corporation, has installed PV/wind hybrid systems in Mexico and Indonesia. These installations have successfully demonstrated the application of pv/wind-based hybrid systems for rural village electrification. The following is a brief description of IPC's existing and imminent hybrid village projects.

Mexico experience: IPC, in collaboration with Compania de Luz y Fuerza Del Centro (CLYF), and Pronasol (the Mexican rural-development fund) installed two hybrid systems in the villages of Santa Maria Magdelena and San Antonio de Aquas Benditas, Mexico. The system that was installed in Maria Magdelena (54 homes) in 1991 has a nominal capacity of 45-kWh/d and is composed of 4.3-kW PV, 5-kW wind generator, 18.4-kVA diesel genset, a 132 kWh battery bank, and a 7-kVA, single-phase inverter. The system that was installed in Aquas Benditas (100 homes) in 1992 has a nominal capacity of 125 kWh/d; and is comprised of 12.4-kW PV, two 10-kW wind turbines, a 60 kVA genset, a 250 kWh battery bank, and two 7.5 kVA inverters operating in parallel. The system serves 100 homes.

The systems were designed to support both residential and commercial loads, and to accommodate load growth. Typical loads include household lights, radios, televisions, commercial refrigerators, and grain mills. Each system provides 24-hour available, utility-grade, 120-VAC power; IPC's Alliance inverter was specially designed for village power applications. Local labor was used for the foundation construction and wind turbine and PV array erection at both sites. The system at Maria Magdelena utilized a modular, factory-built system that was trucked to the site. The system at Aquas Benditas was site built using local contractors and equipment.

Both systems have proven extremely reliable, having been operated unattended, with virtually 100 % availability since installation. Anemometers were recently installed at the sites so that the system performance data can be analyzed. The analysis will be done collaboratively among IPC, NREL, and the appropriate Mexican agencies.

Indonesia experience: IPC has installed two identical systems in 1993 to supply electricity to Julingan and Tanglad, two villages of 200 homes each, on Nusa Penida Island, near Bali, Indonesia. Each system has a rated capacity of 100 kWh/d and is comprised of 9.6-kW PV, one 10-kW wind turbine, a 10-kVA diesel genset; a 2000-Ah battery bank, a 7.7-kVA sine-wave inverter, and a microprocessor controller. An interesting design feature of this installation is the use of two parallel hybrid systems on a single distribution system, thereby demonstrating the feasibility of building up local mini-grids by adding modular hybrid power plants as load demand grows.

Another important feature of this installation is the use of remote monitoring and control capability that utilizes a direct link to a low earth-orbit satellite, VITASAT. The VITASAT link permits uploading and downloading system status and performance data, as well as permitting remote diagnostics and control. This first-of-its-kind application of a satellite for remote village electricity monitoring and control was a collaborative effort between IPC and the Volunteers in Technical Assistance (VITA).

Currently the systems are operating at about 50 % of their design capacity, thereby providing the potential of doubling the load with no loss in reliability or system efficiency. Nearly 90% of the current electrical energy is supplied by renewable sources. Load growth, primarily through new hook-ups by PLN, the national utility, is anticipated.

Currently, IPC is taking its next major step in commercialization of PV/wind hybrid systems by initiating a project to electrify up to 70 villages in the eastern islands of Indonesia. The project will combine the lessons learned to date with a volume-manufactured, standardized system. The next generation system will embody the following improvements: AC-bus, factory assembly and test, transportability, and simplified installation. The AC-bus design allows the diesel to be operated in parallel with the inverter (as compared to the DC-bus design that requires the diesel energy to be stored in the batteries and then inverted to AC). This architecture improves system efficiency by avoiding the diesel rectification, battery run-around losses, and inversion. This system design can meet higher peak loads (both the diesel and the inverter can combine to meet peaks). Additionally, the inverter will be bidirectional and operate as a battery charger, storing excess diesel energy during low to intermediate village loads. The systems will be factory assembled and self-contained to minimize the expense and problems of site-built structures. The systems can be transported in a 6-ton truck and installed in 2 days.

Phase 1 of the project will be completed in 1995 and will include the electrification of up to 10 villages; the systems have the following specifications: 110/120/220/240 VAC, 50/60 Hz, single phase; 25-kW nominal peak power; 50-100-kWh/d energy output; 7.5-kW PV; 10-kW WTG; 25-kVA diesel genset; 625-Ah battery bank; 7.5-kVA, single-phase, bi-directional inverter. Following the successful completion of this initial phase, IPC, in collaboration with the government of Indonesia and technical assistance from NREL, will embark on the replication phase that will include installation of systems to service an additional 60 villages.

NEW WORLD POWER CORPORATION (NWPC)

New World Power Corporation is utilizing its experience in wind, solar, and hybrid power systems, primarily in remote telecommunications and small isolated power applications, to develop the balance of systems components required to reliably integrate renewables into remote mini-grids. NWPC is in its second year of a 5- year program to develop and commercialize a renewable-based, packaged hybrid-power system. NWPC is currently focusing its product development and initial marketing toward harsh, far northern climates, and in the Latin America/Caribbean region.

The core of the prepackaged system is an electronically controlled, renewable energy-based, diesel/battery cycle charging unit. The novelty of this system is the use of a rotary converter, which replaces the need for large-scale power electronic inverters. The combination of an AC alternator and a DC motor/generator inverts the battery-stored and generated DC electricity to AC. The potential benefits in reliability, serviceability, and economics of rotary technology (which has been used for emergency hospitals for years) are the drivers for NWPC to develop larger scale versions for remote village, mini-grid applications. This development is being cost-shared with Sandia National Laboratory and NREL.

The prepackaged system consists of a diesel engine clutch-coupled to a synchronous alternator, which is in turn shaft-coupled to a DC regenerative-drive unit. The DC drive is linked to the battery bank. This architecture allows the load to be supplied either from the diesel or from the battery bank (via the same synchronous alternator). The PLC master-controller monitors the power flows, and automatically makes judgements from preprogrammed data, or for remote commands, allowing for efficient operation of the power sources. Additional controls are included in the package for AC-output and DC-input supervision/protection, and PV and wind turbine generator control. The system is housed in a prefabricated shelter.

The rotary converter can be readily reconfigured to accommodate a variety of village-power electric specifications, including 50/60 Hz, 120/208/240/480 AC, single or three phases. The rotary package has two basic configurations, with or without an integral engine. In most cases, the integral engine will be the preferred configuration as a complete power system. However, in those cases that do not require an engine/genset, the rotary package can be provided without it, and the PV and/or wind generator(s) will be interconnected and controlled by the package. Another feature of the package is the ability to operate multiple packages in parallel, to accommodate load growth. Interconnection of the rotary packages is simpler than the current diesel-genset parallel operation control requirements, not requiring the use of a synchroscope-type controller.

The rotary package can be configured to adapt to a number of different architectures, depending on the renewable resources, the load, and relative economics of the generating sources. Typical generating architectures that the rotary package could accommodate include stand-alone PV, PV/engine, PV/wind, PV/wind-engine, and wind/engine. This last architecture is particularly interesting since the NWPC package can integrate AC and DC wind turbines into the village grid. In large village applications, the wind turbines will most likely use induction generators; NWPC's design provides a stable AC grid without the engine operating (reactive power can be supplied by the engine or the battery bank). NWPC believes this feature is a significant advantage of this architecture.

NWPC's first stage of commercialization focused on systems in the 50-100 kW range. Currently, they are expanding their scope to larger systems in the several hundred kW to multi-megawatt range, using the same principles. These large systems typically do not include batteries. The larger systems employ synchronous alternators/condensers and fast acting "dump loads" for power and frequency control. With this architecture, loads can be met solely by each power source subsystem or with a combination of any or all of them. The key to grid stability is the synchronous alternator acting as the primary power supplier in all the generation modes, resulting in AC power that is free of harmonic content, supplies reactive power, and absorbs large impulse loads.
NWPC has installed its system in southern California for Southern California Edison Company. Additional systems are currently being installed in Alaska, Argentina, and in Para, Brazil.

HYBRID SYSTEM R & D AT NREL

The U.S. DOE has designated NREL as its lead laboratory for wind technology research and development, including wind-hybrid systems. The objective of the hybrid system R&D activities at NREL is to collaborate with the wind industry in the development of technology, analysis tools, and applications analysis for wind-based hybrid systems in off-grid applications. The major activities for 1995 are described below.

Development & Beta-Testing of the Wind/Hybrid Performance Model, "HYBRID2".

In 1993, NREL made an assessment of the available tools from the United States and Europe for predicting the long-term performance of hybrid-power systems. The conclusion was that there was no single tool capable of modeling the full range of hybrid-power technologies being considered for village power in the 1990s and beyond. The existing tools especially lacked flexibility in system configuration and dispatch of components. As a result, NREL developed a specification of a model for making comparisons of competing technology and systems options on a "level playing field."

Development of this tool, called HYBRID2, by NREL and the University of Massachusetts (UMass) is now underway. It builds on the wind/diesel model, HYBRID1, developed previously by UMass with DOE funding, and expands that model to accommodate the wider array of technologies and system architectures now being considered for hybrid village-power systems. In order to accommodate a variety of potential analysts, UMass will incorporate the analytical software into a user-friendly format, using Microsoft Visual Basic. An initial version of HYBRID2 will be completed late in 1994 and beta-tested early in 1995, both internally and by a group of users outside the lab including private and public analysts. The executable version of the code should be available in mid-1995.

Construction & Operation of NREL's Hybrid Power Test Facility.

Because of the need to gather performance data from operating hybrid-power systems, NREL will develop in 1995 a Hybrid-Power Test Facility at the National Wind Technology Center in Golden, Colorado. This facility will test state-of-the-art packaged hybrid power systems developed by the U.S. industry. The facility will include a village load simulator, at least two wind turbines, a photovoltaic array, and a data acquisition system. Repeatable testing will be possible with energy source simulators capable of imitating either wind turbines or PV arrays, either AC or DC connected.

Develop Predictive Tools for Small Wind Turbine Performance.

Predicting the performance of small wind turbines is complicated by the fact they typically operate at variable-speed and are used in a variety of applications. The three most common applications are battery-charging (as in a hybrid system configuration), wind/electric (direct connection to an induction motor), and grid-connected through an inverter. Each application imposes a different electrical load on the wind turbine which impacts the performance of the generator and rotor. As a result, the performance of small wind turbines have been observed to vary significantly depending on the application.

In 1995, NREL will assemble existing models of wind turbine rotor and generator performance into a unified tool for the prediction of small wind turbine performance under various electric loads. Dynamometer testing of one or more generators will be conducted. This data, along with field data on turbine performance, will be used to verify the overall performance model. This model will subsequently be used to develop guidelines for alternator design and for motor selection (in wind/electric applications).

Parametric Experimental Study of Wind/Diesel Configurations.

In 1994, the U.S. DOE initiated a 5-year, cost-shared research collaboration with the U.S. Department of Agriculture (USDA) to investigate a range of wind/diesel system configurations. The goal of this collaboration was to develop systems powered entirely from renewable sources (e.g., wind, solar, and vegetable oils) that would be reliable and cost competitive. The experimental study will focus on performance and stability for various system configurations and will identify necessary controls. This study will be performed in a wind/diesel test facility at the USDA research laboratory at Bushland, Texas.

Field Performance Data.

In order to improve systems' field performance and economics, it is essential that data from power systems operating in field applications be acquired and analyzed. To accomplish this, NREL has a two-pronged program: system monitoring protocol and equipment development, and field data acquisition. NREL will develop and test a portable data acquisition system suitable for commissioning and long-term monitoring of hybrid-power systems in remote locations. This will include demonstrating the capability to down-load data sets by phone or by satellite link. Additionally, NREL will engage in a program with industry and in-country institutions to equip existing and newly installed hybrid systems with data acquisition system in order to develop a data bank on system performance under the variety of conditions that exist in the field. It is anticipated that field performance data will be collected and analyzed from hybrid systems in Mexico, Brazil, and Indonesia. While some of the collected data may be industry sensitive (and will be treated accordingly), there will be valuable general information gleaned from such monitoring that can lead to technology improvements and applications developments.

Renewables for Sustainable Village Power (RSVP) Initiative.

The development of a field performance data bank is an element in NREL's new initiative to address the many issues associated with deploying renewable energy systems in villages in an economically sustainable manner. In addition to supporting technology development appropriate for village-scale systems, RSVP will offer technical assistance to U.S. companies and in-country institutions which are interested in evaluating and deploying renewables. Technical assistance includes training, both through workshops and an on-site visiting professional program, resource assessment, preliminary analysis of alternatives, program/project development, and performance monitoring and evaluation. It is anticipated that RSVP will become a clearing house for experience, technology development, and analysis for both U.S. companies and international institutions involved in village power.

CONCLUSIONS

The developing world will experience rapid growth in the application of electricity to meet community economic and social needs over the next decade. Because renewable resources are abundant (and varied) around the world, renewable hybrid-energy systems offer reliable, economically competitive, and environmentally friendly power for many currently non-electrified villages throughout the developing world. It will be important that emerging hybrid technologies and system architectures be designed such that they consider the communities' needs, including loads, system reliability, ability to pay, economic development opportunities/limitations, and social needs. Although there are many places in the developing world where the current hybrid systems are economically competitive today, it is also important to make improvements in the systems and technologies so that they may be competitive in a larger set of rural situations. The U.S. industry, with assistance from NREL, is on the way to demonstrating the economic and environmental sustainability of alternate hybrid-system configurations and control strategies.