

HYBRID VILLAGE POWER SYSTEMS:

360 kWh/day Kahua, Hawaii

720 kWh/day Nabouwalu, Fiji

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Lessons Learned

- **Reliability** is paramount;
- **Reliability** based on: simplicity, capacity, redundancy and history;
- **Affordability** is another extremely important design consideration;
- **Installation** requirements must match in-country capabilities.

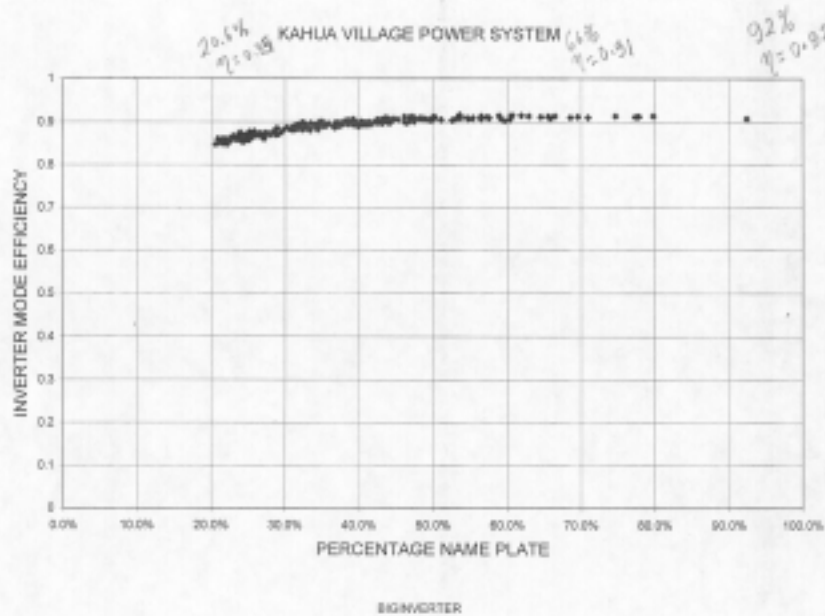
MUSTS:

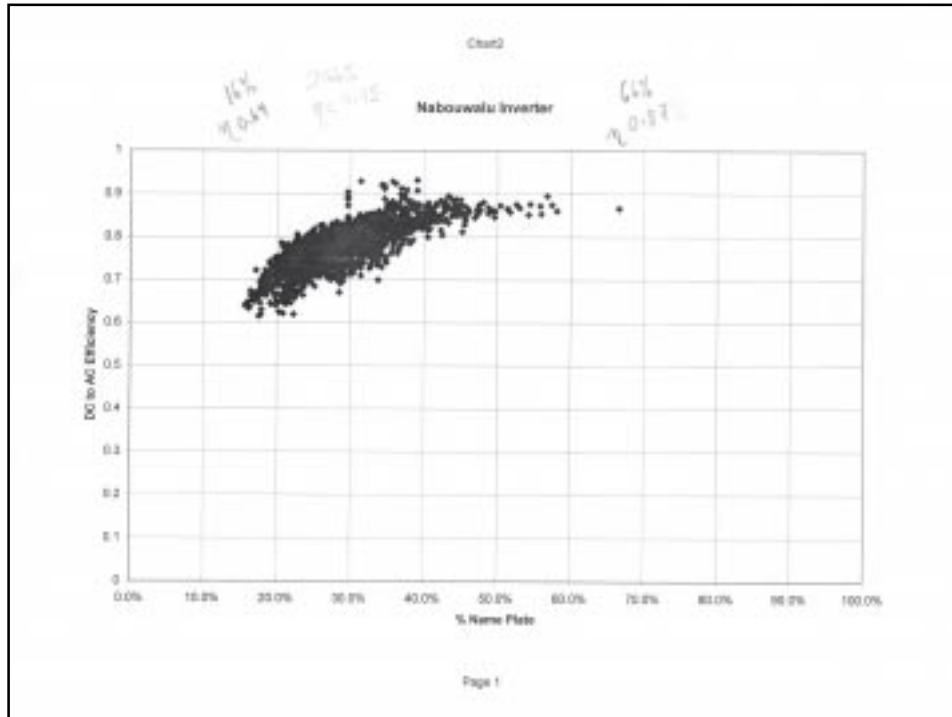
- **involve** the in-country **stakeholders** in all aspects of the project, from resource evaluation to implementation,
- **train** operators,
- use **commercially available equipment**,
- **test** equipment, as part of a system, **before it can be deployed to remote locations**,
- establish appropriate **maintenance** schemes.

The Nabouwalu, Fiji System

- Eight Bergeys provide plenty of **redundancy** but they were difficult to fit into the site. Three or at most four larger turbines would have been better
- ASE Americas PV modules with high voltage cable connections built into the module, take much **less time** to wire (e.g., 40 kW in Fiji took 25% the time to wire 10 kW in Hawaii);
- One (of 144) module had its glass backing shatter from thermal effects, but it is still operational.

- The company chosen to provide the Fiji **inverter** had decades of experience in high power **UPS systems** and needed only minor modifications to turn one of its UPS consoles into a hybrid system inverter.
- The inverter is a hybrid rotary system: ABB **motor drive** powering an **induction motor**, which then turns a synchronous **generator**. The **capacity** of the inverter is such that it easily **supplies the load** and can start the entire load.
- The **efficiency is less** than the Hawaii static inverter, but the system has **been reliable** since installation.





- To allow **easier installation** and better cooling of the cells The battery in Fiji has cell trays one half the size (six cells vs. twelve cells).
- Either genset can run the village, but neither can start the entire village so if diesel is used to bring the village on line, the load must be **segmented** and placed on the grid in sequence;
- The **major problems** with the system have involved the **gensets**. Only one has actually been placed into service, because of a breaker failure in unit 2. This means that when bad fuel caused problems with the lone operational diesel, the system could not supply load. Public Works is attempting to remedy the **fuel quality problem** and repair unit 2.

Summary

- Incremental increases in **simplicity, redundancy, capacity** and **operational history** have **increased** the **reliability** of the Fiji hybrid power system over the Hawaii system;
- Both are connected to existing mini-grids that were served by fossil fueled generation. Both grids have seen an **increase** in **power quality**; and, the Fiji grid has seen an increase in **availability**.

Demonstration and Training Facility in Hawaii

- Kahua Ranch Village on the Big Island of Hawaii. The village is the residential and operational center for a cattle and sheep ranch. Baseline (360 kWh/day) facility was **installed June 1996** and **reliable operations** were achieved in **August of 1997**.
 - 3 x 8 kW_p Bergey Wind Turbine Generators
 - 40 x 245 W_p ASE Americas PV Modules (Crystalline Silicon)
 - 428 kWh, 240 VDC Trojan (flooded lead acid) Battery
 - 30 kW Solid State (Static) Inverter by AES
 - 36 kW Kohler Diesel Generator

SYSTEM PERFORMANCE

Design Conditions

- Annual averages of 5.25 sun-peak-hours/day ($\text{kWh/m}^2\text{-day}$) and 8.9 m/s;
- The **renewable energy** components were expected to meet **72%** of the demand, with the balance supplied by the genset;
- The COE was expected to be in the range of 0.32 to 0.36 \$/kWh (15 years life; 3% to 5% loan; 5-year battery replacement)

Actual Performance (Since 8/97)

- The **PV array** is supplying **94 %** of the **design** value; and,
- The **WTGs** were only supplying **74 %** of the **design** value; however stator **modifications** should increase production to the design value*;
- The actual COE will be in the design range (≤ 0.36 \$/kWh).

*once all stators are replaced.

KAHUA (HAWAII) REPAIR RECORD

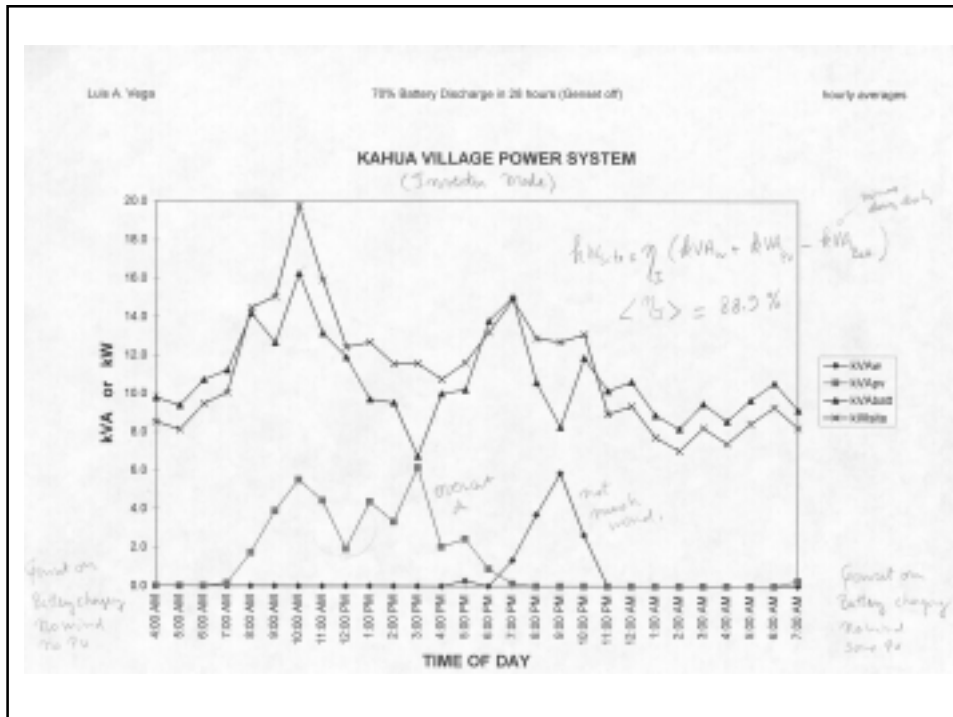
	Date	REPAIRS	I&M
Wind Turbines	4/97	Repaired slip ring brush (unit 3), downtime: 1 day	Monthly:
Installed 6/96	8/97	Replaced leading edge tape (all units), 1d	Visual inspection
	9/97	Tail damper shafts failure observed (all units). Apparently since 6/96.	Quarterly:
	9/97	Tail attachment failure (unit 3); downtime: 1 month	Lower & inspect turbines
	10/97	Replaced tail (unit 3); 1d	Yearly:
			Tighten all connections

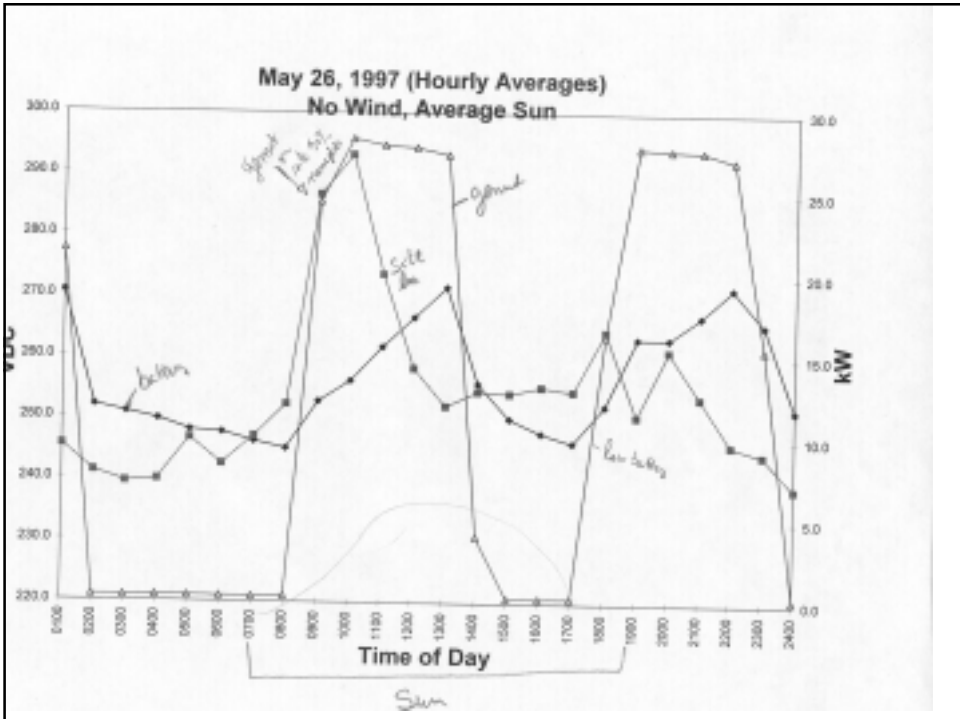
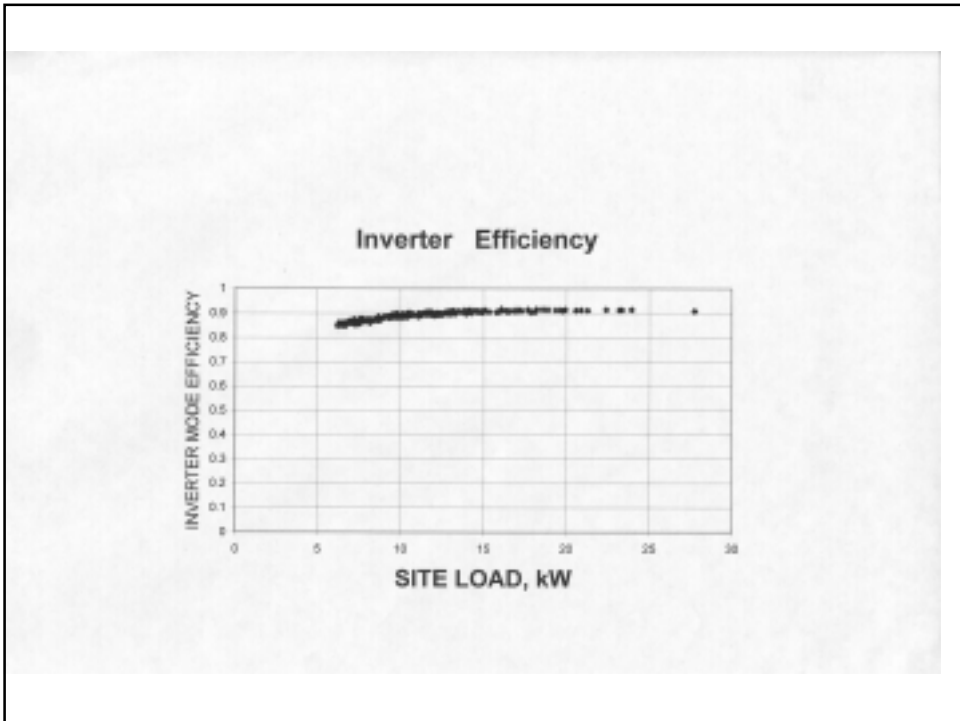
	Date	REPAIRS	I&M
Wind Turbines	3/98	Test of Unit 2 with standard stator vs experimental: Production 1.4 x	See previous page
	5/98	Another tail attachment failure (unit 1); 1 day	
	9/98	New designed tail damper shafts & pins received from Bergey.	
	9/98	Stator for Unit 1 replaced with standard design (higher production).	

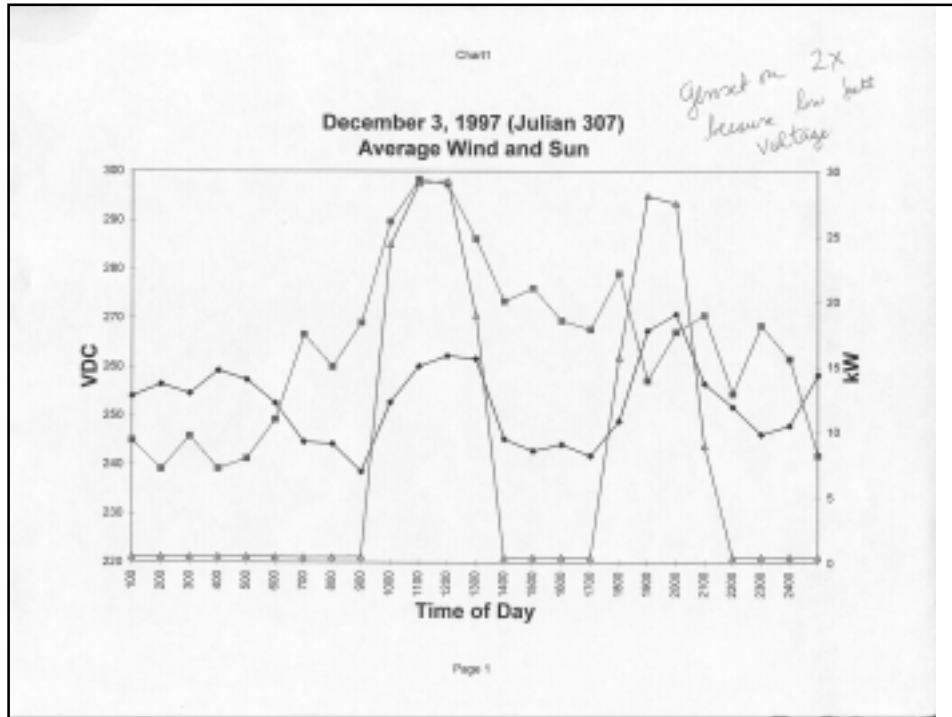
	Date	REPAIRS	I&M
Inverter	4/96 to 3/97	Set point changes	Monthly:
Installed 4/96	9/96	New operating software	Visual inspection
		Replaced failed relay	Yearly:
		Installed diode across contactor	Tighten all connections
	10/96	Replaced burnt capacitors & new firmware	
	12/96	Replaced failed control battery (& 2/97); firmware, etc.	
	8/97	Grounding mods. & ferrite EMI filters to eliminate radiation	

	Date	REPAIRS	I&M
Inverter	8/98	After 1-year of reliable operation, inverter fails to control genset output. IC socket corrosion suspected. Repair of socket requires de- powering control board...another control program (firmware) lost on re-power of control board	See previous page
	9/98	Control board replaced (includes upgraded firmware); downtime: 6- weeks.	

	Date	REPAIRS	I&M
Battery	6/97	Cleaned terminal corrosion	Biweekly: add 10 gallons of water
Installed 4/96	9/98	Cell 55 (of 120) very low voltage (0.82 V). Unable to charge. Cell jumpered across. Waiting for replacement.	Monthly: Visual Inspection. Yearly: tighten connections.



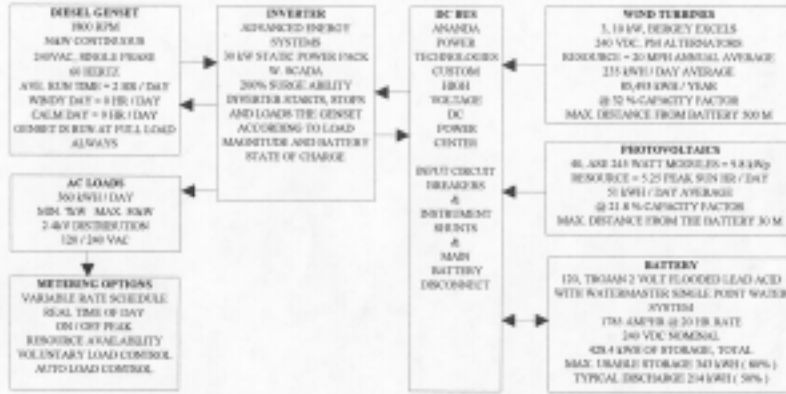




CONCLUSIONS Kahua (Hawaii)

- Testing has confirmed the importance of considering only **equipment with operational records** for applications in **remote locations**.
- Equipment must be tested as **part of a system** supplying electricity to actual users or to a load bank programmed to represent **realistic load profiles**.
- Preliminary **maintenance schedules** for all components have been developed.
- The **experience gained** was used to design a 720 kWh/day system for the village of Nabouwalu in Fiji.

**RENEWABLE HYBRID VILLAGE POWER SYSTEM
BLOCK DIAGRAM**



**THE PACIFIC INTERNATIONAL CENTER FOR HIGH TECHNOLOGY RESEARCH
RENEWABLE HYBRID VILLAGE POWER DEMONSTRATION FACILITY AT KAHUA RANCH**

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LOCATION Kahua Training and Evaluation Center				
Village Power System	Size	Cost		
Diesel	0.4 \$/W	35 kW	\$14 k	
Battery	110 \$/kWh	420 kWh	\$47 k	
Inverter/Controller	1.4 \$/W	30 kW	\$42 k	
Photovoltaics	4.5 \$/W	6.0 kW	\$44 k	
Wind Turbine Generators	2.5 \$/W	30 kW	\$75 k	
Installation & Infrastructure			\$34 k	
Shipping	Included above		\$0 k	20' container OK
TOTAL			\$256 k	
CURRENT DOLLAR LEVELIZATION (Constant Annual Cost)				
Site Average Consumption	280 kWh/day	Annual Average		
Renewables Average Production	286 kWh/day	Wind 6.9 m/s	32.0%	
Installed Cost Renewables (CC)	\$242 k	Sun 5.3 sunhours	21.0%	
OM, Yearly O&M	\$9 k	Includes Replacements		
i, Interest (current-dollar discount rate)	5.00%	ADBWS=5%	Others= 10%	
EP, Annual escalation (inflation) for entire period	2.00%			
N, System Life	15 years			
CAPITAL PAYMENT RENEWABLES				
CRF, Cap. Recor. Fac. or Invest. Level. Fac.(1/N)	0.03%			
Levelized Invest. Cost, CC*CRF/Yearly Production	\$ 22 \$/kWh	"Loan Amortization Payments"		
O&M (Replacement) COSTS RENEWABLES				
CRF, (1/N)	0.03%			
Present Worth Factor with Inflation, 0/N, 0%	11.00			
ELF, Expenses Levelizing Factor 0/N, 0%	1.15			
Levelized Oper. Cost, O&M/Yearly Production	\$ 10 \$/kWh	To cover Battery Replacement (10 years)		
Total COE Production With Renew.	\$ 33 \$/kWh			

Table 2 Levelized COE at Kahua Training and Evaluation Center

LOCATION: LONG TERM COST GOALS APPLIED TO KAHUA RESOURCE				
Village Power System				
Diesel	0.4 \$/Wh	35 kW	\$14 k	Market Price
Battery	110 \$/kWh	428 kWh	\$47 k	Market Price/Double Life
Inverter/Controller	0.7 \$/Wh	30 kW	\$21 k	Price same as Home Inverter
PhotoVoltaics	3.5 \$/Wh	9.8 kW	\$34 k	Production Increase Price
Wind Turbine Generator	2.0 \$/Wh	30 kW	\$60 k	Competition Pricing
Installation & Infrastructure			\$34 k	
Shipping	Included above		\$0 k	20' container Off
TOTAL			\$210 k	
CURRENT DOLLAR LEVELIZATION (Constant Annual Cost)				
Site Average Consumption	390 kWh/day	Annual Average		
Renewables Average Production	288 kWh/day	Wind 8.9 m/s	32.0%	
Installed Cost Renewables (CC)	\$198 k	Sun 5.3 sunhours	21.6%	
OM, Yearly O&M	\$5 k	Includes Replacements		
i, Interest (current-dollar discount rate)	3.00%	ADB/ADB-c5%	Others= 10%	
CR, Annual escalation (inflation) for entire period	2.00%			
N, System Life	15 years			
CAPITAL PAYMENT RENEWABLES				
CRF, Cap. Recou. Pct. @ Interest Level, Factor 1/N	0.39%			
Levelized Invest. Cost, ccr/(1-N) ^N yearly production	0.16 \$/kWh	"Loan Amortization Payments"		
O&M (Replacement) COSTS RENEWABLES				
CRF, 1/N	0.39%			
Present Worth Factor with Inflation, 1/(1+CR) ^N	13.89			
S.P., Expense Levelizing Factor 1/(1+CR) ^N	1.18			
Levelized Oper. Cost, O&M/(1-N) ^N yearly production	0.05 \$/kWh	To cover Battery Replacement (10 years)		
Total COE Production With Renew.	0.21 \$/kWh			

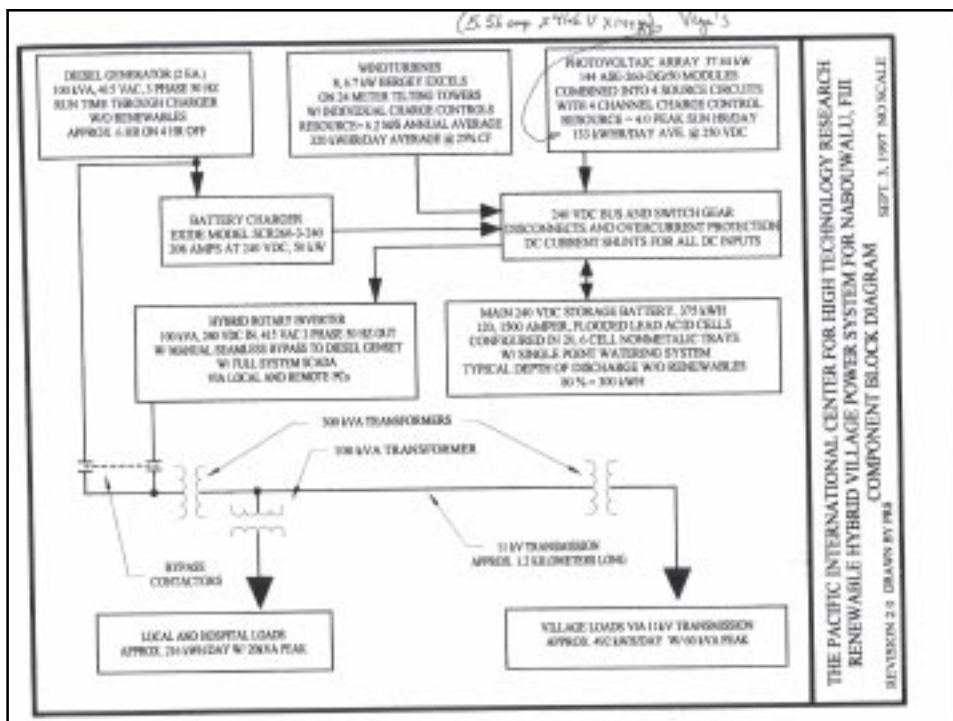
Table 3 Levelized COE for Long Term Cost Goals Applied to Kahua Resource

720 kWh/day Village Power System for Nabouwalu, Fiji

- Government station at Nabouwalu in Vanua Levu
- Wind and solar insolation monitoring station was set up, by FDoE, at a location selected after a field trip and in consultation with the residents
- With six-month environmental and electrical load data records (some correlated with twenty-year long records from a nearby meteorological station), the design was developed by PICHTR working with FDoE and PWD.

Design Configuration:

- 8 x 9 kW_p Bergey Wind Turbine Generators
- 144 x 260 W_p ASE Americas PV Modules
- 428 kWh, 240 VDC Trojan Battery
- 100 kVA Rotary-Hybrid Inverter by PS&C
- 2 x 100 kVA Diesel Generator and Mini-Grid in Nabouwalu



Energy Sources

Renewable sources are used to energize a DC bus, which supplies the energy to run a hybrid rotary inverter which in turn powers the load, the excess is stored in the battery

Wind Turbine Generators

- The WTGs turn permanent-magnet generators which produce three phase AC power of varying frequency ...transmitted to the electrical/control room wherein the power is rectified and the voltage regulated
- With proper IM&R, the life of the wind turbines and towers should exceed 20 years.

PV Array

- DC electrical output of the fixed PV Array is regulated by a controller
- Minimal IM&R is required to attain life cycles of 30 years.

Genset

- The generators produce 50 Hz, three phase, 415 Volt output, to power the load directly and to charge the battery when required (set point 1.9 V/cell)

Energy Storage

- When the renewable resources are insufficient to support the load, the battery discharges to the DC bus.
- Fully charged, the battery can run the village $\frac{1}{2}$ day.
- When the battery is charged (set point 2.4 V/cell), the WTGs and PV controllers limit the charge rate to prevent overcharging (i.e., regulate).
- With Proper IM&R the battery should last 5 to 10 years

DC to AC Conversion

- The hybrid rotary inverter consists of variable frequency motor drive (ABB) which converts the DC bus current to three phase, 50 hz, AC at \approx 150 Volts RMS... to run an induction motor coupled to a synchronous generator which produces the 415 V, three phase, 50 Hz supply.
- The inverter requires no periodic maintenance other than inspection of the coupling between the motor and generator. The bearings in the motor and generator are sealed and cannot be greased. The expected life of these bearings in continuous service is 20 years.

SCADA

- Control of the inverter is shared between a microprocessor based control board and a GE Programmable Logic Controller (PLC-1).
- Another PLC (PLC-2), controls the operation of the diesel powered battery charger and collects data from various power monitoring and environmental sensors and transducers.
- Communication and collection of data from PLC-2 is through a personal computer running AIMAX software produced by T.A. Engineering.