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Energy Storage for Hybrid Remote Power Systems

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ENERGY STORAGE FOR HYBRID REMOTE POWER SYSTEMS

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Abstract

Energy storage can be a cost-effective component of hybrid remote power systems. Storage serves the special role of taking advantage of intermittent renewable power sources. Traditionally this role has been played by lead-acid batteries, which have high life-cycle costs and pose special disposal problems. Hydrogen or zinc-air storage technologies can reduce life-cycle costs and environmental impacts.

Using projected data for advanced energy storage technologies, LLNL ran an optimization for a hypothetical Arctic community with a reasonable wind resource (average wind speed 8 m/s). These simulations showed the life-cycle annualized cost of the total energy system (electric plus space heating) might be reduced by nearly 40% simply by adding wind power to the diesel system. An additional 20 to 40% of the wind-diesel cost might be saved by adding hydrogen storage or zinc-air fuel cells to the system.

Hydrogen produced by electrolysis of water using intermittent, renewable power provides inexpensive long-term energy storage. Conversion back to electricity with fuel cells can be accomplished with available technology. The advantages of a hydrogen electrolysis/fuel cell system include low life-cycle costs for long term storage, no emissions of concern, quiet operation, high reliability with low maintenance, and flexibility to use hydrogen as a direct fuel (heating, transportation). Disadvantages include high capital costs, relatively low electrical turn-around efficiency, and lack of operating experience in utility settings.

Zinc-air fuel cells can lower capital and life-cycle costs compared to hydrogen, with most of the same advantages. Like hydrogen systems, zinc-air technology promises a closed system for long-term storage of energy from intermittent sources. The turn around efficiency is expected to exceed 60%, while use of waste heat can potentially increase overall energy efficiency to over 80%.

Introduction

In remote locations, renewable resources and advanced technologies, coupled with state-of-the-art energy storage methods, compete favorably with conventional fossil fuel generation, when analytical comparisons are optimized to include life-cycle costs for the entire integrated energy system. This is true particularly where electric costs are high because of fuel transportation expense, there is a reasonable renewable resource available (e.g., wind, low-head hydro, solar, geothermal, etc.), and there is no inter-connection to a large-scale power grid. A modular approach to energy systems further allows the transition from a hybrid (for example, the combination of fossil fuel and renewable energy generation) to a totally renewable system, by incorporating new energy storage technologies.

Because resources such as wind and sunlight are not continuously available, the greatest reduction in fossil fuel consumption can be achieved by using energy storage strategies and technologies capable of storing energy for periods of several days to more than a week. Effective long-term storage can, for example, be provided by using surplus power from renewable resources to electrolyze water, producing hydrogen, which can be later used to re-generate electricity in either fuel cells or with internal combustion engines. Alternatively, energy can also be stored in the form of recovered zinc which is later used to generate electricity in a zinc-air fuel cell. In both cases, the technologies exist today and are now being commercialized.[1,2]

Renewable energy combined with energy storage also has the potential to provide the very important benefit of increased system reliability, which has been recognized as one of the highest priorities in the design of remote power systems.[3] Fuel cells, for example, have no moving parts, require almost no maintenance, and have demonstrated long lives. Reliability can be enhanced by a distributed generation facility and combined with storage, potentially using the existing diesel generating system as a backup.

Analysis

This paper presents an analysis of remote power systems for a hypothetical Arctic community, demonstrating how a hybrid of technologies that include storage is superior in optimizing energy efficiency and reducing costs. Two computer codes provide the basis for our analysis. The first is a renewable grid analysis tool, and the second is an optimizer.

This analysis treats optimization primarily as an energy cost problem, not as an environmentally driven problem. Thus no externalities (such as environmental regulations, legislative initiatives, and system reliability), nor potential linkages to water and waste disposal infrastructure are included in the cost analysis. Chapman[4] estimated the substantial cost of environmental degradation due to emissions and spills that result from diesel engine operation at $0.80 per liter of fuel (all costs in US$). If such 'hidden costs' and further integration with other community needs were taken into account, we expect that the advanced technologies discussed herein would appear even more favorable.

Costs are very sensitive to a long list of parameters, both local and external to the community. This sensitivity makes cost comparisons difficult.[5] The results obtained in the analysis are expected to indicate trends that would exist in an actual community in which the conditions are not too different from those assumed here.

The community used in the analysis is fictional, in that it has the energy demands, solar insolation, wind, temperature and other data derived from a number of different remote Arctic locations. Wind speed data have been scaled to 8 m/s average wind speed, which is a realistic value for sites along much of the Arctic coast. Although we considered the possibility of including photovoltaic (PV) cells in the system, this evaluation indicated that wind was the preferred renewable resource in this sample case. Consequently, the optimized solutions presented below do not show a PV component. Other analyses could include PV for remote communities, especially those in sunnier regions lacking reasonable wind resources.

Space and water heating are major contributors to the total energy demand in Arctic communities.[6] For this reason, our integrated approach considers the possibility of covering part of the heating load with waste heat from power generation and storage system equipment, or with surplus renewable energy obtained during periods of high wind speed, to reduce the fuel consumption for heating homes and public buildings. (We use the term 'diesel' to encompass the fuel, often called 'heating or fuel oil', of similar or identical properties to the diesel used in generators.)

Technologies and Systems

Four modular energy systems are analyzed and compared in this paper. The systems are:

<u>Diesel-Only, Base-Case</u>: This is the system that currently exists in most Arctic communities. Diesel gensets produce electricity. Waste heat from the generator and diesel-burning furnaces provide space heating. Our hypothetical community uses 250,000 liters per year (250 kl/yr) of diesel for electrical generation and 135 kl/yr for heating.

Hybrid Wind-Diesel System: This system includes wind turbines and diesel generators. Wind turbines generate electricity to satisfy the power demand (70 kW average, 118 kW one hour peak). If there is surplus electricity after the power demand is satisfied, the surplus electricity provides heating for homes. As in the base-case system, diesel generators cover the electrical load and diesel-furnaces provide the heat when there is not enough wind to satisfy the electrical demand.

Wind -- Hydrogen Storage -- Fuel Cell -- Diesel: This system includes wind turbines, an electrolyzer for producing hydrogen, vessels for low-pressure compressed hydrogen storage (4.1 MPa, 600 psi), a commercially available phosphoric acid fuel cell (PAFC), and backup diesel generators. (Proton Exchange Membrane -- PEM, and Solid Oxide Fuel Cells -- SOFCs -- may soon be available with similar or even more suitable characteristics, but for simplicity, the current analysis included only the PAFCs for use with hydrogen.) Wind turbines first satisfy the power demand. If there is surplus electricity after the power demand is satisfied, it can be used for either heating homes or for generating hydrogen for storage. When the wind turbines cannot satisfy the electrical demand, the fuel cell provides power to the system. If stored hydrogen becomes exhausted, the genset comes on line. Diesel continues to be used for heating, when waste heat is not available.

Hydrogen storage has an economic advantage over lead-acid batteries for long-term storage, in that increased energy storage (measured in kilowatt-hours) is added by increasing only the hydrogen storage, at relatively low cost per kilowatt-hour. Low-pressure hydrogen storage is a safe, proven, and readily available technology. Fuel cells utilize the hydrogen to generate electricity. Although the overall turnaround efficiency of energy storage and retrieval (electricity to electricity) from the system is only about 30%, heat from the fuel cells and electrolyzers can be used for space or process heating, substantially increasing the overall energy efficiency. Because fuel cells are practically noiseless, they can be placed close to facilities that can utilize their ‘waste’ heat.

Wind -- Zinc storage -- Zinc-Air Fuel Cell -- Diesel: This system is similar in strategy and components as the previous one, the only exception being that zinc pellets produced in an electrolytic process are used for energy storage, and a zinc-air fuel cell is used to generate electricity. Prototype zinc-air cells have demonstrated a turn-around electric energy storage efficiency of about 60%, compared to 70% for lead-acid batteries.[7] As with hydrogen fuel cells, use of the waste heat from a zinc-air cell can bring the overall energy efficiency significantly higher. Zinc-air cells present none of the disposal problems of lead-acid batteries and have a considerable per-unit-energy weight advantage, which is important for shipping.

Our energy optimization code includes:

1. Electricity generation components: These are defined by numerical arrays that specify electricity output for every value of energy input (wind speed, solar irradiation, or fuel consumption for a diesel genset or fuel cell).
2. Loads: Electrical loads are taken from Deering, Alaska. Average demand is 70 kW, and the 1-hour peak is 118 kW. Average heating load is assumed equal to 150 kW for the whole community. We assumed that 85% of the heating load goes for space heating and 15% for water heating. The space heating load is distributed along the year based on the temperature data for the site. The water heating load is distributed uniformly throughout the year.
3. Energy storage components: These numerical arrays specify the efficiency as a function of power input.

4. Waste heat recovery: This component specifies the fraction of the total waste heat that can be used for heating, and the maximum percentage of the community that can be heated with waste heat.
5. Energy storage strategy: Surplus electricity can be stored by electrolyzing water to make hydrogen or recovering zinc from the zinc-air fuel cell residue of zinc oxides, or used for heating the homes. The systems analysis code analyzes both of these options for any particular scenario.
6. Economic analysis: The code calculates annualized operating costs and years for return of investment as a function of all the system cost parameters, fuel consumption and maintenance of the system, which are in turn functions of equipment performance and use. Options include separate rates for the cost of capital (interest rate), fuel cost escalation, and maintenance cost escalation.

Optimization

Table 1 lists the parameters and assumptions used in the illustrated analysis. The analysis assumes that 40% of the waste heat generated from the diesel engine can be used for heating. This value corresponds closely to the amount of waste heat transferred to the cooling water.[8] The rest of the waste heat is lost through the exhaust, and it is not recovered in current power plants. For fuel cells, we assume that most of the waste heat (60%) is transferred to the cooling water, making it available for heating. We also assumed that in the diesel-only base-case a maximum of 30% of the community can be heated with waste heat. This is because diesel engines are likely to be located at a central power plant located away from the community center, so that waste heat can only be economically used in a few buildings. Fuel cells can be located within or distributed throughout the community. If desired, each home could potentially have its own fuel cell. This affords a significantly higher potential for heating with waste heat recovery (50%).

We calculated the costs based on several different economic assumptions in order to understand their effects. We found that changing the economic assumptions do not significantly alter the magnitude of benefit derived from the optimized power system scenarios described above.

For illustration, we show the results based on the fairly conservative economic assumptions that (1) diesel fuel costs do not escalate (based on recent history rather than escalating predictions such as those of the Energy Information Administration[9]), (2) maintenance costs escalate at a 3% general rate of inflation, and (3) money for capital improvements can be borrowed at an 8% interest rate. The results are also presented in terms of simple payback, which is independent on the interest rate.

Table 2 gives cost parameters for the main components in the power grid. Capital costs include transportation of equipment to the site and power system installation. Maintenance costs are very important since they can make or break the economics of an installation.[10] Renewable modular energy systems are expected to have significantly lower maintenance costs than diesel systems.[8,11,12] The individual components of wind-turbines, electrolyzers, and fuel cells have a good history from which to estimate maintenance costs.[5] Zinc-air technology is new, but the simple principles and similarity to hydrogen fuel cell technology provide a basis for assuming similar low maintenance costs.

Optimization in this example is based on the yearly cost of the system. This includes capital, maintenance and fuel costs. The cost of fuel is assumed to be in the range of \$0.40/liter to \$0.92/liter.

Results

Table 3 shows the results of the example system optimization for minimum yearly cost, for a $0.66/l fuel cost, 8% interest, 3% maintenance cost escalation, but no fuel cost escalation. The table lists the values of the five decision variables, as well as the fuel consumption and cost values.

The results in Table 3 indicate that maintenance costs dominate the economics for the base-case system. The importance of maintenance costs has been stressed in previous reports.[13,14] Most of the maintenance cost is associated with diesel genset operation. For this reason, optimum renewable systems tend to reduce diesel genset operation as much as possible. For example with the zinc-air fuel cell system, there is almost no need to operate the diesel genset, although the analysis considers that the diesel genset is kept as a part of the system for increased reliability (i.e., capital cost for the genset is included).

The wind-diesel system reduces diesel genset use to about a third, and total fuel consumption to less than half of the base-case values. Considering the moderate investment and the short time for payback required for these systems, installation of wind turbines constitutes a good first step that can later be enhanced to include energy storage as additional capital is available for investment.

Figure 1 shows optimization results for the same economic assumptions. The figure shows total system cost and total diesel consumption for the four systems being considered. In addition to the fuel cost considered for Table 3 ($0.66/l), two more values are used: $0.40/l, and $0.92/l. The figures show that the yearly cost for the base-case system is very sensitive to fuel cost. For the systems with storage, fuel consumption is significantly reduced so that the yearly cost is less sensitive to fuel cost. The figure illustrates the potential for cost and fuel consumption reduction obtainable by using renewable electricity generation couple with energy storage in remote applications.

Conclusions

For the conditions used for this analysis, fuel consumption and annualized life-cycle costs can be substantially reduced by using renewable electricity generation technologies with energy storage devices. Specific results from the analyses demonstrate that:

1. When wind turbines are added to diesel gensets ("wind-diesel" hybrid), the saving of diesel fuel can be more than 50% at a cost savings of over 30%. This is the most cost effective, quickest payback configuration for a remote community that has sufficient wind resource.
2. When energy storage devices are added (e.g., hydrogen or zinc), diesel fuel consumption and costs can be reduced substantially more. Optimized energy storage allows diesel gensets to be eliminated. However, about one quarter of the original diesel consumption is still required to satisfy heating demands.
3. Costs using optimized hydrogen storage can be over 10% lower than for wind-diesel alone, while displacing about an additional 15% of the original diesel fuel consumption.
4. Using estimated costs for zinc-air technology for energy storage, as much as 75% of the current diesel fuel can be displaced with over 30% cost savings over wind-diesel without storage.

It is expected that refinements possible during the analysis of a real community could potentially make the economics more or less favorable. In general, we believe the benefits shown possible in these analyses should be realizable at numerous sites throughout the Arctic; certainly at those sites that have significant wind resources.

The systems described in this paper should be robust enough for application in real communities and could be modular enough for additions and substitutions of new technologies as they become available. In short, a key concept is the creation of new energy systems that are economically viable and sufficiently flexible for the implementation of new technological advances.

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Table 1. Parameters for remote community electric grid.

distance from wind turbines to community, km	10
average electric demand for community, kW	70
1-hour peak demand for community, kW	118
average wind speed, m/s	8
1-hour peak wind speed, m/s	35
average heating demand, kW	150
1-hour peak heating demand, kW	365
efficiency of diesel-fueled heater, %	80
fraction of waste heat that can be used for heating, fuel cells, %	60
fraction of heating load that can be met with waste heat, fuel cells, %	50
fraction of waste heat that can be used for heating, diesel genset, %	40
fraction of heating load that can be met with waste heat, base-case, %	30
number of diesel gensets	3
maximum diesel genset power, kW	60
minimum diesel genset power, kW	24
wind turbine maximum power output, kW	20
maximum solar irradiation, kW/m^2	0.82
fuel energy density, kWh/liter	9.51
fuel cost, $/liter	0.40-0.92
interest rate, %	8.0
maintenance cost escalation, %	3.0
fuel cost escalation, %	0.0

Table 2. Parameters for cost analysis of grid.

Component	life, yrs	cost	maintenance, $/kWh
transmission lines	20	$10000/km	0.001
compressed hydrogen storage	20	$10/kWh	0.001
electrolyzer	20[a]	$1000/kW	0.001
diesel heater	10	$100/kW	0.001
electrical resistive heaters	20	$20/kW	0.001
engine-generator	4[a]	$200/kW[a]	0.12[c]
wind turbine	20	$2400/kW (installed)	0.03
PAFC fuel cell	20[a]	$1500/kW[b]	0.01
photovoltaic cells	20[a]	$770/m^2 or $5000/kW (peak)	0.0[a]
zinc storage	20	$4/kWh	0.001
zinc-air fuel cell	20	$150/kW	0.01
zinc recovery unit	20	$150/kW	0.001

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a. From Guichard (1994).
b. From Guichard (1994). Projection to 1998.
c. From Malosh et al., 1985.

Table 3. System parameters for optimum designs presented in Figure 1, for a fuel cost of $0.66/l, 8% interest, 3% maintenance cost escalation, and no fuel cost escalation.

	Base-case	wind-diesel	hydrogen PAFC	zinc-air
optimum system parameters:				
wind power, kW	0.0	351	538	446
energy storage, MWh	0.0	0.0	22.3	47.6
electrolyzer power, kW	0.0	0.0	294	298
fuel cell power, kW	0.0	0.0	75.6	153
photovoltaic power, kW	0.0	0.0	0.0	0.0
annual diesel fuel consumption, kl:				
for electricity generation*	250	90.6	24.0	6.55
for heating (only)	135	95.9	82.5	94.5
total	384	187	106	101
system costs:				
capital, k$/yr	19.0	115	225	165
maintenance, k$/yr	386	224	123	78.0
fuel, k$/yr	274	133	76.1	72.3
total, k$/yr	679	472	424	315
years for payback	-	3.75	5.34	3.44

* Through the use of waste heat, much of this ultimately contributes to heating

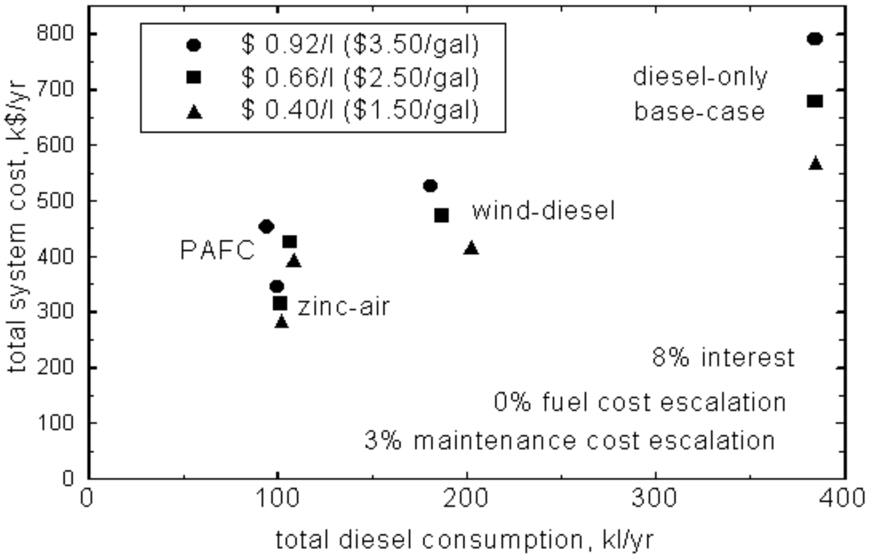

Figure 1. Total system cost and total diesel consumption for the four systems being illustrated, for fuel costs of $0.66/l, $0.40/l, and $0.92/l, with 8% interest on capital, 3% maintenance cost escalation, and no cost escalation. (PAFC = Phosphoric Acid Fuel Cell)

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