DESIGN OF AN ENERGY-EFFICIENT HYBRID POWER SOURCE FOR REMOTE LOCATIONS AS A STUDENT PROJECT

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Abstract -- This paper describes an undergraduate or graduate level student project that involves the design of an energy-efficient hybrid power source for remote communities that have no connection to other electric utility systems. One such application is the development of stand-alone electric power sources for Native American villages in rural Alaska. This student project addresses many facets of engineering design and development including system component design and system integration, as well as environmental and social impacts, and economic concerns. The design requires consideration of all possible energy sources and energy conversion alternatives in the development of a hybrid system. Available energy sources may include wind, solar, small head or river hydro, thermoelectric generators, microturbine technology, and thermoelectric systems, battery and other energy storage devices combined with the existing diesel/electric or gasoline/electric generators. The selection of energy sources for this application depends not only on the power requirements and location, but also on environmental, economic, social, and political concerns. Economic considerations include the life cycle cost and estimated unit cost of electricity generated. System efficiency must also be determined, including the possibility of utilizing waste thermal energy. A major factor in this design is the transfer of the technology to rural Alaskan communities which have limited technical literacy.

Introduction

The need for energy-efficient electric power sources in remote areas is a driving force for research in alternative and hybrid energy systems. This topic is very important for Alaska which has more than 200 remote communities [1] and for developing countries such as Mexico, which has approximately 85,000 villages each with a population less than 1000 persons. Most of the remote Alaskan communities have no access to the electric utility system and rely on diesel-electric generators (DEGs) for electric power. These systems are typically uneconomical due to the shipping costs of fuel and require routine maintenance due to operating conditions [2,3]. Efforts are already underway to build hybrid systems in remote villages of Alaska such as the diesel/photovoltaic/battery electric power system in Lime Village, Alaska backed by the Alaska Energy Authority (AEA). The University of Alaska Fairbanks (UAF) College of Science, Engineering, and Mathematics is stepping up to the challenge with the newly developed Arctic Energy Technology Development Laboratory (AEDTL) whose mission is to promote research and development of energy technologies in Arctic regions. Projects which involve remote power technologies in Arctic climates will combine student and faculty research efforts with government and private industry collaboration.

The goal of this student project is to develop a hybrid power system for a remote Alaskan village. The project will provide undergraduate and graduate students in all facets of engineering with valuable research and design experience while helping them to develop working relationships with other engineering students and with industry partners. Students will be exposed to the process of engineering design and development including system component design and system integration. Students will need to consider the economic and environmental aspects of the design, as well as the impact of the technology on the community. The criteria for the design include:

1. finding the most economical solution in terms of life-cycle costs,
2. making the best use of existing and donated equipment,
3. optimizing the system performance for a projected load profile,
4. lowering the operating and maintenance costs, and
5. assessing the impacts of the design on the environment and the community.

The design criteria require consideration of all possible energy sources and energy conversion alternatives in the development of a hybrid power system. Students will make use of computer design and simulations tools for system design and analysis while also working with an actual system.

Educational Benefits

This project was designed with both the undergraduate and the graduate level student in mind. This project will be offered to undergraduate students in all engineering disciplines as a design course in electrical engineering which satisfies part of the design requirements for an undergraduate degree. Participation from all engineering disciplines is encouraged with the intent of students from electrical, mechanical, civil, and environmental engineering working together to achieve a complete system design. The project also involves students at the graduate level who will work with the undergraduate students and faculty on the design, simulation, and analysis of the hybrid power system as part of a thesis project requirement.

Design Process

Students will work with the recently-installed hybrid power system at Lime Village, Alaska. The design process begins with an assessment of the site, including the current system specifications, load requirements, and available sources of electric power production. This information will aid in developing a hybrid system which best fits the needs of the community with the optimum life cycle costs and use of available energy sources. After a site survey has been established five configurations are examined using the existing load profile and an economic analysis is performed using the original system for comparison. The components for the hybrid power system are selected based on optimal operation and cost savings.

Background Information

The current power system at Lime Village incorporates two diesel-electric generators rated at 50 kW and 35 kW. The 50 kW DEG has been damaged and is unusable without major repairs.

Generation efficiencies are 3 to 5 kW-hrs/gallon and the operation and maintenance costs for the DEGs are high because the 35 kW generator is delivering power well below its efficient operating range. DEGs are usually sized to the maximum peak load. Fluctuating demand requires that sufficient spinning reserve be supplied to avoid system imbalances. These two conditions, oversizing and spinning reserve requirements result in keeping the diesel generator sets operating in less than optimal fuel saving conditions. Fuel savings is important in this design since fuel is shipped by air at a cost of $2.80 to $4.80 per gallon [2]. The current rate for electricity in Lime Village is $0.30/kW-hr [2].

A 4 kW photovoltaic (PV) array and a 100 kW-hr valve regulated lead-acid (VRLA) battery bank are also in place, but unusable because the system lacks a suitable energy conversion device. Other system components in place include the system controller, switchgear, warm secure building, operational software, electrical distribution system, fuel storage and handling, and PV panel support framing. A backhoe, a truck, and a bobcat are available and in working order on location in Lime Village for use in this project.

The 35 kW DEG in Lime Village is oversized for the current load profile which is not expected to increase for some time. Current operation is with one manually operated 35 kW DEG without back-up capability. If this DEG fails or is off-line for maintenance, the community will be without electricity. The average load in Lime Village is less than 12 kW. A newly opened laundry and telephone utility in Lime Village are considered in the future load profile for the design. Figure 1 below shows a sample 24-hour load profile for the system [3].

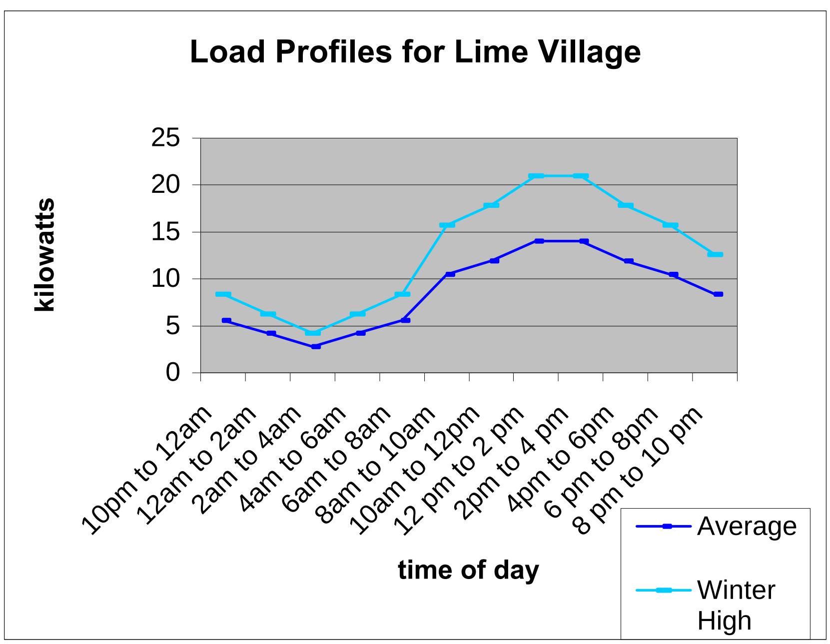

Figure 1: Load Profile for Lime Village, Alaska

Proposed System

The proposed system solution is to replace the damaged 50 kW DEG and rotary power converter with a smaller DEG and an electronic inverter. The smaller DEG and inverter would be sized to meet the average load. The other components will be configured to reduce the use of the DEGs while optimizing the system for the load requirements. Wind is not considered as a generation source in this analysis. Each option assumes a revised load profile incorporating the newly opened laundry and telephone utility in Lime Village.

The following hybrid power system configurations were considered with Case 1 as the base.

Case 1:
Base case and lowest cost option. This analysis consists of adding a 15 kW DEG to avoid running the 35 kW DEG. This option discontinues the use of the battery bank and PV panels. Manual operation is assumed.

Case 2:
Installation of two new DEGs rated at 15 kW and 21 kW. Diesel dispatch is automated.

Case 3:
Installation of two new 15 and 21 kW DEGs and a stock 16 kW three-phase inverter which allows the system to make use of the existing 4 kW PV array and battery bank.

Case 4:
Same as Case 3 with 8 kW of new PV capacity added to the system. Costs associated with the additional PV panels do not include the cost of the panels themselves ($40,000). The PV panels have been donated by BP Solar. Included are costs for structural improvements to the support framing, additional wiring, freight, and installation labor. Analysis supports Case 4 as the preferred configuration.

Case 5:
Similar to Case 4 with an increased battery storage capacity.

Preliminary Budget

The preliminary budgets for the proposed Lime Village hybrid electric power system configurations are outlined in Table 1 below [2].

Table 1: Preliminary Budget for Lime Village Hybrid Power System Configurations

Case 0: Existing System - Insufficient, Non-compliant	
35 kW DEG manually controlled	
Case 1: 15, 35 kW DEGs	
15 kW diesel added (misc. parts)	$ 18,000
Switch gear to automate control of both DEGs	$ 15,000
Engineering/Labor/freight/travel	$ 11,000

TOTAL	$ 44,000
Case 2: 15, 20 kW DEGs	
New 15 kW DEG	$ 14,000
New 20 kW DEG (misc. parts)	$ 18,500
Switch gear to automate control of both diesels	$ 15,000
Engineering	$ 4,000
Commissioning, Installation, freight, travel	$ 14,000
TOTAL	$ 65,500
Case 3: 15, 20 kW DEGs with Existing PV and Batteries	
New 15 kW DEG	$ 14,000
New 20 kW DEG (misc. parts)	$ 18,500
Switch gear to automate control of both diesels	$ 15,000
Add Trace package for rectification/inversion(wholesale)	$ 15,000
Use existing battery bank	$ -
Use existing 4 kW PV	$ -
Engineering	$ 4,500
Commissioning, Installation, freight, travel	$ 15,700
TOTAL	$ 82,700
Case 4: 15, 20 kW DEGs with Existing Batteries, Increase PV to 12 kW	
New 15 kW DEG	$ 14,000
New 20 kW DEG (misc. parts)	$ 18,500
Switch gear to automate control of both diesels	$ 15,000
Add Trace package for rectification/inversion(wholesale)	$ 15,000
Use existing battery bank	$ -
Increase to 12 kW PV (8 kW of panels donated by BP Solar)	$ 7,000
Engineering	$ 4,500
Commissioning, Installation, freight, travel	$ 16,000
TOTAL	$ 90,000
Case 5: 15, 20 kW DEGs with More Batteries, Increase PV to 12 kW	
New 15 kW DEG	$ 14,000
New 20 kW DEG	$ 18,500
Switch gear to automate control of both diesels	$ 15,000
Add Trace package for rectification/inversion	$ 15,000
New batteries to double size of bank	$ 27,000
Increase to 12 kW PV (8 kW of panels donated by BP Solar)	$ 7,000
Engineering	$ 4,000
Commissioning, Installation, freight, travel	$ 16,000
TOTAL	$116,500

Outcomes Assessment

An assessment of the proposed Lime Village hybrid electric power system configurations using Case 1 (addition of a 15 kW DEG and automated control) as the base with a one-year simulation period is shown in Tables 2-5 [2]. Calculations are based on the following base case fuel use, fuel cost, and discount rate [3].

Fuel Saving Simulation Period	1 year
Base Case Fuel Use, gallons	20,578 (15, 35 kW DEGs)
Fuel Cost, $/gallon	3 ($3.00/gal)
Discount Rate	6.0%

Table 2: Lime Village Hybrid Power System Configurations

Case	DEGs, kW	PV, kW	Battery, cells
2	15, 20	None	None
3	15, 20	4	96
4	15, 20	12	96
5	15, 20	12	192

Table 3: Fuel Savings for Lime Village Hybrid Power System Configurations

Case	Fuel Use, gal	Fuel Saved, gal	% Fuel Saved
2	17,234	3,345	16.3%
3	15,342	5,236	25.4%
4	14,698	5,881	28.6%
5	14,722	5,856	28.5%

Table 4: Economics for Lime Village Hybrid Power System Configurations

Case	Annual Savings, $	Present Value of 10-Year Savings	Cost of System	Net
2	$ 10,033.85	$ 73,849.99	$ 65,500.00	$ 8,349.99
3	$ 15,709.32	$ 115,621.96	$ 82,700.00	$ 32,921.96
4	$ 17,641.80	$ 129,845.18	$ 90,000.00	$ 39,845.18
5	$ 17,567.35	$ 129,297.24	$ 116,500.00	$ 12,797.24

Table 5: DEG Cycling for Lime Village Hybrid Power System Configurations

Case	15 kW DEG		35 kW DEG	
	On-time (hours)	Number of Starts	On-time (hours)	Number of Starts
1 (Base)	990	90	7770	91
Case	15 kW DEG		20 kW DEG	
	On-time (hours)	Number of Starts	On-time (hours)	Number of Starts
2	3190	640	7770	91
3	4758	471	4212	438
4	5350	506	3578	482
5	5375	507	3571	485

Preferred Configuration

Results from the economic outcomes assessment (see Table 4) and the provision of donated equipment suggest that the Lime Village load is best served by the system outlined in Case 4. This will involve the installation of two smaller generator sets configured with a bi-directional converter to make use of the existing batteries and an expanded photovoltaic array. A block diagram of the system is shown in Figure 2 below. The preferred configuration makes use of a donation of 108 photovoltaic panels from BP Solar, as well as the existing battery bank, and existing power system infrastructure. These features give this alternative an economic advantage. The total project cost will be $130,000 including the $40,000 cost of the additional solar panels which were donated.

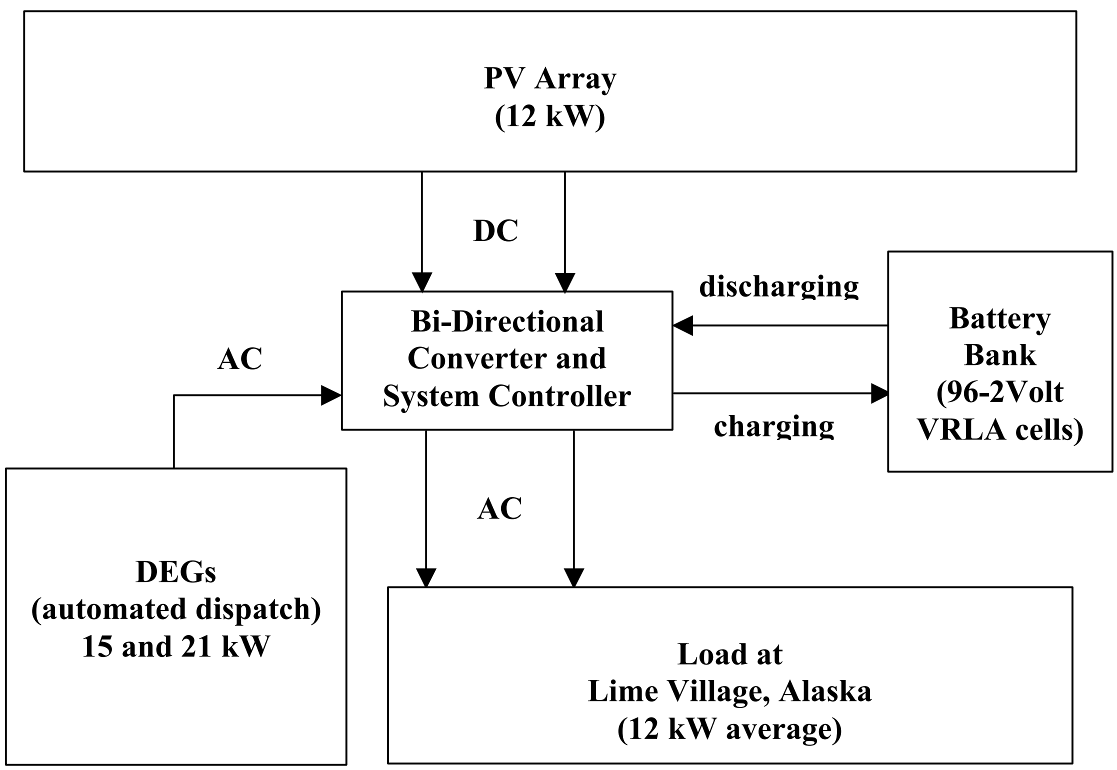

Figure 2: Block Diagram of Hybrid Power System

This proposed system satisfies the design criteria for the project by:

1) providing the largest net fuel and cost savings over a 1 year simulation period
2) making the best use of existing and donated equipment,
3) optimizing DEG performance, and
4) lowering operating and maintenance costs.

The addition of two newer more efficient DEGs, an expanded photovoltaic array, and the use of battery storage are estimated to reduce diesel fuel use by 28%, or 5800 gallons annually. This reduction in fuel consumption is expected to decrease electrical rates by $0.10/kW-hr to $0.20/kW-hr.

Equipment List

The following list outlines the equipment required for the proposed design.

1. 1-25 kW diesel generator
2. 1-15 kW diesel generator
3. 12 kW photovoltaic array
4. 95-530 Ah lead-acid batteries
5. 1-30 kVA bi-directional power converter with data acquisition system
6. 1-16 kW Trace inverter as an addition to the bi-directional converter

The specifications for each of these items is listed in Tables 6-10 below [4].

Table 6: Generator A

Engine	John Deere (manufactured by Yanmar)
Model	Model 4020TS106
Number of cylinders	4
Engine type	In-line, 4-cycle
Aspiration	Turbocharged
Net rated power, prime	24.3 kW
Generator	Marathon
Model	283PSL1506
Rated power	23KW @105 degree C rise

Table 7: Generator B

Engine	Undetermined
Model	Undetermined
Number of cylinders	4
Engine type	In-line, 4-cycle
Aspiration	Natural
Net rated power, prime	~15kW
Generator	Undetermined
Model	Undetermined
Rated power	15 kW

Table 8: Photovoltaic Array

75-Siemens M55 panels	
Configuration	15 panels in series X 5 strings in parallel
Rated capacity	4 kW
105-BP Solar BP275UL panels (1 spare)	
Configuration	15 panels in series X 7 strings in parallel
Rated capacity	8 kW
Total rated capacity	12 kW

Table 9: Batteries

95-GNB Absolyte IIP, 6-90A13	Valve regulated, absorbent glass mat, lead-calcium battery
Configuration	95 cells in series
Nominal voltage of string	190 V
Nominal capacity (8-hour rate)	530 Ah

Table 10: Bi-Directional Power Converter/Controller

AES Static Power Pack (SPP)	
Rated capacity	30 kVA
AC Bus	3-phase, 120/208 V, 60 Hz
DC Bus	192 V
PV controller	PWM
Interface	Touch screen
Data acquisition	
Data summary	Summation data since last reset.
Error log	
Variable averaging period	1 minute to 24 hour
Data columns	40
Data rows	150
Description	The SPP maintains 150 records (40 columns each) in its internal memory. The site computer runs Telix terminal software to monitor the SPP, as well as to automatically retrieve the data log. This is facilitated by a script, which is always running under Telix. Currently, the SPP is recording 15 minute averages and the site computer is retrieving the data once per day. The download frequency can be increased.

Equipment and Design Considerations

A number of important equipment and design considerations surfaced in the overall implementation and control of the hybrid power system project. These topics open the door for individual undergraduate and graduate projects as part of the overall design.

DEGs:

The operating and maintenance costs for the DEGs is a primary concern in this design. This analysis considers using the John Deere 4020 DF and the TF models. These engines differ by fuel system configuration. The DF is naturally aspirated and is the primary unit. The TF model is the turbocharged unit. Depending on the load characteristics the DF is expected to provide additional fuel savings at lower loads. If the load grows the DF can be upgraded from a 14.7 kW continuous rating to a 21 kW continuous rating or easily replaced [2]. This engine selection provides additional parts redundancy.

Photovoltaics:

Photovoltaic cells are semiconductors which generate electricity from sunlight [5]. The level of current generated by an array of cells is directly proportional to light intensity. It is conservatively estimated that the combined solar array will displace about 950 gallons of diesel fuel per year [2]. The current photovoltaic system consists of approximately 4 kW of panels. BP Exploration Alaska has donated an additional 8 kW of panels to increase the capacity of this system to 12 kW to match the average load on the system.

Battery Energy Storage:

The battery energy storage component of the system performs three primary tasks [2]:

1. Energy storage
2. Spinning reserve
3. Voltage stabilization

Battery storage acts as a reversible demand-side management system which stores energy and shifts excess peak load to off-peak hours. PV arrays and DEGs often produce energy when it not needed, or in the case of DEGs, excess energy is available at very little marginal cost under certain operating conditions. The battery bank stores electricity when it is in excess or cheaper to produce, saving it for periods when it is unavailable or more costly [2,6].

Maintenance consists of: 1. freeze protection; 2. specific gravity checks every 4-6 months; 3. battery terminal cleaning; 4. maintaining electrolyte concentration and amount and type of any impurities in the batteries; and 5. monitoring of charge levels. These maintenance tasks are simple and anticipated to be incorporated into existing maintenance routines at a cost of approximately $1000 per year.

The existing battery bank has reached half of its life expectancy. It is anticipated that this system will work for the next 5 years [2]. This request does not include funds for a new battery bank, since the existing battery bank has some life left. A major battery purchase should be deferred until such a time as it is determined to be needed and that its effectiveness has been clearly demonstrated. Two major battery replacement expenses are freight and proper disposal. It is anticipated that old batteries would be recycled at the time of battery replacement. Costs would be saved through airfreight backhauling. The investment in the inverter is needed to permit the use of the PV panels and batteries.

System Converter/Controller:

The system controller provides [4]:

1. Remote data acquisition and control

2. Power distribution control
3. Station data logging

In a typical application, the smallest DEG would run during most periods of consumer demand, and all DEGs would be shut down during periods of very low load [2, 7, 8]. This situation is expected to occur on most summer nights and occasionally during the winter. As the load increases throughout the day, the control system selects between various power options to meet demand. These options include, running the smallest DEG and using battery energy to smooth out the peaks, or if the peaks continue, bringing the next largest DEG on line. The inverter system has a built in controller which can respond to a number of signals it receives from load sensors and remote users. Signals automatically initiate or manually override operating routines. In Lime Village shutting off or limiting large customer loads and establishing artificial diesel generator set points could be an important next step for system optimization.

There are four important considerations in assuring the long-term viability of this project [2, 6, 7, 8].

1. accurate sizing
2. ability to manage the load,
3. adequate long-lasting battery capacity,
4. automation,
5. addition of wind generators, and
6. addition of fuel cells.

<u>Sizing:</u>

The load data has been estimated in a conservative manner, taking into consideration all available data. Several days of one-minute data have been collected and are available to investigate system sizing. Future load projections are uncertain since the current average daily load of 12 kW is not expected to increase in the next few years. This leaves an open door for analysis of possible contingencies in the future load profile for Lime Village.

<u>Load Management</u>:

One of the largest and most unpredictable loads are the two 5900 watt dryers in the new laundry. These dryers could at times make up 80% of the community load. The supervisory controller has the ability to sense, limit, or switch off this load. Other strategies such as restricting hours of dryer operation or disconnecting one dryer are possible. Management of the dryer loads will be important for scheduling generation.

Fluctuating demand requires sufficient spinning reserve to be supplied by the DEGs. Spinning reserve is essential to prevent system collapse in the event of a sudden increase in load. Usually spinning reserve is met by keeping excess DEG capacity on line. The battery energy storage system allows the most efficient operation of the DEGs close to rated power by balancing the fluctuations in load by charging and discharging as needed [6].

During peak loads, usually between noon and 8 p.m. the battery system is to be used to level out variations in loading, collecting and storing surplus energy, or providing short term (minutes to hours, depending on the control strategy) energy. Many other opportunities can be found to manage and reduce generator operations. It is expected that there will be periods of low, or manageable load, when the DEGs can be shut-off entirely. Peaking strategies can be implemented which avoid starts and stops of the next largest generator set, save fuel, and extend generator life [6]. The supervisory controller adds to this performance by monitoring the load and implementing a strategy based on parameters learned over time. In addition, the battery system provides for the moderation of high voltages during periods of charging and peak demand.

Battery Capacity:

Battery energy storage is not a new technology in Alaska. Several demonstration projects and operational systems have been built. Most recently a 1 MW energy storage project was built in Metlakatla, Alaska. Golden Valley Electric Association in Fairbanks, Alaska is constructing a 40 MW battery back-up system.

Much research has been conducted and advances have been made in extending the life of battery energy storage systems. Power conditioning equipment and system control advances have lowered maintenance costs and extended the life of battery systems. GNB Technologies, (Lombard, Illinois) have demonstrated a 20-year lifetime of the same valve regulated lead-acid (VRLA) batteries as those installed in Lime Village [9].

Automation:

Future work on this project will include the addition of the capability to manage the system and the load from a remote location. The system controller has the ability to automatically dial the McGrath Light and Power office and report system faults [2, 4]. The staff in McGrath and other locations could receive a detailed analysis of the situation. It is also possible to add an automatic meter reading system allowing the parent utility in McGrath to keep track of specific load and use information. These two features would allow much better management of resources and coordination of service tasks, thus significantly reducing travel expenses, and the cost of administration, management, and maintenance. Telephone service improvements in Lime Village are needed before these features can be implemented reliably. Phone service improvements are dependent on reliable, low-cost electrical service.

Wind Generators:

Wind generators are only viable if the site exhibits an average wind speed of 5 mph or more [6, 7, 8]. At this time there is not enough information about the wind speeds in Lime Village to accurately assess the cost-effectiveness of adding wind as a source of electric generation in the hybrid system. Weather data collected over the next two years should serve this purpose.

Fuel Cells:

Fuel cells face some of the same issues as batteries. One of the key components in a fuel cell is the power section which acts as a hydrogen-air battery [5]. The addition of fuel cells to this system depends on reliability, cost, and life-span considerations. The reliability of fuel cells has not yet been proven. Furthermore, current fuel cell systems are expensive because of the fuel processor and the stack requirements to eliminate NOx and SOx by-products from the hydrogen rich fuel which is produced [5]. The life-span of the fuel cell reactor is currently about 5-7 years which limits the distribution of the initial costs over time.

A future project will include the simulation of a fuel cell and its integration into the hybrid power system. The capability for hands-on experience and the collection of performance data from actual systems is also available. A fuel cell research laboratory headed by the mechanical engineering department is already in place at UAF. The students also have access to data from a 1 MW fuel cell demonstration project which powers the US Post Office in Anchorage, Alaska sponsored by Chugach Electric Association.

Conclusions

This paper proposes an undergraduate or graduate level student project that involves the design of an energy-efficient hybrid power source for remote communities. The University of Alaska Fairbanks (UAF) College of Science, Engineering, and Mathematics through the newly developed Arctic Energy Technology Development Laboratory (AEDTL) has a vested interest in research related to hybrid power systems in remote villages of Alaska. This project provides an avenue for student involvement in responding to the challenge of promoting research and development of energy technologies in Arctic regions. The availability of an existing system in a rural Alaskan village from which data has been collected provides the students with the basis for the design. The project addresses many facets of engineering design and development. The design criteria require consideration of all available energy sources and conversion devices and the economics of the proposed system. The impact of the design on the community and the need for system automation is also addressed in this design. The educational benefits of the project include design credit and hands-on experience. Students are also provided with the experience of working with others on a design team and building relationships with the participating organizations including the state and private industry.

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Biography

Richard W. Wies is an assistant professor in the Department of Electrical and Computer Engineering at the University of Alaska Fairbanks. He received his Ph.D. in Electrical Engineering from the University of Wyoming in 1999. He concentrates his teaching and research efforts in the areas of electric machines, power electronics, and electric power systems.

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