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# Analysis of Village Hybrid Systems in Chile

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# ANALYSIS OF VILLAGE HYBRID SYSTEMS IN CHILE

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## ABSTRACT

Chile recently began a major rural electrification program to electrify those 240,000 families (about half of the rural people) who lack electricity access. In this paper, we discuss a pilot project to electrify three remote villages in Chile's Region IX using wind/genset/battery hybrids. The intent of this project is to demonstrate the reliability and cost-effectiveness of wind/genset/battery hybrids and to encourage replication of these types of systems in Chile's electrification program.

For each village, electricity connections are planned for several residences, and also schools, health posts, community centers, or chapels. Projected average daily loads are small, ranging from 4 to 10 kWh. Using the optimization program HOMER and the simulation program Hybrid2, we evaluated options to maximize technical performance, minimize costs, and gain experience with a variety of systems and components. We find that wind/genset/battery hybrids will be able to provide cost-effective, reliable power for these sites. More importantly, their inherent flexibility allows for variations in load and resource without greatly affecting the cost of energy.

## INTRODUCTION

In the summer of 1994, Chile's Comision Nacional de Energia (CNE) met with representatives of the American Wind Energy Association (AWEA), U.S. Department of Energy (DOE), and the National Renewable Energy Laboratory (NREL) and initiated a cooperative program to develop a sustainable approach to applying renewable energy systems to Chile's rural electrification program. As part of this program, a group of pilot projects will be implemented. Region IX (See Figure 1) was selected by CNE for the initial pilot projects, because it is the region with the most unelectrified homes and is central to Regions VII–X, which represent 80% of the unelectrified rural population in Chile. NREL and its regional partner, the National Rural Electric Cooperative Association, have provided technical assistance and training to CNE and the regional utility implementers. DOE and CNE are cost-sharing the pilot installations. The regional private utility Frontel will own, operate, and maintain the systems. NREL will monitor and assess technical performance with site data acquisition systems.

The three sites in Region IX to be electrified are Puaucho, Villa Las Araucarias (VLA), and Isla Nahuel Huapi (INH). Puaucho is a small coastal village with good winds. There is a plan to extend the grid in the next 1 to 2 years, so the system there will be a temporary installation to supply the school and some of the residences until this site can be grid-connected. This system can then be removed and used to electrify another site. INH is an island about 200 m from the mainland in Lago Budi, which is east of Puaucho; because of transportation difficulties, this site needs to be self-sufficient. VLA, the largest of the villages, is located further inland, where the winds are weaker. Because of government resettlement programs, this site is expected to see high growth. Both INH and VLA systems are permanent installations and are expected to last 20 years.

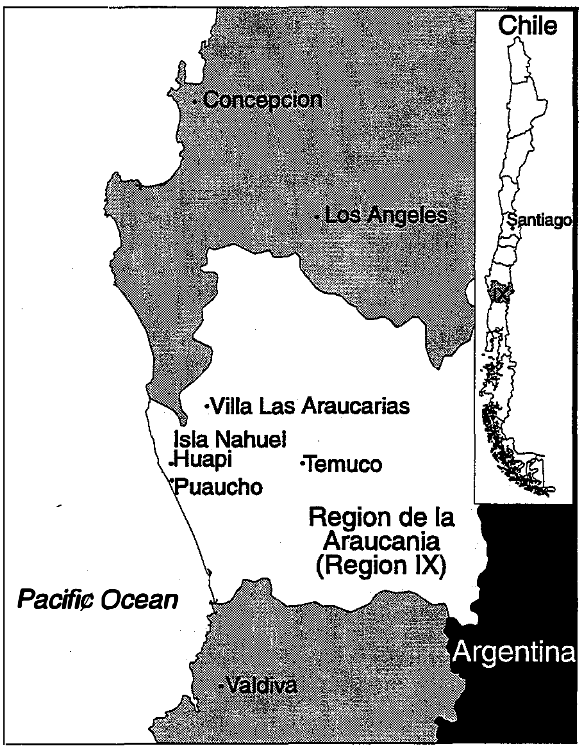


*FIGURE 1. REGION IX OF CHILE, SHOWING THE LOCATION OF SITES PUAUCHO, ISLA NAHUEL HUAPI, AND VILLA LAS ARAUCARIAS.*

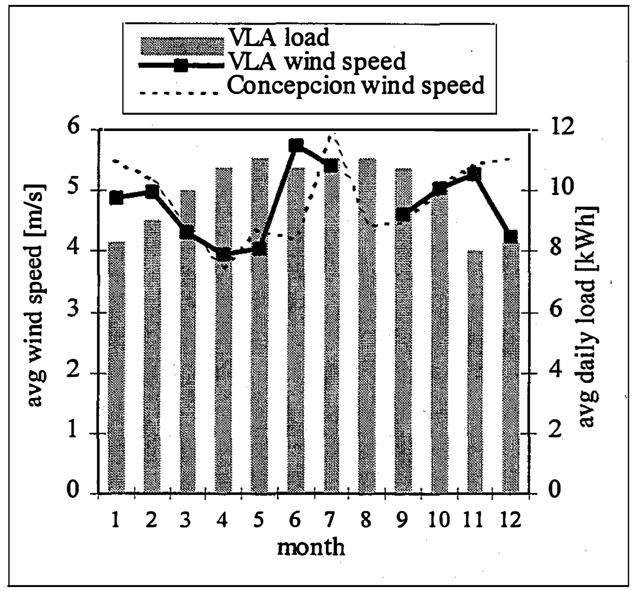


*FIGURE 2. MONTHLY AVERAGE WIND SPEEDS (AT 24M HEIGHT) AND DAILY LOADS FOR VILLA LAS ARAUCARIAS, AND CONCEPCION AIRPORT DATA AVERAGED OVER 1977–80.*

RESOURCE

As part of this project, anemometers have been installed at four sites in Chile, three of which are in Region IX: Puaucho, Vegas Blancas, and Villa Las Araucarias, and Isla Tac in Region X. The wind resource at Puaucho has been monitored at two heights – 10 m and 24 m – since June 1995. These data, combined with long-term Concepcion airport data, indicate Class 2–3 winds. The Puaucho data set of 7710 hours of wind data was collected from June 1, 1995, to May 21, 1996. Data for the month of August 1995 is missing. This data set is well fit to a Weibull distribution of $v_C = 1.9$ and $k = 6.1$. The average wind speed is 5.3 m/s. Storm-driven winds in the winter months (June–September) result in high wind speeds with long lulls between storms. The rest of the year is marked by steady, medium winds with the lowest wind speeds in the spring.

Continuous wind data were not available for INH or VLA, so these data sets were derived from the Puaucho data set. Wind speeds at VLA were estimated to be 10% less than that at Puaucho, because VLA is located farther inland. INH is also inland, but on a lake, so wind speeds have been derated by only 5% from Puaucho. Brief periods of simultaneous data taken at both Puaucho and VLA in the fall and in the spring indicate that the VLA wind speeds are 3% and 30%, respectively, less than that at Puaucho. A summary of the data is shown in Table 1.

*TABLE 1. WIND RESOURCE ASSESSMENT OF PUAUCHO MONITORED AT 24M HEIGHT FROM JUNE 1, 1995, TO MAY 21, 1996. INH AND VLA DATA ARE ESTIMATED FROM PUAUCHO.*

| Site | Average Wind Speed [m/s] | Average Wind Power Density [W/m$^2$] |
|---|---|---|
| *Puaucho* | 5.3 | 190 |
| *INH* | 5.1 | 165 |
| *VLA* | 4.8 | 140 |

Missing data (for example, the entire month of August) were not filled in, so that one year's performance has been extrapolated from a partial year's run. Figure 2 shows the average monthly wind speed for VLA. For the purposes of this graph, monthly averaged wind speeds from 1977–80 from nearby Concepcion airport have been shown.

The solar resource in this area is not good. The daily global horizontal insolation averages 3 kWh/m$^2$, with highs in the summer of 5.2 and lows in the winter of 1.0 kWh/m$^2$.

## LOAD

A loads analysis was performed for each site and is described in Table 2. Each school, health post and residential connection was evaluated for present energy needs and predicted future needs. The loads represent the greatest uncertainty in the modeling process. It is likely that household consumption will increase after electrification as the villagers acquire appliances and expand lighting usage. In particular, the VLA load is expected to grow quickly, as the population may double in the next few years, due to possible resettlement from the surrounding areas.

*TABLE 2. LOAD REQUIREMENTS FOR THE THREE VILLAGES. IN THESE SIMULATIONS, AN ADDITIONAL 5% WAS ADDED TO THE GIVEN ANNUAL LOAD TO ACCOUNT FOR TRANSMISSION LINE LOSSES.*

| Site | Daily Load [kWh] | Peak Load [kW] | Annual Load [kWh] |
|---|---|---|---|
| *Puaucho* | 4.0 | 0.7 | 1470 |
| *INH* | 5.1 | 0.7 | 1810 |
| *VLA* | 9.8 | 1.2 | 3460 |

Both VLA and INH are assumed to include continuous-duty refrigerator loads. All loads peak in the evening and have minor peaks in the morning and noontime. Although water pumping would normally operate as a deferrable load, it was included as a primary scheduled load for these simulations. All loads are based on the use of efficient appliances, such as compact fluorescent light bulbs, which will be purchased by Frontel. Traditional inefficient appliances bought by the users may increase the load estimate by a factor of 2.

## TECHNICAL OPTIONS AND DESIGN CONSIDERATIONS

System requirements are for 220 V, 50 Hz delivered power, with a loss of load probability not to exceed 3%. These systems have been designed conservatively for zero loss of load. The basic wind/genset system architecture is shown in Figure 4. A different turbine is used for each site, to gain a variety of operating and maintenance experience in the field. Systems were deliberately oversized to allow for load growth, especially in the case of VLA, where load growth is expected to be most rapid. Local equipment (e.g., towers or gensets ) is used wherever possible. The batteries are manufactured in the United States and purchased through a Chilean distributor. The only components that must be purchased from the United States are the turbines and electronics.

*TABLE 3. HOMER RESULTS. FIXED CONSTRAINTS ARE SHOWN IN* ***BOLDFACE.***

| *Site* | Constraint | COE [$/kWh] | Turbine [kW] | Genset [kW] | Battery [kWh] | Inverter [kW] | Excess Energy [kWh/yr] |
|---|---|---|---|---|---|---|---|
| *Puaucho* | none | 0.86 | 0.9 | 2.3 | 4.5 | 0.9 | 393 |
| | turbine | 1.17 | **1.5** | 0 | 11.6 | 1.53 | 1370 |
| | turbine, genset | 1.31 | **1.5** | **2.3** | 9 | 1.53 | 1424 |
| *INH* | none | 0.96 | 3 | 0 | 13.4 | 3.2 | 4451 |
| | turbine | 0.96 | **3** | 0 | 13.4 | 3.2 | 4451 |
| | turbine, genset | 1.21 | **3** | **4** | 8 | 3.2 | 4562 |
| *VLA* | none | 0.64 | 3 | 0 | 28.8 | 3.2 | 2102 |
| | turbine | 1.40 | **6** | 0 | 28.8 | 5.6 | 7516 |
| | turbine, genset | 1.52 | **6** | **4** | 11.7 | 5.6 | 7975 |

Two design tools developed at NREL – HOMER and Hybrid2 – have been used to evaluate the system options. HOMER is an optimization program, which takes load, cost and resource inputs and finds the set of components that minimize the lifecycle cost of energy [Lilienthal *et al.* 1995]. HOMER can constrain part of the system and optimize the remaining parts of the system. These outputs can then be given to Hybrid2, which performs a more detailed simulation of this system with the given load and resource [Green and Manwell 1995].

HOMER was first run with all components completely unconstrained, to find the system that minimized the cost of energy (COE). These results are listed in Table 3.

### Turbines

Using the given Puaucho wind data and estimated deratings for INH and VLA, the energy outputs of various turbines (see Table 4) were calculated. For the case of Puaucho, the 850 W turbine output is just enough to cover the load and additional line losses, but the 1.5 kW turbine allows a wider margin of error for load and resource variations. The INH load could also be met by the 1.5 kW turbine, but the 3 kW gives Frontel an opportunity to gain experience with a variety of turbines. This system will have a high-voltage output with a long wire run to a step-down transformer at the village[1]. The current VLA load is easily met by the 3 kW, but given the strong possibility of load growth, the larger 6 kW is a conservative choice. The VLA system will have a transformer between the turbine and the rectifier[1].

*TABLE 4. ENERGY OUTPUT OF VARIOUS TURBINES AT EACH SITE. THE CHOSEN TURBINE FOR EACH SITE IS GIVEN IN* ***BOLDFACE.***

| Site | Load + 5% Losses [kWh/yr] | Turbine | Turbine Output [kWh/yr] |
|---|---|---|---|
| *Puaucho* | 1540 | 850 W | 1670 |
| | | **1.5 kW** | **2850** |
| | | 3kW | 6920 |
| | | 6 kW | 13610 |
| *INH* | 1900 | 1.5 kW | 2290 |
| | | **3 kW** | **5590** |
| *VLA* | 3630 | 3kW | 4960 |
| | | **6 kW** | **9540** |

## Gensets

The life of a genset depends on a number of factors including maintenance, run time, and loading. Regular maintenance is assumed. In order to minimize wear and optimize efficiency of the genset, the genset is only started when absolutely necessary to meet the load and charge the batteries; once the genset is on, it is run at full power until the batteries are charged. Finally the total lifetime for these small gensets has been estimated at 3500 hours (about 5 years based on 2 hr/day run times). All of the gensets described for these systems are gasoline-fueled.

Table 3 shows the HOMER results with the turbine choices described above. The choice of turbine especially affects the COE of VLA, where the system is particularly oversized. Detailed Hybrid2 simulations of the winter lulls show that the genset is needed for reliability. The smallest electric start genset manufactured in Chile, a 4 kW unit, is used for INH and VLA. The genset chosen for Puaucho is a 2.3 kW manual-start unit, due to the temporary nature of the system in Puaucho.

## Battery sizing and dispatch strategies

For these pilot projects, utility involvement is a major design consideration. Before this project, Frontel's alternatives were a genset-only system or grid-extension. Utilities find hybrid systems potentially attractive for remote areas because of their minimal operations, maintenance, and fuel needs. These requirements are not only problematic for the utility because of the remoteness of the sites but are also costly and involve skilled technicians. In this analysis, solutions have been sought for reduced fuel usage (which is expensive and can involve transportation difficulties, as is the case for INH and Puaucho) and genset starts (which require operator involvement for manual-starting gensets).

The final HOMER run in Table 3, which constrained the turbine and genset selection and evaluated the battery bank sizing, reveals that the necessary storage is quite small. The batteries are U.S.-

[1] The transformer and wire runs are assumed to have losses of 10%.

manufactured deep-cycle batteries, which can be purchased through a local distributor. These batteries have a 2.1 kWh capacity (6V, 350 Ah) and a lifetime throughput of 1225 kWh. However, the bus voltage of the mini-grid is required to be high in order to minimize resistive losses. Bus voltages of 24 V for Puaucho and INH and 48 V for VLA have been chosen. This constrains the number of batteries used.

*TABLE 5. HYBRID2 RESULTS OF GENSET OPERATION FOR THE GIVEN TURBINE AND GENSET CAPACITY.*

| Site | # Batteries | Genset [kWh/yr] | Genset [L/yr] | Genset [h/yr] | Genset [starts/yr] |
|---|---|---|---|---|---|
| *Puaucho* | 4 | 1277 | 1013 | 993 | 108 |
| *Puaucho* | 8 | 877 | 541 | 441 | 31 |
| *Puaucho* | 12 | 745 | 441 | 344 | 18 |
| *INH* | 4 | 701 | 407 | 427 | 82 |
| *INH* | 8 | 413 | 191 | 179 | 28 |
| *INH* | 12 | 262 | 142 | 145 | 18 |
| *VLA* | 8 | 1980 | 846 | 754 | 108 |
| *VLA* | 16 | 1248 | 518 | 452 | 39 |
| *VLA* | 24 | 776 | 356 | 332 | 23 |

In the case of Puaucho, where the load coincides with waking hours, a small manual-start genset is used as a backup. This genset will be run only when the load exceeds the wind power and the batteries are low (30%–35% state of charge), and it will run at full power for about 12 hours until the batteries are fully (95%) charged. Because it will be manually operated, its operating hours will be confined to 8 a.m.–10 p.m. and the system is designed to limit start times. Hybrid2 results with 8 batteries indicate 31 starts per year. Frontel has agreed that about one start or less per week is reasonable, so 8 batteries are used.

For VLA and INH, where there is a constant refrigeration load, an electrical-starting gasoline genset was used. This genset can be run at any time of day or night and the electrical start will minimize interruptions caused by loss of power. This genset will start when the load exceeds the wind power and the batteries drop to a 30% state of charge (SOC), and it will operate at full power until the batteries are charged to 80% SOC. An equalization charge will be performed every 2 to 4 weeks and will charge all batteries to 95% SOC. The fuel consumption for INH drops by about 200 L/yr as the batteries are increased from 4 to 8, but only 50 L/yr as batteries are increased to 12, so 8 batteries were chosen as a reasonable size. For similar reasons, 16 batteries are used for VLA. As the next section will show, the battery bank sizing mostly acts to reduce fuel use and has little effect on the COE.

## Inverters

Inverter sizing is tricky using HOMER, because HOMER does not allow for surge capability. Inverters have been sized with a large margin above the current peak demand. INH and VLA both use 3.3 kW sine wave inverters with charging capabilities. Due to the temporary nature of the Puaucho system, the inverter will be a less expensive, modified sine wave inverter/charger with a 2.4 kW continuous rating. It should be noted that although the inversion efficiency of these inverters is quite high, about 85%–90% at full load, the rectification efficiency is much lower, 55%–75%. The basecase system architectures and costs are listed in Table 6.

ECONOMICS

The economics of these hybrid systems have been calculated based on the system configurations described above. These costs include all generation equipment and mini-grid costs. They do not include materials and installation costs for service drops and customer connections. Based on a preliminary study of Puaucho, the costs per residential and school/health post connections are $180 and $420, respectively. Installation costs and all taxes are included (10% shipping charge, 11% import tariff and 18% VAT for imported goods; 18% VAT for domestic goods) in all capital costs.

*TABLE 6. SYSTEM CONFIGURATION AND CAPITAL COSTS FOR GENERATION EQUIPMENT.*

| Site | System Components | Capacity | Installed Cost [$] |
|---|---|---|---|
| *PUAUCHO* | wind turbine with 24 m tower | 1.5 kW | 10159 |
| | modified sine wave inverter/charger | 2.4 kW | 1698 |
| | 8 deep cycle batteries and housing | 16.8 kWh | 2313 |
| | 2.3 kW manual-start gas genset | 2.3 kW | 1770 |
| | Balance of System and Grid costs | | 3486 |
| | Total Capital Cost of generation | | 19426 |
| *ISLA NAHUEL HUAPI* | wind turbine with 24m tower | 3 kW | 9384 |
| | sine wave inverter/charger | 3.3 kW | 4416 |
| | 8 deep cycle batteries and housing | 16.8 kWh | 2313 |
| | 4 kW electric start gas genset | 4 kW | 3776 |
| | Balance of System and Grid costs | | 7891 |
| | Total Capital Cost of generation | | 27780 |
| *VILLA LAS ARAUCARIAS* | wind turbine with 24m tower | 6 kW | 29616 |
| | sine wave inverter/charger | 3.3 kW | 4416 |
| | 16 deep cycle batteries and housing | 33.8 kWh | 4626 |
| | 4 kW electric start gas genset | 4 kW | 3776 |
| | Balance of System and Grid costs | | 6931 |
| | Total Capital Cost of generation | | 49365 |

Operations and maintenance (O&M) and replacement/overhaul costs were estimated based on limited and varied previous experience and are listed in Table 7. There is a large amount of uncertainty in these values, but as can seen by Figure 5, their contribution to the overall COE of hybrid systems is relatively small.

Figure 5 shows the disaggregated COE for the hybrid systems, assuming an 8.7% constant-dollar discount rate (18.2% current-dollar discount rate and 8.7% inflation rate) and a 20-year system lifetime. The estimated cost of gasoline in these remote regions is $0.56/liter. The hybrid systems are attractive to the utility because utility costs for these hybrids in daily operation (O&M, fuel, replacement, and overhaul costs) are quite low. In comparison, genset-only systems would have much lower capital outlays, but much higher operational costs to the utility. The genset-only systems in Figure 5 and Table 8 are all 2.3 kW gensets, which represent least-cost genset-only systems. The COE of the genset-only system at INH is extremely high because of the continuous load, i.e., refrigerator. This results in long operating hours with a very small load, where generators are most inefficient. It also result in large replacement and overhaul costs. VLA's total fuel and genset overhaul costs are similar, but because the total load served is higher, the COE is lower.

As can be seen from Figure 5, the capital cost of equipment has the greatest effect on the energy generation costs for the hybrid systems. The COE is somewhat dependent on gasoline prices and only slightly dependent upon turbine and genset O&M costs. Table 8 shows that tariffs comprise a significant 25% to 30% of the COE. The mini-grid costs vary from about 5% to 15% of the COE.

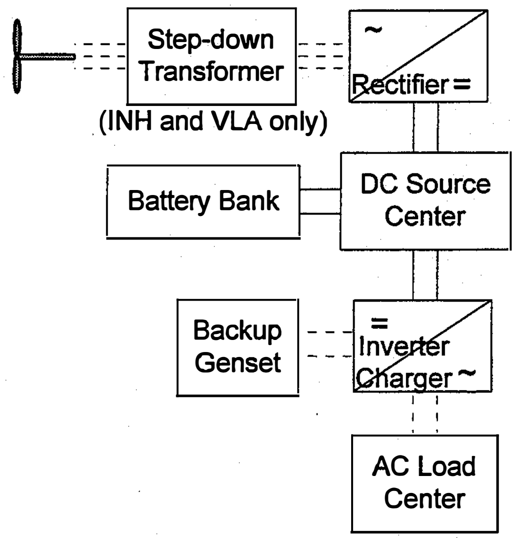


*FIGURE 4. SYSTEM DIAGRAM FOR THE WIND/GENSET ARCHITECTURE.*

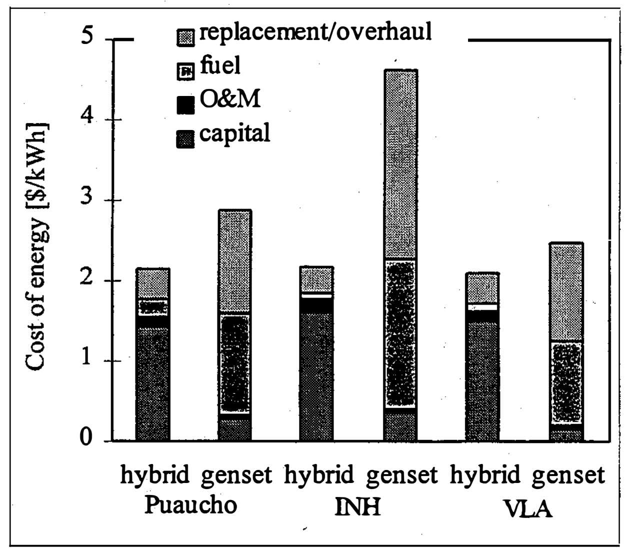


*FIGURE 5. COST OF ENERGY FOR THE HYBRID AND GENSET-ONLY SYSTEMS.*

*TABLE 7. O&M COSTS AND OVERHAUL COSTS USED IN THIS ANALYSIS.*

| System Component | O&M | Overhaul Cost | Overhaul Period |
|---|---|---|---|
| 1.5kW turbine | $0.02/kWh[2] | $1000 | 10 years |
| 3kW turbine | $0.03/kWh | $1000 | 10 years |
| 10kW turbine | $0.02/kWh[2] | $2000 | 10 years |
| 2.3 kW gas genset | $0.05/kWh | $1770 | 3500 hours |
| 4 kW gas genset | $0.05/kWh | $3776 | 3500 hours |
| 2.1 kWh batteries | $10/yr | $236 | lesser of 1225 kWh throughput or 5 years |
| 2.4 kW inverters/chargers | none | $1588 | 10 years |
| 3.3 kW inverters/chargers | none | $4129 | 10 years |

Table 8 shows that the given system configurations produce a large amount of excess energy. This can be used for optional loads, such as water-pumping or a battery-charging station, or this can provide for load growth. A battery-charging station is planned for one of the sites. Those villagers who live outside the mini-grid can have their batteries charged with the less expensive, excess electricity from the wind turbine. The economics of this use of excess energy have not yet been determined.

[2] Operations and maintenance costs are assumed to be minimal for these two turbines.

*TABLE 8. HYBRID2 RESULTS OF COE AND FUEL CONSUMPTION FOR BASECASE HYBRID AND 2.3 KW GENSET-ONLY SYSTEMS.*

| Site | Hybrid COE [$/kWh] | | | Total COE [$/kWh] | Fuel Use [L/yr] | | Excess Energy [kWh/yr] |
|---|---|---|---|---|---|---|---|
| | busbar w/o tax | busbar w/tax | total COE | genset-only | hybrid | genset-only | hybrid |
| *Puaucho* | 1.62 | 2.01 | 2.15 | 2.88 | 541 | 3330 | 990 |
| *INH* | 1.42 | 1.93 | 2.18 | 4.63 | 191 | 6176 | 3076 |
| *VLA* | 1.56 | 1.99 | 2.09 | 2.48 | 518 | 6503 | 5228 |

SENSITIVITY ANALYSIS

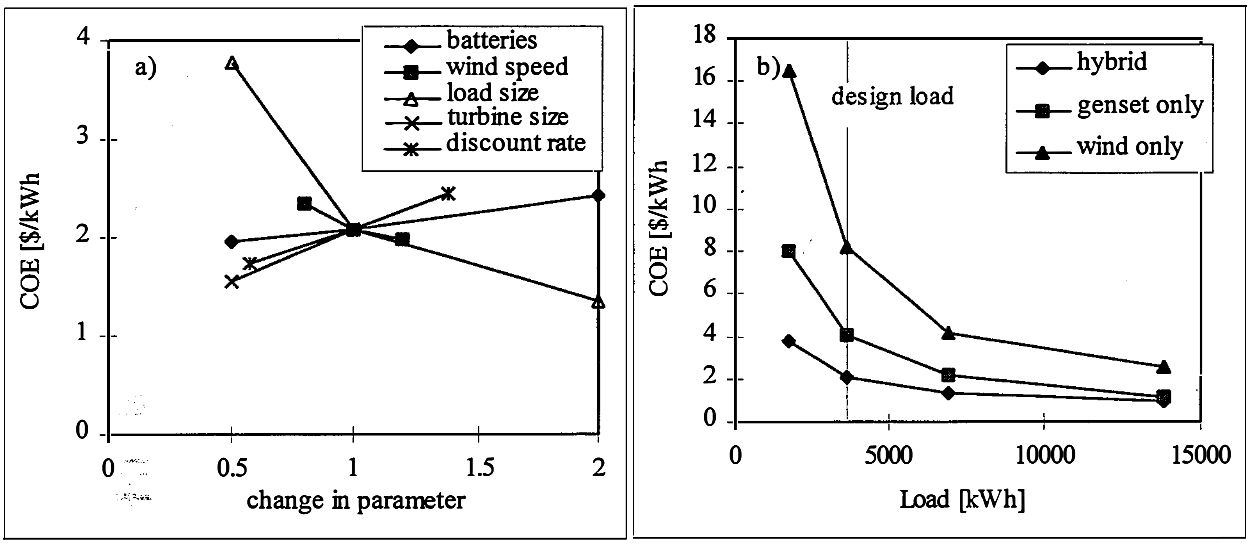


*FIGURE 6. SENSITIVITY ANALYSIS OF (A) THE VLA HYBRID SYSTEM AND (B) THE EFFECT OF LOAD SIZE ON THE COE FOR THREE TYPES OF SYSTEMS.*

Figure 6a shows the dependence of the COE on variations in storage, annual wind speed, load size, and turbine choice for VLA. Because this particular system has been deliberately oversized, the COE is highly dependent on the sizes of the load and turbine. Doubling the load decreases the COE significantly and halving the load almost doubles the COE. For systems that are sized closer to the load, this effect is less dramatic. A 20–year record of wind data at Concepcion Airport shows a maximum variation in annual wind speed of 20%. A variation of the VLA wind data set by 20% in Figure 6a shows a modest effect on the COE. As the average wind speed increases by 20%, fuel consumption is cut in half, but the COE decreases by about 5%. The same effect occurs with a variation of battery storage. Doubling the number of batteries results in a 15% increase in the COE, because the decreased fuel and genset costs are offset by the increased battery capital and replacement costs. The hybrid system also provides protection from the effects of general inflation and fuel inflation. Inflation is often high and unpredictable in the developing world. Figure 6 shows a modest dependence of the COE on the constant-dollar discount rate, which is a function of inflation.

This illustrates the inherent insensitivity to system uncertainties of wind/genset/battery systems. The COE of a wind-only system would be highly dependent upon storage size and interannual wind variation; these hybrid systems allow for design uncertainty/flexibility, load growth, and lack of long–term resource information.

As an example, Figure 6b compares the effect of load size on the COE for a 4 kW genset-only system, a 24 kW wind/battery system, and the hybrid system. The genset-only and hybrid systems are nearly able to meet the entire load at 14,000 kWh/yr, and for the same COE, but at lower load levels, the hybrid system is more cost-effective. The wind/battery system can only meet 80% of the 14,000 kWh/yr load, and is the most expensive system even at lower loads. This figure clearly shows that for VLA, the hybrid system is best able to cover a wide range of loads for not only the lowest cost, but also for the least variation in cost.

## FUTURE PLANS

The pilot projects are intended to demonstrate the reliability of wind–hybrid technology in remote community applications. The process of site identification and evaluation for renewables versus conventional line extension for the replication phase has already begun. Monitoring the performance of these pilots will help identify opportunities for reducing the cost and improving the performance of similar systems in the replication phase. It is expected that as more experience is developed, a lower cost of energy will result through in-country capacity building.

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