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INITIAL RESULTS FROM THE OPERATION OF VILLAGE HYBRID SYSTEMS IN CHILE

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ABSTRACT

The government of Chile has undertaken a rural electrification program to electrify 75% of the population by the year 2000. Renewable energy is considered within this program, and its application facilitated through a technical cooperation agreement between Chile's national energy commission (CNE) and the U.S. Department of Energy. In order to introduce isolated mini-grid hybrid wind-energy systems into Chile, three pilot projects were implemented in Region IX. The goal of the pilot systems is to establish renewables as a viable option for rural electrification in the Chilean context.

In this paper we report on the first six months of operation of three pilot projects. Presented as background information are brief descriptions of the power systems, data acquisition systems, and the operation and maintenance (O&M) protocols. Analyses of loads, component performance, system operation, and balance of payments for O&M are the primary points presented. Important lessons learned and future plans are also discussed.

INTRODUCTION

In October 1994, the U.S. Department of Energy (USDOE) and the National Energy Commission of Chile (CNE) signed a technical cooperation agreement for the implementation of renewable energy in rural electrification projects within the framework of the Chilean Rural Electrification Program (PER). The goal of the PER is to have 75% electrification in the rural areas of Chile by the year 2000. This goal is to be met through a process of partial project funding from the FNDR (National Fund for Regional Development) at the national level, project selection by the regional authorities (SERPLAC), and implementation by private enterprises.

In December 1995, the SERPLAC of Region IX and a private electricity distribution company, SAESA/Frontel, signed an agreement to implement hybrid wind-energy projects in Region IX for purposes of demonstration of an alternative solution to line extension. Region IX (shown in Figure 1) is characterized by having the most unelectrified homes of all twelve regions in Chile, a good wind resource all year, and a poor solar resource in winter. The Region IX *pilot projects* are intended to: (1) demonstrate that isolated mini-grids powered by hybrid wind-energy systems are technically and economically viable alternatives to grid extension and solar home systems and, consequently, encourage replication in Regions VI through XI; (2) start the building of an infrastructure and knowledge base in

Chile for designing and supporting such projects; and (3) provide information and data to improve the design of future projects. The pilot projects were funded in the same way that future projects will be; that is, the bulk of the cost (50-100%) is subsidized by the FNDR while the remainder comes from direct contributions of the implementing enterprise (10-25%) and income from consumer tariffs (5-25%). The subsidy for each project is fixed at a level which allows the implementing enterprise to at least break even over 30 years. In the case of the pilot projects, half of the FNDR subsidy was provided by USDOE in the form of the renewable energy components of the systems.

There are three pilot project sites in Region IX - Puaucho, Isla Nahuel Huapi, and Villa Las Araucarias (see Figure 1). Puaucho (PUA) is a small hamlet on a hill overlooking the Pacific Ocean. The modest electric load at Puaucho consists of a regional school, a health post, and three residences. The national electric grid is expected to arrive at Puaucho sometime in 1998 and, at that time, the hybrid system will be moved to a different site. Isla Nahuel Huapi (INH) is a small island in Budi Lake, just inland of the Pacific Ocean. It has a health post and 11 residences. Villa Las Araucarias (VLA) is located in a relatively flat area on the top of a coastal mountain range at approximately 800 meters above sea level. This site presently has an area school, health post, church, forestry office, and 17 residences. Due to an ongoing resettlement project, it is possible that the number of residences at VLA could double in the near future.

Work on the pilot projects began in January 1996 and all three systems were commissioned in January of 1997. Commissioning was delayed about 6 months due to a number of factors including equipment importation problems, wind turbine tower fabrication delays, weather-related installation delays, and a lengthy tariff setting process. To date all systems have been running for about 6 months. The purpose of this paper is to describe those first 6 months of operation and share the lessons learned from these "first-of-a-kind" systems in Chile.

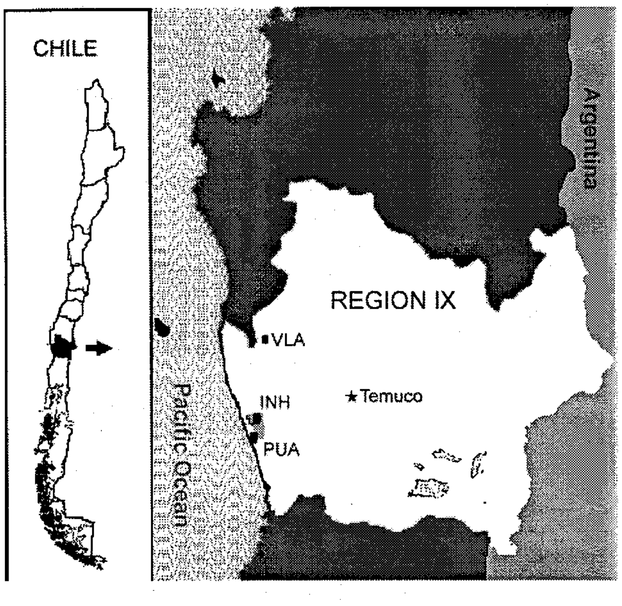

FIGURE 1. REGION IX OF CHILE WITH PILOT PROJECT SITES AND ITS CAPITAL, TEMUCO.

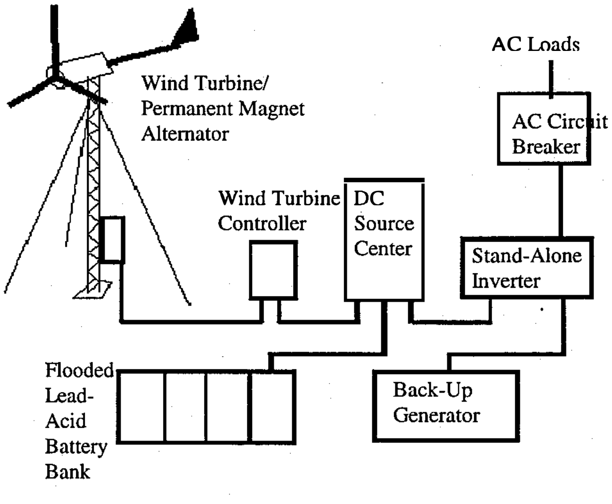

FIGURE 2. GENERAL HYBRID SYSTEM ARCHITECTURE USED IN CHILE

SYSTEM ARCHITECTURE

Each of the hybrid power systems consists of a permanent magnet wind turbine generator, wind turbine rectifier/controller, DC source center, stand-alone inverter, flooded lead-acid battery bank, and a back-up generator as shown in Figure 2. The specific components in each system differ somewhat due to the differing village loads and the need to demonstrate different types of equipment. The power system equipment was placed in a small shelter at the base of the turbine towers. The shelter was divided into three separate compartments for the generator, batteries, and power electronics. The distribution system is a bare copper, 2-wire line and pole system carrying 220 Vac, 50 Hz to the individual buildings. The electricity use is metered in the shelter and at each termination in the distribution system. The longest distribution runs range from 300 meters at Puaucho to about 1,300 meters at Isla Nahuel Huapi.

Table 1 shows the major equipment used at each site. Bergey Windpower Company (BWC) of Norman, Oklahoma and World Power Technologies (WPT) of Duluth, Minnesota provided the wind turbines and rectifier/controllers. The two BWC wind turbines are three-bladed and the WPT turbine is two-bladed. All turbines are mounted on locally-fabricated, 24-meter, guyed, tilt-up towers. Step-down transformers are located between the turbine and controller at Isla Nahuel Huapi and Villa Las Araucarias.

Two different models of Trace (Arlington, Washington) inverter were used. The DR series produces a modified-sine output and the SW series produces a true-sine output. The SW series also incorporates very sophisticated controls including automatic generator start-up. At Puaucho, the generator must be started manually. Two types of Trojan (Santa Fe Springs, California) flooded lead-acid, deep-cycle batteries are used: the T-105 (200 amp-hour) and L-16 (350 amp-hour). Both batteries are available from distributors in Santiago, Chile. The Honda gasoline generators were also purchased from a distributor in Santiago. All three generators are nominally 3.8 kW with the two at INH and VLA having an electric start circuit. A 100-liter reserve fuel tank is included in each system. The DC source centers included fuse and/or circuit breaker protection and manual disconnects for the batteries, controller, and inverter. The systems at PUA and INH utilize fuses and disconnects which were purchased and assembled in Chile while at VLA the DC source center was provided by BWC.

TABLE 1. HYBRID SYSTEM EQUIPMENT

Site	**DC Bus Voltage**	**Wind Turbine**	**Inverter**	**Batteries**	**Generator**
Puaucho	24 Vdc	BWC1500 (1.5 kW)	Trace DR2424E (modified sine)	12 Trojan T-105 (14.4 kWh)	Honda EZ4500 (manual start)
Isla Nahuel Huapi	24 Vdc	WPT3000 (3.0 kW)	Trace SW3024E (sine wave)	8 Trojan L-16 (16.8 kWh)	Honda EM4500SX (auto start)
Villa Las Araucarias	48 Vdc	BWC EXCEL (7 kW)	Trace SW3048E (sine wave)	16 Trojan L-16 (33.6 kWh)	Honda EM4500SX (auto start)

DATA ACQUISITION SYSTEM

A data acquisition system (DAS) was installed at each site to meet the aforementioned goals of the pilot projects. More specifically, the DAS will provide data to: (1) determine component and system efficiencies, (2) verify proper system functioning, (3) aid in problem troubleshooting, (4) detect and analyze significant village load changes, and (5) calculate actual cost of utilized energy.

Table 2 summarizes the DAS instrumentation. The measurements are recorded on Campbell Scientific, Inc. (Salt Lake City, Utah) CR10X dataloggers with one megabyte internal memory. The dataloggers are powered by a small sealed lead-acid battery pack which is float charged off of the power system battery bank. Data is sampled every second and then averaged for each hour. The generator on/off status is sampled and recorded every 10 minutes.

TABLE 2. DATA ACQUISITION SYSTEM INSTRUMENTATION

Measurement	Sensor(s)/Instrumentation
Wind Speed (2 heights)	NRG Systems Maximum 40 Anemometer
Wind Direction	NRG Systems 200P Wind Vane
DC Current from Controller	Ohio Semitronics, Inc. CTFB-100TT Current Transducer
DC Current into Inverter	Ohio Semitronics, Inc. CTFB-100TT Current Transducer
DC Bus Voltage	Campbell Scientific, Inc. 20:1 Voltage Divider
Load Real Power	Ohio Semitronics, Inc. PC20-104CX5 Power Transducer, Ohio Semitronics, Inc. 20:1 Current Transformer, and Campbell Scientific, Inc. 2:1 Voltage Divider
Load Power Factor	Same equipment as above for Load Real Power
Generator On/Off Status	NAIS HC2-H-240 Relay
Battery Temperature	Type J Thermocouple

OPERATION AND MAINTENANCE (O&M) PROTOCOL

The ultimate goals for the O&M protocol for these systems are: (1) a utility worker make no more than semi-annual visits to the sites primarily for battery and generator maintenance while the day-to-day affairs of the system are handled by someone in each community, and (2) system failures are reported by the local person in charge and immediately repaired by a qualified specialist. At the present time, however, SAESA/Frontel workers and engineers are responsible for most of the maintenance and repair. While there have already been several training sessions for utility personnel, local operators, and the communities, training is an ongoing process which will continue through 1997. Furthermore, a maintenance manual has been developed and translated into Spanish for these systems, and forms the basis for a routine maintenance program

The maintenance of the systems is broken down into tasks which must be performed on daily to annual intervals. Table 3 summarizes the current maintenance program for the pilot projects. In accordance with the aforementioned goals, the monthly and tri-monthly responsibilities will be eventually transferred to the local operators. Our experience indicates that the local operators are willing and able to take on these expanded responsibilities. This move should make the systems much less expensive to operate for Frontel (cost issues are discussed in more detail in the next section).

At all three sites, there are a few primary rules which govern the operation of these hybrid systems. They are: (1) the battery bank should not be discharged below 20% state-of-charge (SOC) or 1.75 volts per cell (temperature compensated); (2) the generator should run at least 30 minutes every two weeks; (3) the batteries should be equalized at least once every month; and (4) the generator should not be used to finish charge the batteries. The first rule implies two other rules. First, that the batteries be disconnected from the load at 20% SOC and, second, that the generator begins charging the batteries when they reach

TABLE 3. SUMMARY OF MAINTENANCE PROGRAM FOR CHILE PILOT SYSTEMS

Maintenance Interval	Person(s) Responsible	Description
Once per Day	Local Operator	Check generator oil and fuel levels and fill if necessary; Record battery bank voltage; Inform Frontel if there are any problems
Every 15 Days	Local Operator	Run the generator for 1/2 hour; Check generator oil filter
Once per Month	Frontel Worker/Contractor	Check battery specific gravity and electrolyte levels - fill if necessary; Equalize charge battery bank; Clean battery terminals; Visually inspect system for loosened fasteners/connections and signs of overheating; Check generator carburetor
Once per 3 Months	Frontel Worker/Contractor	Clean generator air filter.
Once per 6 Months	Frontel Worker/Contractor	Change generator oil, oil filter, and air filter; Clean generator gas filter; Adjust/clean spark plug.
Once per Year	Frontel Worker/Contractor	Generator maintenance: clean points, change spark plug, adjust valves, check exhaust system, clean fuel tank and fuel line; Climb turbine tower to inspect turbine and anemometers/direction vanes. Inspect distribution system

25% SOC. The fourth rule implies that the generator stop charging the batteries when they reach 80% SOC. The Trace SW series inverters can execute all of the above operations except for automatic periodic equalizations. This is not a problem since the equalizations should involve human intervention in any case, to loosen battery caps and open the doors on the battery compartment. At Puaucho, where the generator operation is manual, the local operator must start the generator after the inverter shuts off due to the low battery condition. The operator in Puaucho seems perfectly amenable to this type of operation.

TARIFFS AND COSTS

One of the most important, yet often controversial, issues of any rural electrification program is cost recovery through tariffs. The paradox is well-known. It is very expensive to provide electricity to remote, sparsely populated areas and yet the people in these areas are usually the least able to afford this service. Consequently, most rural electrification programs require some sort of subsidy, direct or indirect, and these systems in Chile are no exception.

The initial costs of each of the pilot hybrid systems are presented in Table 4. For comparison, the estimated costs of grid extension to each project site are also given. The costs of the local distribution system and the interior wiring are kept separate because they must be added to the costs of both electrification solutions. Hybrid system costs cover all equipment (except the DAS) including spare parts, transportation, fabrication, and installation. Grid extension costs cover the equipment and installation for the transmission line from substation to local step-down transformer.

TABLE 4. COST COMPARISON OF HYBRID SYSTEMS AND GRID EXTENSIONS (ALL COSTS IN US DOLLAR EQUIVALENTS)

Project Site	Hybrid System	Grid Extension	Distribution/Interior
PUA	$19,000	$27,500	$3,500
INH	$23,700	$82,500	$12,400
VLA	$36,400	$110,000	$11,100

The electricity tariffs charged to the end-users at the three pilot project sites were negotiated between Frontel and the local governments. The tariffs were all structured as follows (all amounts have been converted to US dollar equivalents): fixed monthly charge = US$1.57; energy charge = US$0.13 per kWh; distance multiplier (multiplies sum of fixed and energy charges) = 1.25. A household which consumes 10 kWh in a month would be billed (1.57 + (10)(.13)) x 1.25 or US$3.59 before taxes (a final tax multiplier of 1.18 could be used to determine the actual total electricity bill). The tariff setting process was a long and political one. The result was that the hybrid system users are paying approximately the same tariff that one would pay in this region of Chile for grid service. Small connection charges were paid by the local governments for the people of Puaucho and Isla Nahuel Huapi. At Villa Las Araucarias, the people agreed to pay the connection charge. At projected load levels, each of the communities will generate the following revenues for SAESA/Frontel per month: PUA = US$30; INH = US$50; and VLA = US$90. Currently, the communities generate not more than half of these amounts due to initial low energy consumption and, at VLA, unconnected households.

Figure 3 has been constructed to show the maintenance intervals at which SAESA/Frontel will break even on revenues minus O&M costs. The following items have been incorporated into Figure 3: (1) site visit cost of approximately US$75 which includes wages for a Frontel worker, transportation to the sites, and costs of miscellaneous parts such as air filters and oil, (2) two unscheduled repair visits by a qualified technician at US$200 each, (3) cost per liter of gasoline of US$0.60, (4) "net revenues" equal to the tariff income minus gasoline expenditures for each site, and (5) annual tariff income based on the long-term estimates of the village load.

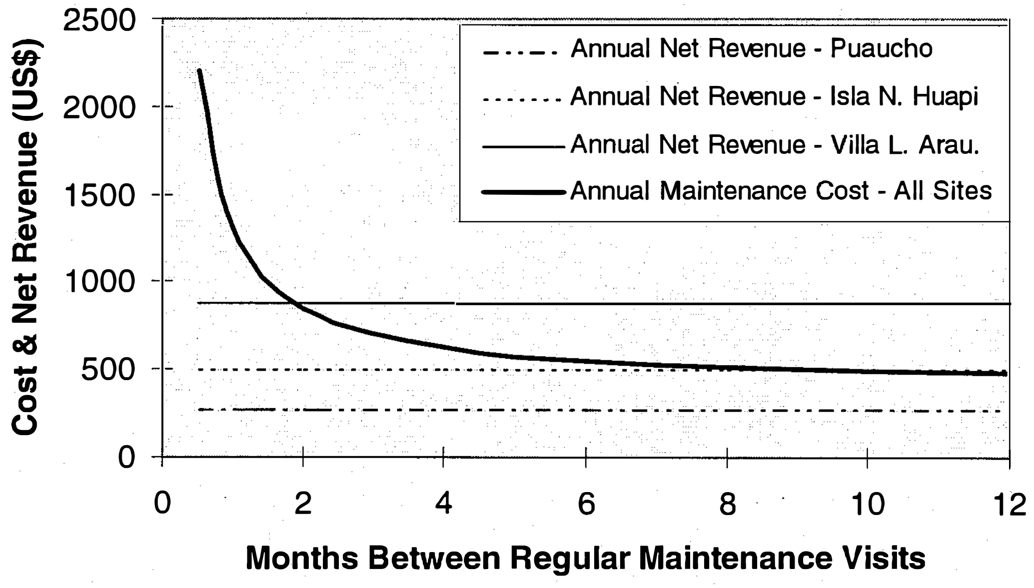

FIGURE 3. NET REVENUES (TARIFF INCOME - FUEL EXPENDITURE) AND MAINTENANCE COSTS (SITE VISITS) FOR CHILE PILOT PROJECTS

The result of Figure 3 is that the minimum time period between regularly-scheduled maintenance visits to the sites should be as follows (on a break-even basis): PUA = more than 12 months; INH = 8 months; and VLA = 2 months. If the actual maintenance interval is stretched to 6 months at all of the sites, SAESA/Frontel could make some profit on these systems if the Puaucho system is moved to a community with higher energy consumption. The battery replacements will be funded by regular tariff increases.

INITIAL OPERATION AND PERFORMANCE RESULTS

The village loads, both energy consumption and peak power demand, were very small. Table 5 summarizes the actual and long-term anticipated loads for all three communities. At all of the sites, 20-watt compact fluorescent lighting presently accounts for the majority of the loads. There are some radios in use as well as a small water pump at Puaucho. Refrigeration in the residences has been discouraged from the outset of the projects. We anticipate that the loads will eventually include televisions, kitchen appliances, more water pumps, and refrigeration for the health posts. The difference in the actual and long-term loads for Villa Las Araucarias is the result of only 9 of 21 buildings being connected. The load shapes shown in Figure 4 have the typical village profile with the pronounced evening peak. An important feature of the load profiles is that a few loads, presumably lights, remain on all day, despite our recommendations to the contrary.

TABLE 5. VILLAGE LOADS - ACTUAL VS. LONG-TERM ANTICIPATED

Site	Actual Monthly Energy Consumption (kWh)	Long-Term Monthly Energy Consumption (kWh)	Actual Peak Demand (Watts)	Long-Term Peak Demand (Watts)
Puaucho	48	120	190	700
Isla Nahuel Huapi	30	153	105	700
Villa L. Araucarias	38	294	205	1200

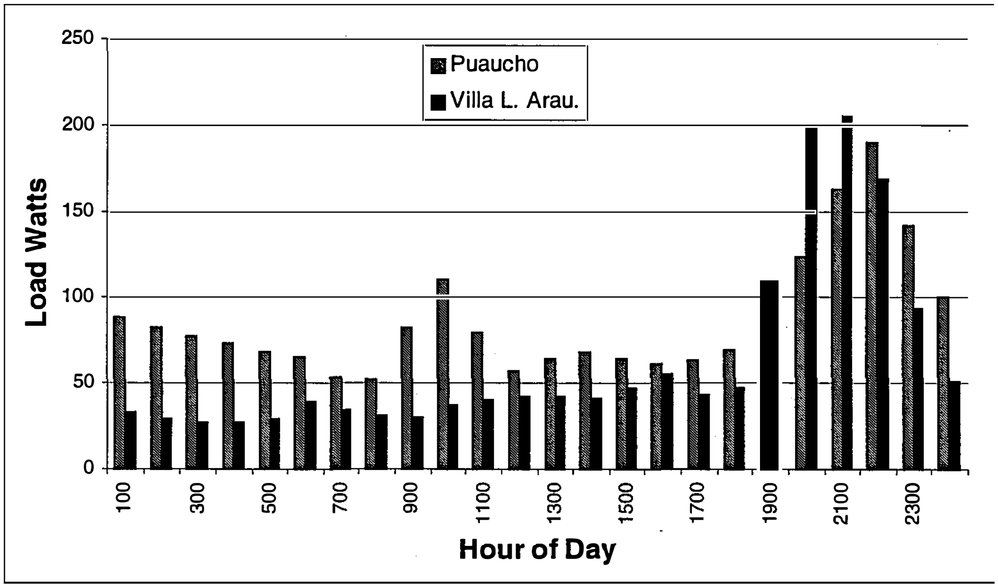

FIGURE 4. AVERAGE DAILY VILLAGE LOAD PROFILES

The battery banks have experienced severe cycling in their first six months of use due to the generator shut-down from overheating, a wind turbine controller dump load failure at Isla Nahuel Huapi, and the annual low wind period in southern Chile March through May. Despite these problems, low loads and sufficient winds between lulls helped to keep the batteries from remaining at a low state-of-charge for long periods (see Figure 5). Due to inadequate ventilation and high March temperatures, the generators were only able to run for 2 or 3 hours before overheating and shutting down. This prevented adequate bulk and equalization charging of the batteries. The lack of equalization charging resulted in battery cell imbalances which further compounded the battery charging problems. The dump load failure at Isla Nahuel Huapi caused the batteries to overcharge at times and to lose excessive amounts of water. It was May before all of these problems were fixed. Quick response to these problems was hampered both by a lack of personnel, fully knowledgeable in hybrid wind systems, and by the lack of suitable replacement parts in this region of Chile. The infrastructure that is developing with these pilot projects will help to prevent such delays in the future.

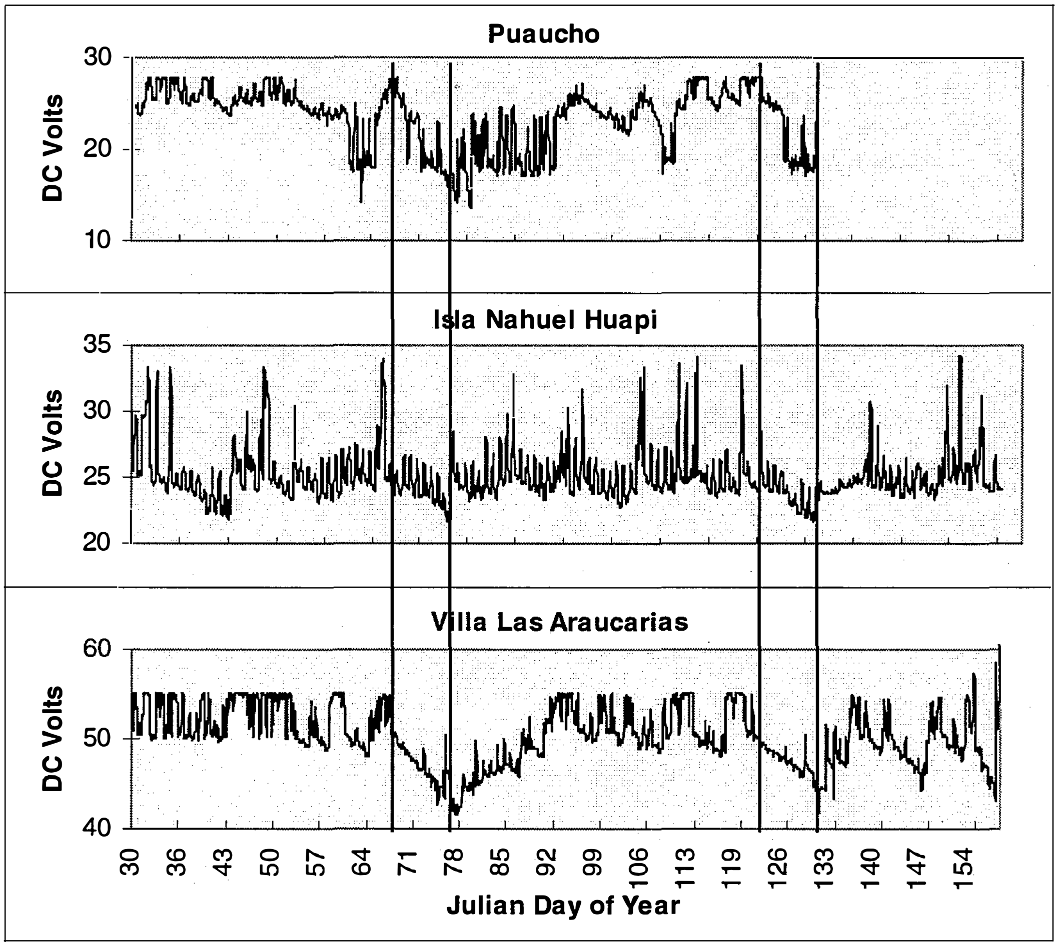

FIGURE 5. DC VOLTAGE HISTORIES WITH WIND LULLS SHOWN BETWEEN THE BARS

Monitoring component outputs and efficiencies is important for two reasons, both of which tie into the goals of maximizing system performance and reducing cost of energy. The first reason is to make sure that the equipment is operating to the manufacturer specifications. The second is to know how the actual operating conditions affect equipment utilization and performance. As an example, Figure 6 shows monthly DC outputs in kilowatt-hours of the BWC 1.5 kW wind turbine at Puaucho compared to its potential output. Due to the small loads and relatively high battery voltages during this initial period, the output of the turbine fell below its potential due to regulation by the turbine's controller. This underutilization will improve over time as the village loads increase. We are also investigating the possibility of increasing the size of the battery bank in order to improve wind turbine utilization.

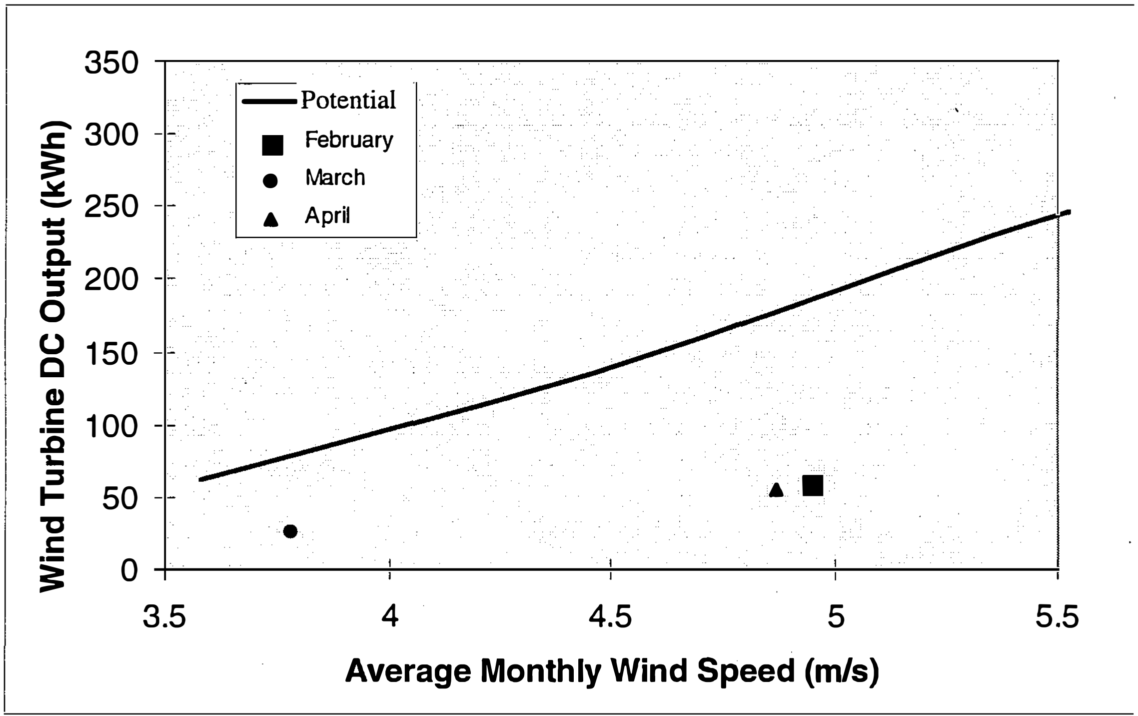

FIGURE 6. DC OUTPUT OF BWC 1500 WIND TURBINE BY MONTH

The data acquisition systems do not determine how efficiently the generators are charging the batteries; however, we have been able to examine the voltage waveforms during generator-to-battery charging with a digital oscilloscope. The charging waveforms produced by the Trace SW series inverters at Villa Las Araucarias and Isla Nahuel Huapi are very close to being true sinewaves. However, the DR series modified-sine inverter at Puaucho produced a flattened sinewave which is shown in Figure 7. By clipping the higher voltages from the generator waveform, the inverter was unable to produce the required 30 volts for equalization. The highest voltage reached was around 27 to 28 volts. Consequently, the batteries must be equalized with the wind turbine. Changing over to this type of operation could have the added benefit of saving fuel.

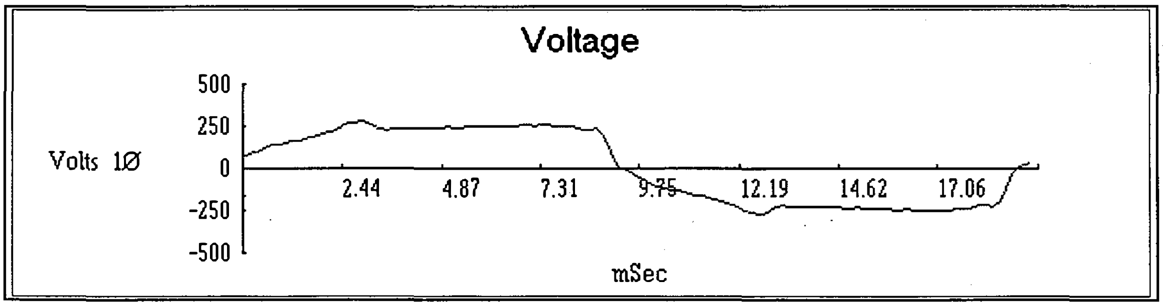

FIGURE 7. WAVEFORM CAPTURED BETWEEN GENERATOR AND INVERTER DURING BATTERY

LESSONS LEARNED AND FUTURE PLANS

The challenges encountered during the initial implementation of the three pilot projects in Region IX can be broadly grouped as follows: (1) minimizing costs while maintaining an acceptable quality of service, (2) setting proper tariffs, (3) providing timely technical assistance, and (4) getting the most local participation possible.

Minimizing cost is necessary for ensuring the successful introduction of hybrid wind systems into Chile. Initial cost will affect the benefit/cost ratio as well as limit the total number of systems which can be subsidized. O&M costs will determine the attractiveness of these systems to the Chilean implementing entities as well as the regional planning officials. Maintenance costs and fuel consumption for these pilot projects were minimized to practical limits (a requirement imposed by Frontel) at the expense of installing "oversized" wind systems (at least for the current village loads). If the systems are downsized while utilization is improved, the quality of service (as related to availability) can remain high. As discussed earlier, one way of improving utilization is to schedule more battery equalizations with the wind turbine. Productive and commercial uses of electricity such as pumping water, making ice, powering tools, and charging batteries for people in surrounding areas not only improve system utilization and profitability, but could also improve village welfare and income.

System downsizing also touches on two other load issues. First, there is the question: to which load should the system be sized? For these projects, long-term load growth was considered. Several new strategies to deal with the load growth issue will be proposed. They include designing the system based on fixed-term (perhaps two-year) load steps and building in the option of increasing system size as the load increases. This strategy may involve rotating equipment between several communities at different stages along the electrification path. The second load issue regards availability of power. The people in our three pilot villages accept short term power outages, at least when the outage is limited to a few days. Social impact analyses have been planned which will help to determine how load losses can be factored into system sizing criteria.

Alignment between costs, both initial and O&M, and revenue generated by tariffs is another important factor for making the introduction of wind hybrid systems in Chile a success. The issue of raising tariffs above what grid-connected consumers pay for similar service is politically difficult. These hybrid systems cost less than the line extensions that would otherwise be required for the pilot sites. Consequently, charging the hybrid systems' end-users more for their service appears to them as a social inequity. For the time, our best strategy continues to be minimizing O&M costs by transferring more responsibilities to the local operator which lengthens the periods between expensive visits to the sites.

The final two challenges of providing timely technical assistance and getting the most local participation possible are related. Certainly it is time-consuming and often difficult to respond to needs in Chile from the United States. It is, therefore, crucial that local people be trained to operate, maintain, and repair the systems. And while much training has already taken place, it is evident that much more must be done. Similarly, while there is a large spare part inventory at Frontel's Temuco office, this inventory should be expanded to include all US-sourced equipment, particularly the inverters and wind turbine controllers. Although such an inventory represents a relatively large expense, it is certainly justified for the pilot projects. As projects are replicated throughout Chile, the inventory will not represent such a high percentage of the total investment. Finally, it is worth mention that in-country "champions" or facilitators with a vested interest in the program are necessary. We were fortunate to have such persons in Chile who were able to deal with the political and business hurdles which almost always accompany the introduction of a new technology application.

FINAL REMARKS

The first six months of operation for the three pilot projects have helped to clarify the strengths and weaknesses in our wind hybrid program in southern Chile. The issues of system sizing, O&M, training, comparative economics, tariff design, and quality of service will be addressed in the next phase of the program, based on the experiences from this initial phase.

These early results are most important because new projects are being designed for Regions VIII and X. In fact, funding has already been approved for one pilot project on the Pacific coast of Region X at Bahía San Pedro. In the other regions interest is building. This solution for electrifying remote communities has been hailed by the local mayors, the CNE secretary, and the SAESA/Frontel management. Furthermore, it is the considered opinion of these authors that hybrid wind-energized mini-grids are economically competitive with grid extensions for a large number of communities in southern Chile.

While up to now the Chilean PER only recognizes 230 volt/50 Hz AC service, it is becoming clear that other types of service such as 12 volt DC for individual buildings may be allowed in the future. If so, this could open the possibility of adding battery charging stations to the applications suitable for wind hybrid systems in Chile.

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