UCRL-ID-129289

Remote Power Systems with Advanced Storage Technologies for Remote Alaskan Villages

W. Isherwood, R. Smith, S. Aceves, G. Berry, W. Clark,
R. Johnson, D. Das, D. Goering and R. Seifert

December 1997

Lawrence Livermore National Laboratory

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-ENG-48.

UCRL-ID-129289

Remote Power Systems with Advanced Storage Technologies for Alaskan Villages

by
William Isherwood, Ray Smith, Salvador Aceves, Gene Berry and Woodrow Clark
Lawrence Livermore National Laboratory (LLNL)
and
Ronald Johnson, Deben Das, Douglas Goering, and Richard Seifert
University of Alaska Fairbanks (UAF)

Abstract

Remote Alaskan communities pay economic and environmental penalties for electricity, because they must import diesel as their primary fuel for electric power production, paying heavy transportation costs and potentially causing environmental damage with empty drums, leakage, and spills. For these reasons, remote villages offer a viable niche market where sustainable energy systems based on renewable resources and advanced energy storage technologies can compete favorably on purely economic grounds, while providing environmental benefits. These villages can also serve as a robust proving ground for systematic analysis, study, improvement, and optimization of sustainable energy systems with advanced technologies.

This paper presents an analytical optimization of a remote power system for a hypothetical Alaskan village. The analysis considers the potential of generating renewable energy (e.g., wind and solar), along with the possibility of using energy storage to take full advantage of the intermittent renewable sources available to these villages. Storage in the form of either compressed hydrogen or zinc pellets can then provide electricity from hydrogen or zinc-air fuel cells when renewable sources are unavailable.

The analytical results show a great potential to reduce fossil fuel consumption and costs by using renewable energy combined with advanced energy storage devices. The best solution for our hypothetical village appears to be a hybrid energy system, which can reduce consumption of diesel fuel by over 50% with annualized cost savings by over 30% by adding wind turbines to the existing diesel generators. When energy storage devices are added, diesel fuel consumption and costs can be reduced substantially more. With optimized energy storage, use of the diesel gensets can be reduced to almost zero, with the existing equipment only maintained for added reliability. However about one quarter of the original diesel consumption is still used for heating purposes. (We use the term ‘diesel’ to encompass the fuel, often called ‘heating or fuel oil’, of similar or identical properties.)

Introduction

Most remote Alaskan communities pay economic penalties for electricity (ARECA, 1996), because they must import diesel as their primary fuel for electric power production, paying heavy transportation costs and potentially causing environmental damage. Furthermore, the consumption of fossil fuels and the local negative environmental impact caused by communities befouling the region with leaking tanks and discarded drums must be considered when examining remote energy options. High fuel costs and environmental impacts occur not just in Alaska but also many locations worldwide where remote communities need power, regardless of climate.

In theses remote locations, renewable resources and advanced technologies, coupled with state-of-the-art energy storage methods, can 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 as new technologies and applications become commercially available.

Resources such as wind and sunlight, however, are not continuously available in any region. The greatest reduction in fossil fuel consumption can be achieved, therefore, by using energy storage strategies and newly available 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 (see Moore, 1997, and The Economist, 1997).

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 (Brown et al., 1996). 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, combined with storage, and optimized through systems codes; potentially using the existing diesel generating system as a backup.

Public and private sector research has developed and demonstrated numerous renewable energy technologies. Widespread use of renewable energy technologies has been limited, however, by high costs (US Department of Commerce, 1997, and EPRI, 1997). Among other problems cited that prevent the commercialization of "environmentally sound technologies" have been (1) the market has been insufficient to stimulate mass production, (2) competition from inexpensive fossil fuels (the price of which commonly fails to include full environmental costs), and (3) the lack of integrated systems that take advantage of synergies possible between new technologies (The Economist, 1997). Nevertheless, a growing literature indicates that environmental and energy market demand is being created and supported through changes in governmental regulations. This leads to a stronger competitive advantage for private sector firms marketing 'alternative' technologies (Porter and van der Linde, 1995; UN Reports, 1994 and 1995; Clark, 1997; and Clark and Paolucci, 1997).

Scope

This paper presents an analysis of remote power systems for an Alaskan community, demonstrating how a hybrid of technologies is superior in optimizing energy efficiency, reducing environmental degradation, 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. These two codes combine to obtain optimum designs for any number of decision variables, as well as equality and inequality constraints.

This hypothetical remote village 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 (1996) 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 ($3/gal). If such 'hidden costs' and further integration with other community needs were taken into account, we expect 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 village. This sensitivity makes cost comparisons difficult (Guichard, 1994). The results obtained in the analysis are expected to indicate trends that would exist in an actual village in which the conditions are not too different from those assumed here.

Remote Village Scenarios

The coastal village used in the analysis is fictional, in that it has the demands of Deering (48 homes, population 150), and the solar insolation, wind and temperature resources of Kotzebue. The parameters, data, and verification are based on profiles provided by the University of Alaska, Mechanical Engineering Department. Further data were provided directly from actual remote Alaskan communities. Wind speed data have been scaled to 8 m/s average wind speed, which is a realistic value for sites along coastal Alaska. 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 all show zero 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 Alaskan villages (Koniag, Inc., 1995). For this reason, our integrated approach considers the possibility of covering part of the heating load with waste heat from power generation equipment, or with surplus renewable energy obtained during periods of high wind speed, to reduce the fuel consumption for heating homes and public buildings.

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 Alaskan villages. Diesel gensets produce electricity, with heating provided by available waste heat first, then by diesel-burning furnaces (except that most real villages do not fully utilize available waste

heat from gensets, partly because noise and safety factors place gensets far away from the greatest heating loads.). Our hypothetical village 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 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 (Cooper et al., 1995). 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.

Zinc-air fuel cells should soon (within 2 years) become commercially available and the total production costs should easily compete with lead-acid batteries on a per kilowatt (kW, power) basis. But as with hydrogen, the cost of incremental energy storage capacity (kilowatt-hour, kWh) is quite low, making these cells particularly advantageous for long-term storage. Zinc-air fuel cell costs used in this study are based upon an industrial partner's estimate for commercialization of new technologies.

Optimization Code Analyses

A remote village system analysis code has been developed specifically for this project and then integrated with an optimizer. This work does not to duplicate the extensive capabilities of an existing hybrid systems code (HYBRID2, Baring-Gould, 1996; Manwell et al., 1996), which can also be linked to an optimizer (Flowers, 1997). Instead, the purpose is to evaluate new advanced technologies (such as energy storage devices), waste heat recovery systems, and operating strategies, for optimization into modular systems suitable for remote villages.

The U.S. Magnetic Fusion Program at Lawrence Livermore National Laboratory originally developed SUPERCODE in the early 1990's for optimizing tokamak reactors and experimental designs (Galambos et al., 1995). SUPERCODE is a shell that incorporates process models, uncertainty, and non-linear equations, which has subsequently been used to optimize inertial fusion devices, rail-guns, and hybrid-electric vehicles (Haney et al, 1992; Aceves et al, 1995), in addition to the present application.

A powerful programmable shell that takes input using a variant of the C++ language controls SUPERCODE, and has recently been converted to Mathematica (Perkins et al., 1997). Input can be from a terminal or from files, allowing interactive or batch operation. The user can define real, integer, complex, array, and string variables. In addition, the language supports control statements, loops and functions. The SUPERCODE shell can exploit the multi-processing capabilities of UNIX to run external programs, such as this village simulation code, to compute constraint and figure-of-merit values. It is also possible to use the parallel virtual machine system (Beguelin et al., 1991) to simultaneously run multiple copies of the external program in parallel on a number of workstations thereby dramatically reducing execution time.

This programmable shell offers tremendous flexibility for the user to specify an optimization problem. Once the optimization is completed, the user can interrogate the shell for variable and figure-of-merit values. Also, variables can be fixed, or new constraints applied to investigate "what-if" scenarios. Loops can also be written to perform parameter scans.

Our village optimization code includes:

1. Electricity generation components: These are defined by vectors 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 village. 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 village. The water heating load is distributed uniformly throughout the year.

3. Energy storage components: These vectors 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 village that can be heated with waste heat.
5. Energy storage strategy: Surplus electricity can be either 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 Methodology

Table 1 list the parameters and assumptions used in the test village 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 (Malosh et al., 1985). 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 village 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 village center, so that waste heat can only be economically used in a few buildings. Fuel cells can be located within or distributed throughout the village. If desired, each home could potentially have its own fuel cell. This affords a significantly higher potential for heating with waste heat recovery (50%).

Diesel engines present operating difficulties if operated at very low load. For that reason, a minimum operating power (40% of full load, Malosh et al., 1985) is defined.

We present here two separate sets of economic assumptions to illustrate their effect. First we assumed no escalation of fuel or maintenance costs and used a 0% interest rate on capital, due to State or Federal subsidizes or other investment incentives. Published scenarios project fuel cost escalation to approximate or exceed the borrowing rate, making this approach a plausible first assumption. Furthermore, the state of Alaska currently subsidizes the electricity for the remote villages to a level of $0.27/kWh (Jensen, 1997), so this case assumes that the State might be willing to provide low- or no-interest loans in order to reduce the future amount of the subsidies. The results are also presented in terms of simple payback, which is independent on the interest rate.

For comparison, we also show 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 [1997]), (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, As will be seen, these economic assumptions do not significantly alter the magnitude of benefit derived from the optimized power system scenarios described above.

Table 2 gives cost parameters for the main components in the power grid. Capital costs include transportation of equipment to the village and power system installation. Maintenance costs are very important since they can make or brake the economics of an installation (Energy Mines and Resources Canada, 1988; UN 1994 and 1997). Renewable modular energy systems are expected to have significantly lower maintenance costs than diesel systems (Malosh et al, 1985; Ontario Hydro, 1997; Bergey Windpower, 1997). The individual components of wind-turbines, electrolyzers, and fuel cells have a good history from which to estimate maintenance costs (see, for instance, Guichard, 1994). 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.

Five parameters are used as decision variables:

1. Total wind turbine power capacity, in kW
2. Total PV energy capacity, in kW
3. Energy storage capacity, in kWh
4. Maximum possible power into storage (maximum electrolyzer or zinc recovery unit power).
5. Maximum possible power out of storage (maximum fuel cell power).

The specific figure-of-merit used for this optimization example is 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 ($1.50 per gallon) to $0.92/liter ($3.50 per gallon).

The energy control strategy for the storage system is critical to the operation of the grid itself. Two of the possible options are:

1. Heating first: Surplus renewable electricity is used for resistive heating within the village. If there is surplus electricity after providing all the required heat, the electricity is used for generating either hydrogen or zinc for the storage.

2. Storage first: Surplus renewable electricity is stored as either hydrogen or zinc. If the storage system is full, surplus electricity is then used for heating the homes.

A preliminary analysis has shown that the heating first strategy has an advantage for the conditions analyzed in this paper. Heating first is the strategy selected because heating with renewable sources is more efficient than storage and recovery of energy.

Results

Table 3a shows the results of the example system optimization for minimum yearly cost, for a $0.66/l ($2.50/gal) fuel cost, and the zero interest rate, no cost escalation scenario. Table 3b shows results of the same optimization with the alternative economic assumptions; 8% interest, 3% maintenance cost escalation, but still no fuel cost escalation.

The tables list the values of the five decision variables, as well as the fuel consumption and cost values.

The tables indicate that none of the lowest cost systems have a photovoltaic component. Intrinsic solar irradiation is low at our model village, but the lack of PV here is most directly a consequence of today's still relatively high PV costs. However, PV costs have declined sharply in the past, and further declines are expected, perhaps sufficient for PV electricity to compete economically with other sources used in rural Alaskan communities in the future.

The results in Tables 3a and 3b indicate that maintenance costs dominate the economics for the base-case system. The importance of maintenance costs has been stressed in previous reports (e.g., AVEC, 1996; Harris et al, 1997). 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.

Figures 1a and 1b show optimization results for the same two economic assumptions. The figures show 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; $2.50/gal), two more values are used: $0.40/l ($1.50/gal), and $0.92/l ($2.50/gal). 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 figures illustrate clearly the potential for cost and fuel consumption reduction obtainable by using renewable electricity generation in the village. Note the general similarity in results between the different economic cases. For brevity, the following figures present data only from the simple -- no interest, no escalation -- case, with confidence that general conclusions will not differ significantly over a broad spectrum of realistic economic assumptions.

Figure 2 illustrates the results of a system optimization when only the electricity demand is considered (no heating load is satisfied). The cost and fuel savings for systems with storage appear even greater when heating is neglected. We show this for comparison with other studies that do not integrate heating with power. Consideration of the total energy picture makes more sense for village planners. Optimum (lowest yearly cost) designs for the zinc-air fuel cell can reduce diesel fuel consumption to almost zero, so that the operating cost is independent of fuel cost (note, however, that the time for payback is still a function of fuel cost). Wind-diesel systems can reduce fuel consumption to about 40% of the original value, and the cost to almost 50%.

Figures 3 and 4 show the results of a parametric analysis for a system with hydrogen storage and a PAFC. Figure 3 shows lines of constant total fuel consumption as a function of energy storage capacity and installed wind power. The numbers on the curves indicate the fraction of the fuel consumed in the base-case (384,000 liters/year). Decision variables are set to the optimum values for the PAFC system from Table 3a. For low wind capacity ('low-penetration'), storage provides little benefit, since all of the electricity produced is immediately used to satisfy either electrical load or electrical-heating load, and the storage system remains empty. As the wind capacity increases ('high penetration'), the benefit of energy storage increases. A point in the figure indicates the optimum design from Table 3a.

Figure 4 shows lines of constant fuel consumption for electricity generation only, as a function of energy storage capacity and installed wind power for the same system with hydrogen storage and a PAFC, with the optimum values for the decision variables from Table 3a. The numbers on the curves indicate the fraction of the fuel consumed in the base-case (250,000 liters/year). As previously discussed, operation and maintenance of the diesel engines is expensive, and therefore the optimum design reduces considerably the fuel consumption for electricity generation.

Figures 5 and 6 show results that are similar to those presented in Figures 3 and 4, except that now the system being considered is the zinc-air fuel cell as energy storage. The decision variables take their optimum values from Table 3a. Zinc-air fuel cells and storage are expected to be cheaper that PAFC and hydrogen storage, so that the optimum amount of storage, indicated by a point in the figure, is higher than for hydrogen. The higher efficiency of the zinc-air fuel cell results in a very low fuel consumption for electricity generation. Total fuel consumption remains at about the same level as obtained for the PAFC system.

Conclusions

Application of an energy production and use simulation code and an optimizer to the problem of sizing a renewable electricity generation grid in a remote Alaskan village demonstrates significant potential for life-cycle cost savings. We compared a base-case system, which consists of (1) diesel gensets and diesel heaters, to three highly reliable systems that include renewable electricity generation: (2) a wind-diesel system, (3) a wind-diesel system with hydrogen storage and a phosphoric acid fuel cell (available 'off-the-shelf'), and (4) a wind-diesel system with zinc storage and a zinc-air fuel cell (expected to be available within 2 years). The results show that, for the conditions used for this analysis, fuel consumption and annualized life-cycle costs can be substantially reduced by using renewable electricity generation technologies as well as 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 village that has sufficient wind resource. Furthermore, wind turbines can be added incrementally, with additional maintenance and operational savings at every increment.

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 10-20% lower than for wind-diesel alone, while displacing about an additional 20% 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 30-40% cost savings over wind-diesel without storage. This result provides a strong incentive to further speed the commercialization of this technology.

There are a number of externalities that have not been factored in at this point, but could be in future analyses. For Alaska, we suggest the externalities include: environmental impact and regulations, political legislation and funding (direct investment, incentives, and taxes), and specific community-based variables such as employment opportunities and need for reliable service.

It is expected that refinements possible during the analysis of a real village 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 Alaska; 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 implementation of new technological advances.

References

Aceves, S.M., J.R. Smith, L.J. Perkins, S.W. Haney, and D.L. Flowers, 1995, "Optimization of a CNG Series Hybrid Concept Vehicle", LLNL paper for 1996 Society of Automotive Engineers International Congress and Exposition, Detroit, MI, 27 pp, UCRL-JC-121374.

ARECA, 1996, "Affordable Power in Rural Alaska," ARECA Rural Issues Forum Report, Alaska Rural Electricity Cooperative Association, Anchorage, AK.

AVEC, 1996, "1995 Annual Report", Alaskan Village Electric Cooperative, Inc., Anchorage, AK.

Baring-Gould, E.I., 1996, "HYBRID2, The Hybrid System Simulation Model, Version 1.0 User Manual," National Renewable Energy Laboratory Report NREL/TP-440-21272, Golden, CO.

Beguelin, A., Dongarra, J., Geist, A., Manchek, R., and Sunderam, V., 1991, "Users Guide to PVM: Parallel Virtual Machine," ORNL/TM-11826, Mathematical Sciences Section, Oak Ridge National Laboratory.

Bergey Windpower Co., 1997, “Wind Energy Tutorial”, available on the Internet at http://www.bergey.com/tut1.html.

Brown, C., Guichard, A., and Lyons, D., 1996, “Wind Energy in Polar Regions: Casey Station Antarctica,” Proceedings of the 12th Annual Conference of the Canadian Wind Energy Association, Kananaskis, Canada.

Chapman, R.N., 1996, “Hybrid Power Technology for Remote Military Facilities,” Power Quality Solutions/Alternative Energy Proceedings, September, pp. 415-427.

Clark, Woodrow W., 1997, “Publicly-Funded Research and Development in Environmentally Sound Technologies: The Case of the US”, Report for United Nations (one of ten industrialized countries). New York, NY and Geneva.

Clark, Woodrow W. and Emilio Paolucci, 1997, “The development of environmental technologies for automotive industry: issues for a new model of innovation,” EIASM, Brussels, to be published.

Cooper, J.F., Fleming, D., Hargrove, D., Koopman, R., and Peterman, K., 1995, “A Refuelable Zinc/Air Battery for Fleet Electric Vehicle Propulsion,” SAE Paper 951948.

Cooper, John F. and Woodrow W. Clark Jr., 1996, “Zinc/Air Fuel Cell: an alternative to clean fuels in fleet electric vehicle applications”, International Journal of Environmentally Conscious Design & Manufacturing, vol. 5 No. 3-4, pp. 49-54.

The Economist, 1997, Science and Technology Section: “At last, the fuel cell.” London, UK: October 25, pp. 89-92.

Energy Information Administration, 1997, “Annual Energy Outlook 1998”, advance copy available on the Internet at http://www.eia.doe.gov.

Energy Mines and Resources Canada, 1988, “Small Power Production in Remote Communities: A Shared Opportunity,” Energy Mines and Resources Canada, Ottawa, Canada.

Flowers, L., 1997, “Renewables for Sustainable Village Power,” Proceedings of the International Conference of Village Electrification Through Renewable Energy, New Delhi, India. National Renewable Energy Laboratory Report NREL/CP-440-22608, Golden, CO.

Galambos, J.D., Perkins, L.J., Haney, S.W., and Mandrekas, J., 1995, "Commercial Tokamak Reactor Potential with Advanced Tokamak Operation," Nuclear Fusion, Vol. 35, p. 551.

Guichard, A., 1994, “Towards New Energy Systems for Antarctic Stations,” Proceedings of the Sixth Symposium on Antarctic Logistics and Operations, Rome, Italy, pp. 81-95.

Haney, S.W., Barr, W.L., Crotinger, J.A., Perkins, L.J., Solomon, C.J., Chaniotakis, E.A., Freidberg, J.P., Wei, J., Galambos, J.D., and Mandrekas, J., 1992, "A SUPERCODE for Systems Analysis of Tokamak Experiments and Reactors," Fusion Technology, Vol. 21, p. 1749-1758.

Harris, R.E., Lyons, J.G., and Rinehart, P., 1997, “Remote Monitoring and Control of Electric Power Systems to Decrease Costs and Improve System Performance in Remote Arctic Locations,” unpublished paper prepared for AVEC, Anchorage, AK.

Jensen, H., 1997, Personal Communication, Igiugig Electric Utility, Anchorage, AK.

Koniag, Inc., 1995, “Native Alaska Energy Efficiency Feasibility Study,” U.S. Department of Energy Report, Prepared under Grant No. DE-FG51-94R020502.

Malosh, J.B., Johnson, R., and Bubendorf, S., 1985, “Part-Load Economy of Diesel-Electric Generators,” Final Report, State of Alaska, Department of Transportation and Public Facilities, Division of Planning, Fairbanks, AK.

Manwell, J.F., Rogers, A., Hayman, G., Avelar, C.T., and McGowan, J.G., 1996, “Theory Manual for Hybrid2, The Hybrid System Simulation Model,” National Renewable Energy Laboratory Report NREL/TP-440-21182, Golden, CO.

Moore, Taylor, 1997, “Market Potential High for Fuel Cells”, in EPRI Journal, May-June 1997, pp. 6-17, Palo Alto, CA.

Perkins, John, Alan Lamont, and Woodrow Clark, 1997, “Global Sustainability though SUPERCODE Optimization and Meta*Net Economic Equilibrium Codes”, LLNL, LDRD Project Proposal and Report.

Porter, Michael E. and Claas van der Linde, 1995, "Green and Competitive", Harvard Business Review, September-October, pp. 120-134.

Ontatio Hydro, 1997, “Renewable Energy Technologies Program”, available on the Internet at http://www.ohrets.com/kasabonika.htm.

“Summary of Selected R&D Funding Levels”, 1996, Science & Technology in Congress, May, p. 3.

United Nations, 1994, “Report of the Workshop (Oslo, 13-15 October, 1993) on the Transfer and Development of Environmentally Sound Technologies (ESTs)”, New York and Geneva: UNCTAD, pp. 1-51.

United Nations, 1997, “Promoting the transfer and use of Environmentally Sound Technology: A Review of Policies”, New York and Geneva: Science and Technology Issues, UNCTAD, pp. 1-53.

US Department of Commerce, 1997, “The Global context for US Technology Policy”, Washington, DC.

Table 1. Parameters for remote village electric grid.

distance from wind turbines to village, km	10
average electric demand for village, kW	70
1-hour peak demand for village, 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 (kWh/gal)	9.51 (36)
fuel cost, \$/liter (\$/gal)	0.40-0.92 (1.50-3.50)
interest rate, %	0.0 and 8.0
maintenance cost escalation, %	0.0 and 3.0
fuel cost escalation, %	0.0 and 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

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

Table 3a. System parameters for optimum designs presented in Figure 1a, for a fuel cost of \$0.66/l (\$2.50/gal), zero interest and no cost escalation.

	Base-case	wind-diesel	hydrogen PAFC	zinc-air
optimum system parameters:				
wind power, kW	0.0	403	580	451
energy storage, MWh	0.0	0.0	35.7	82.2
electrolyzer power, kW	0.0	0.0	358	287
fuel cell power, kW	0.0	0.0	96.8	122
photovoltaic power, kW	0.0	0.0	0.0	0.0
annual diesel fuel consumption, kl (kgal):				
for electricity generation	250(66.0)	85.6(22.6)	11.1(2.94)	0.0(0.0)
for heating	135(35.6)	78.1(20.6)	78.9(20.8)	95.9(25.3)
total	384(101)	164(43.3)	90.0(23.8)	95.9(25.3)
system costs:				
capital, k\$/yr	13.4	66.5	130	91.4
maintenance, k\$/yr	286	164	77.5	49.2
fuel, k\$/yr	253	108	59.5	63.3
total, k\$/yr	553	338	267	204
years for payback	-	4.0	5.84	3.68

Table 3b. System parameters for optimum designs presented in Figure 1b, for a fuel cost of \$0.66/l (\$2.50/gal), 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 (kgal):				
for electricity generation	250(66.0)	90.6(24.0)	24.0(6.38)	6.55(1.73)
for heating	135(35.6)	95.9(25.4)	82.5(25.4)	94.5(25.0)
total	384(101)	187(49.4)	106(28.2)	101(26.8)
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

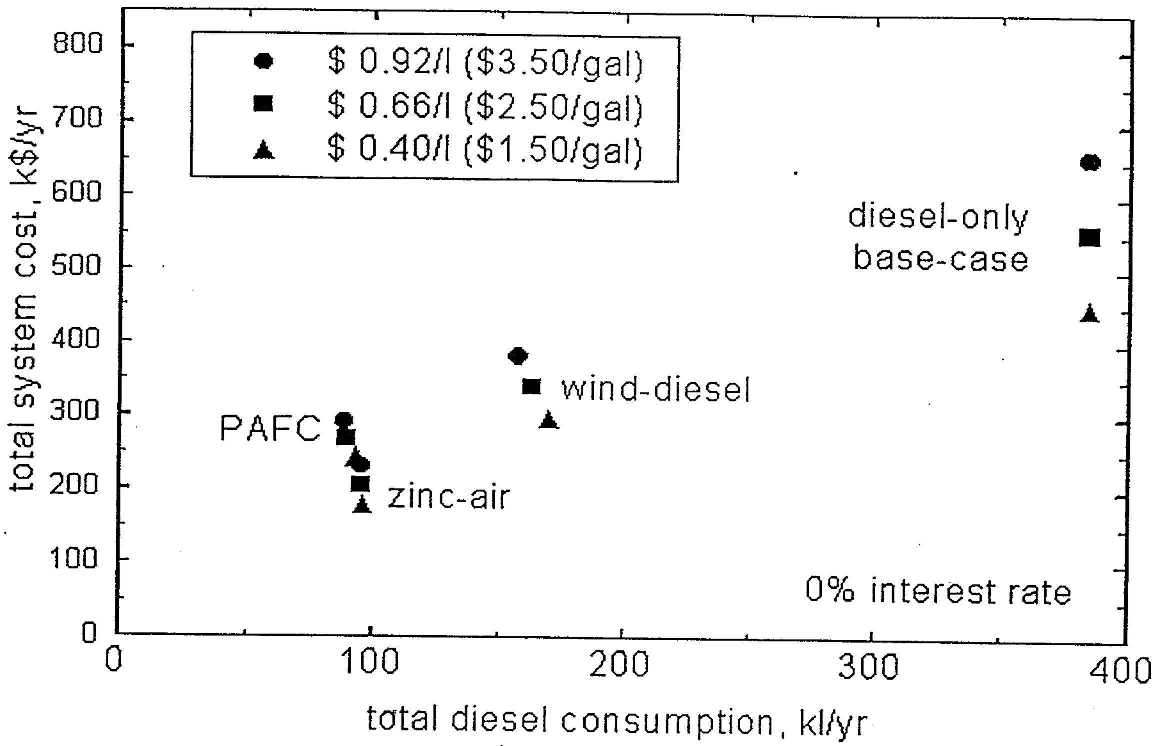

Figure 1a. Total system cost and total diesel consumption for the four systems being illustrated, for fuel costs of $0.66/l ($2.50/gal), $0.40/l ($1.50/gal), and $0.92/l ($2.50/gal), zero interest and no cost escalation.

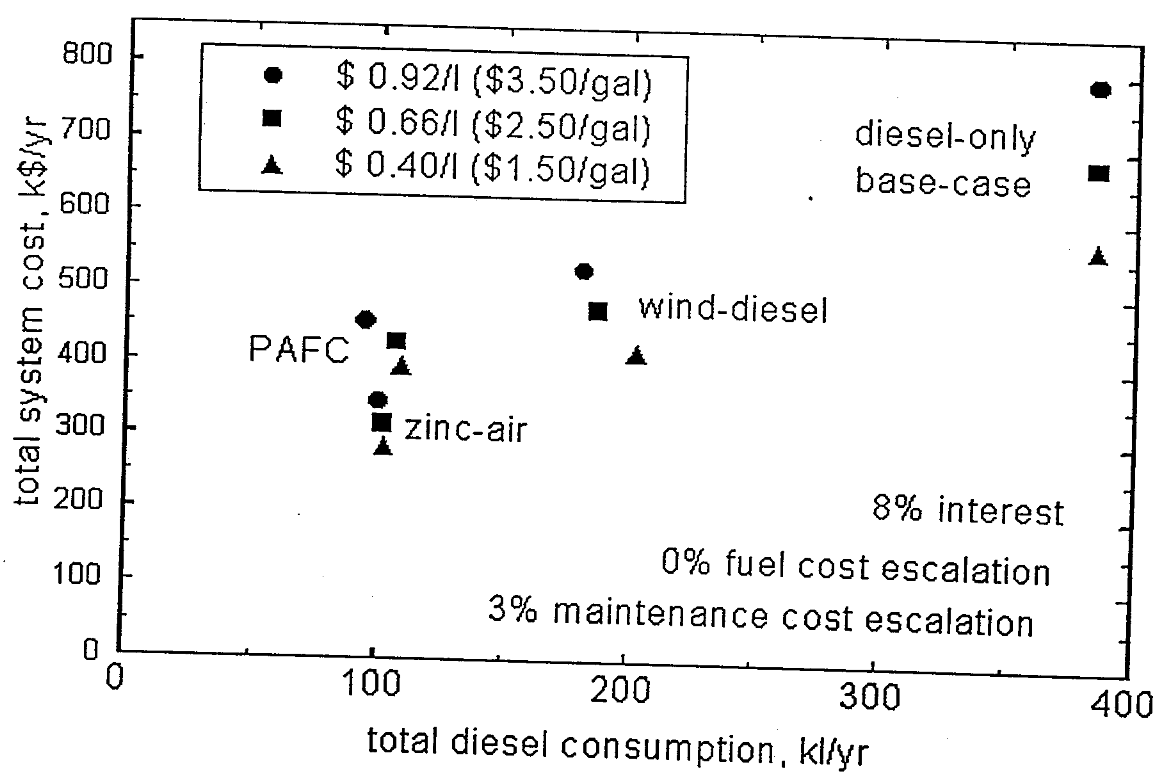

Figure 1b. Total system cost and total diesel consumption for the four systems being illustrated, for fuel costs of $0.66/l ($2.50/gal), $0.40/l ($1.50/gal), and $0.92/l ($2.50/gal), with 8% interest on capital, 3% maintenance cost escalation, and no cost escalation.

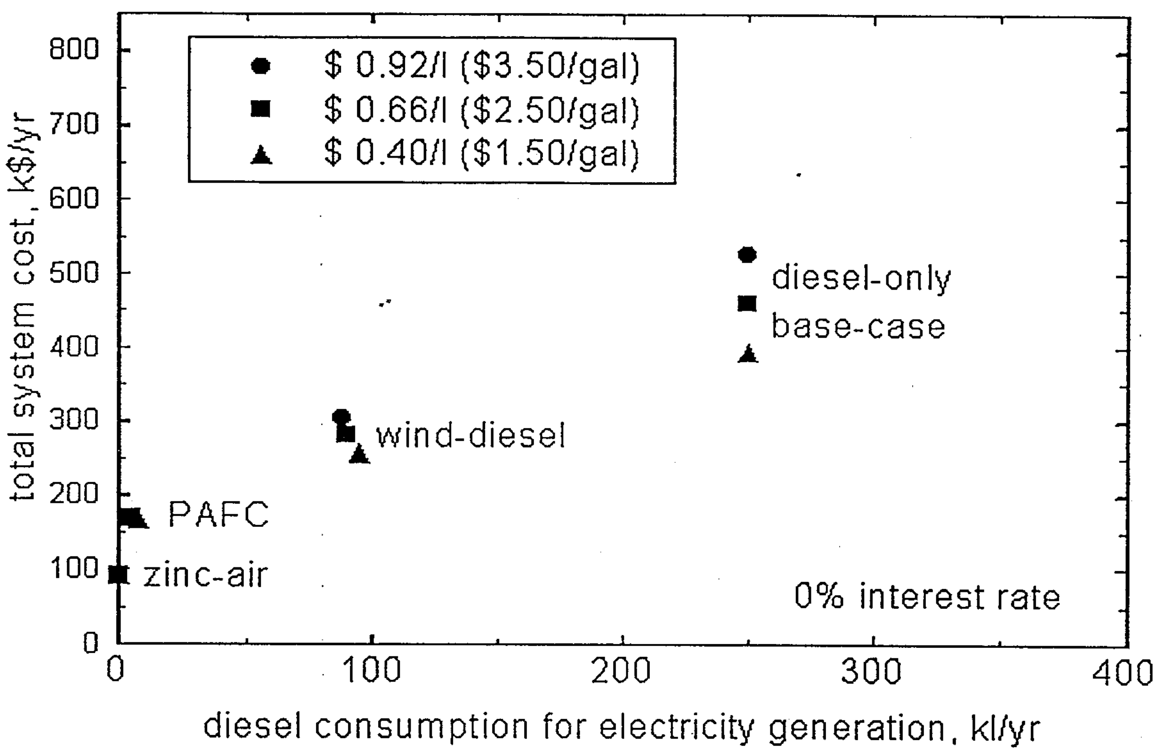

Figure 2. Total system cost and diesel consumption for a system optimization when only the electricity demand is considered (no heating load is satisfied, for the four systems being illustrated, for fuel costs of $0.66/l ($2.50/gal), $0.40/l ($1.50/gal), and $0.92/l ($2.50/gal).

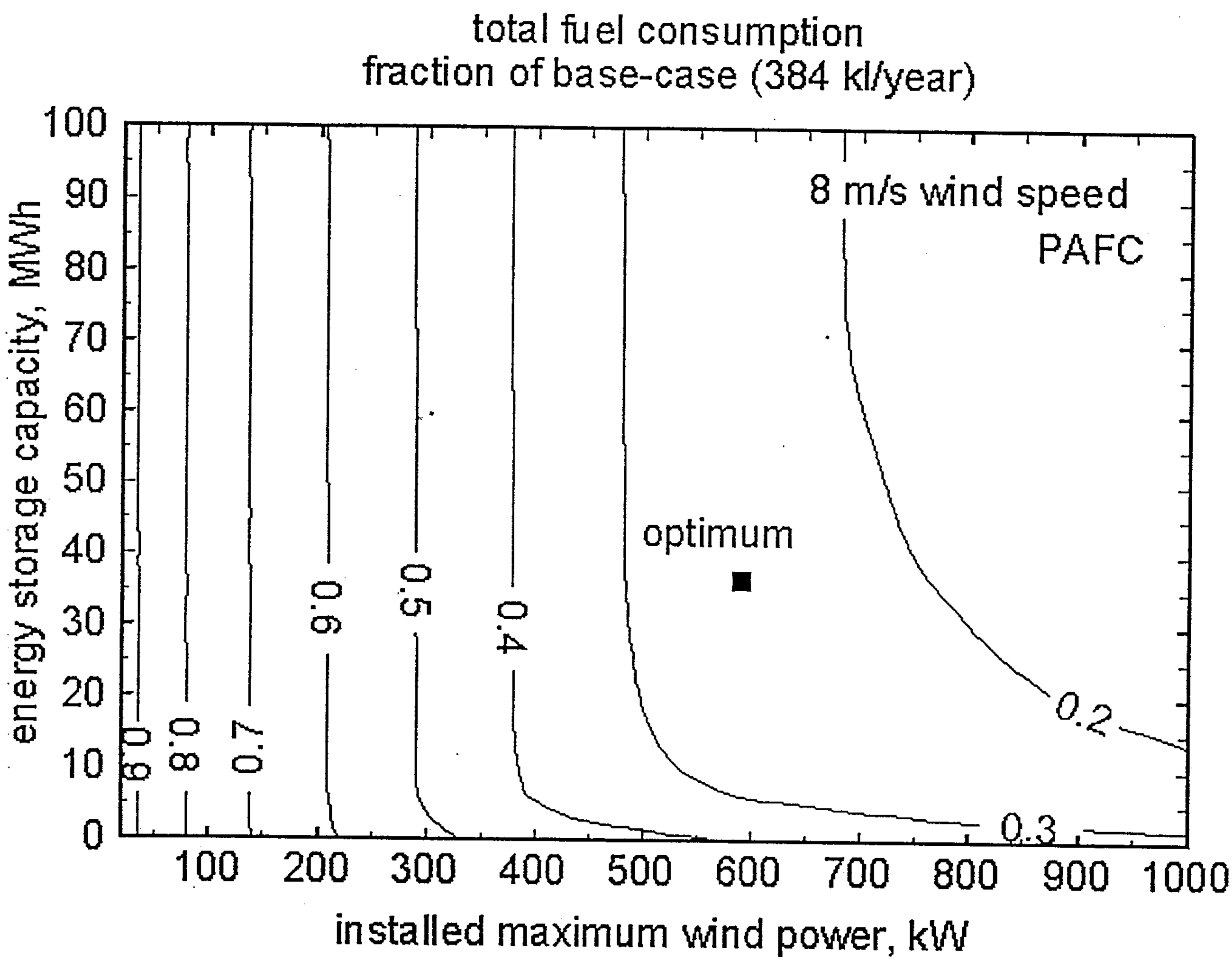

Figure 3. Lines of constant total fuel consumption as a function of energy storage capacity and installed wind power for a system with hydrogen storage and a PAFC. The number on the curves indicates the fraction of the fuel consumed in the base-case (384,000 liters/year). Decision variables are set to the optimum values for the PAFC system from Table 3a. Note that this indicates storage becomes more important with higher wind power penetration.

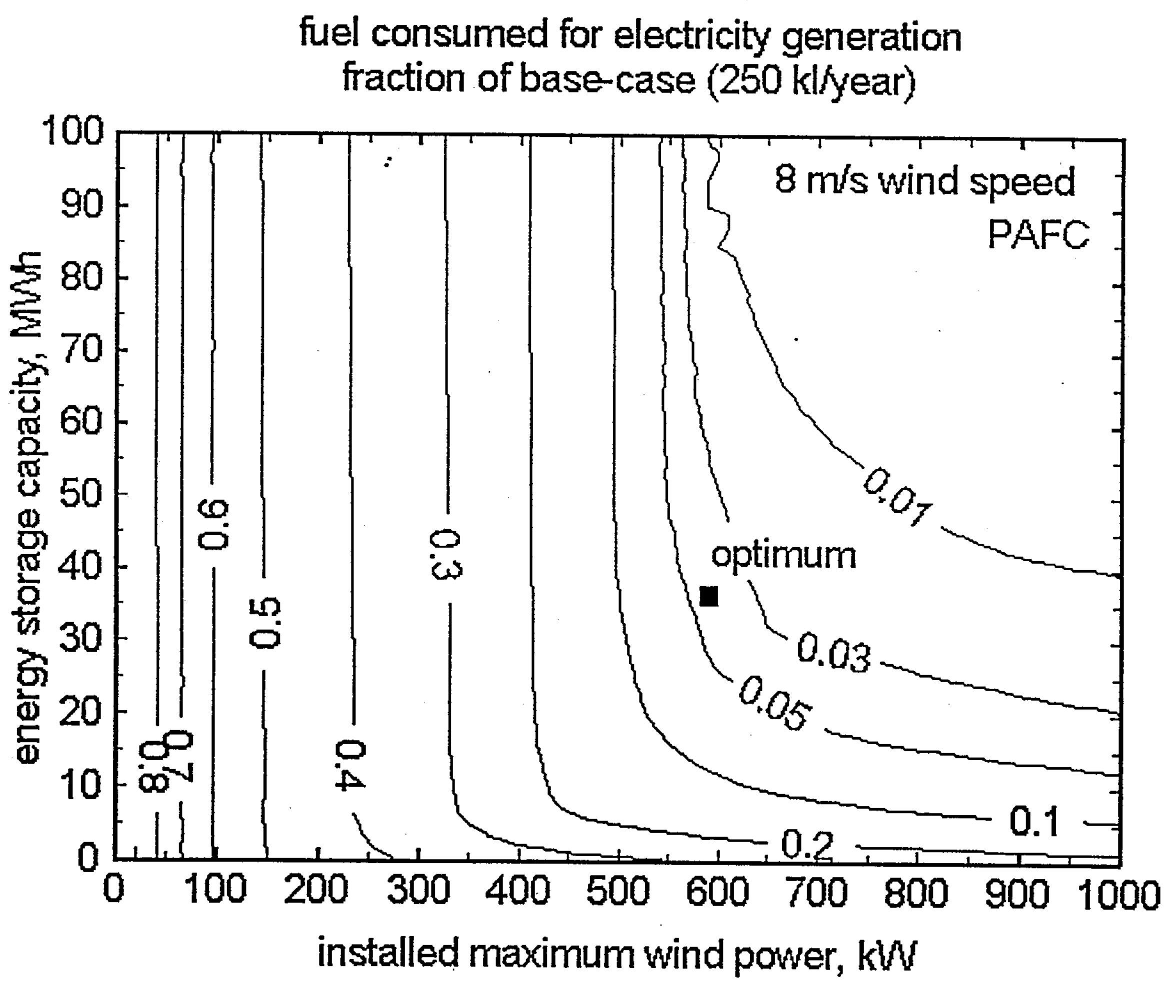

Figure 4. Lines of constant fuel consumption for electricity generation as a function of energy storage capacity and installed wind power for a system with hydrogen storage and a PAFC. The number on the curves indicates the fraction of the fuel consumed in the base-case (250,000 liters/year). Decision variables are set to the optimum values for the PAFC system from Table 3a.

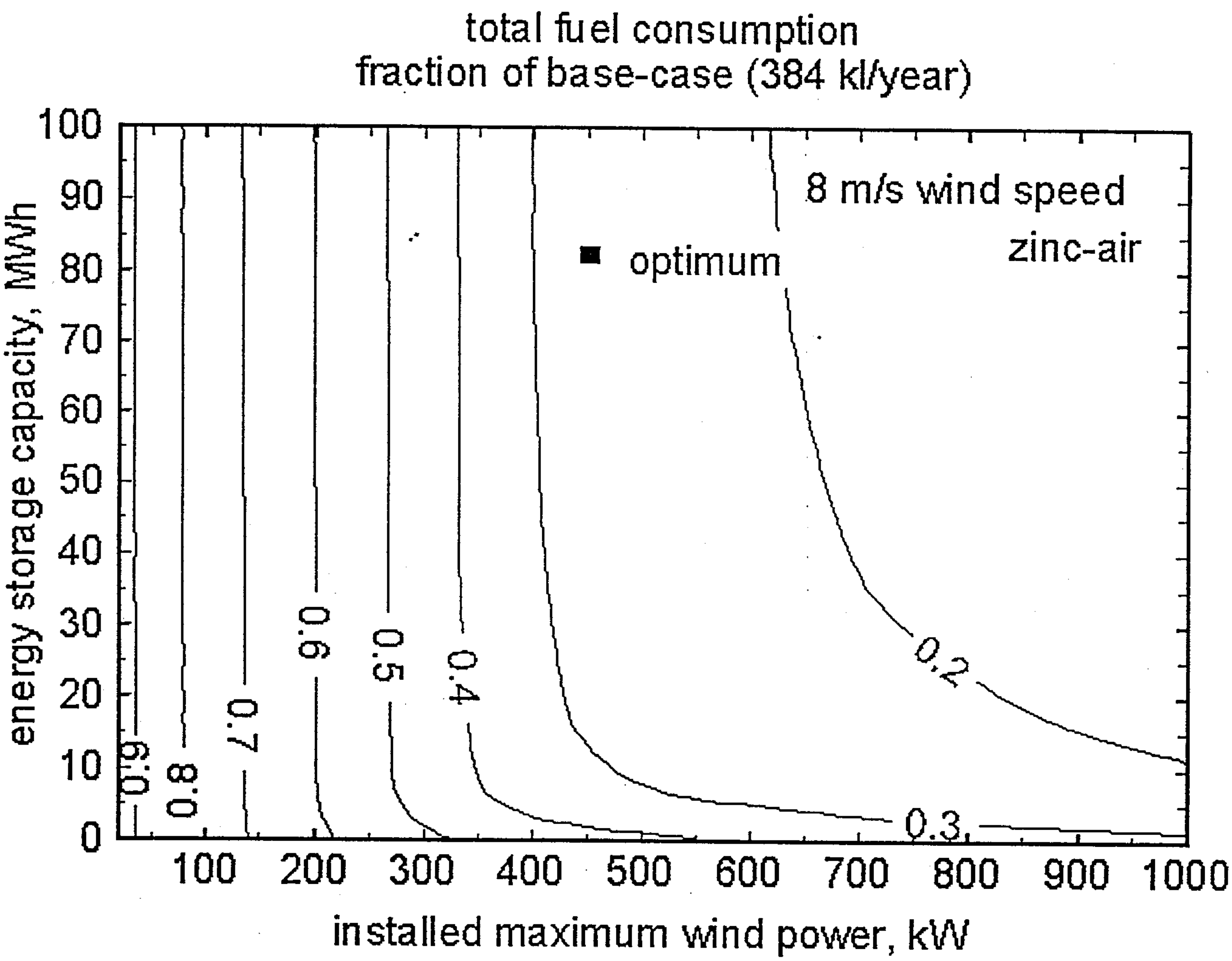

Figure 5. Lines of constant total fuel consumption as a function of energy storage capacity and installed wind power for a system with zinc storage and a zinc-air fuel cell. The number on the curves indicates the fraction of the fuel consumed in the base-case (384,000 liters/year). Decision variables are set to the optimum values for the zinc-air system from Table 3a.

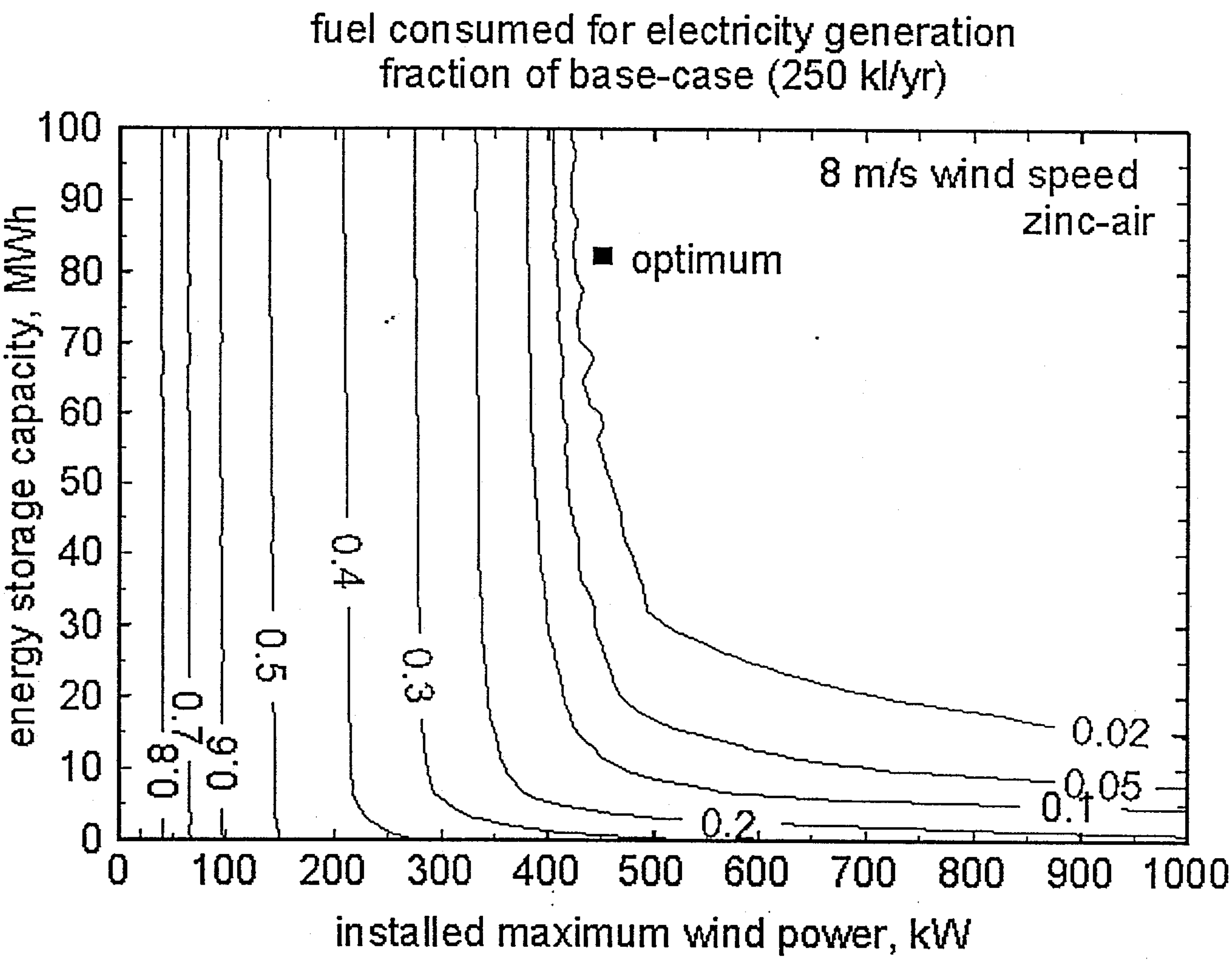

Figure 6. Lines of constant fuel consumption for electricity generation as a function of energy storage capacity and installed wind power for a system with zinc storage and a zinc-air fuel cell. The number on the curves indicates the fraction of the fuel consumed in the base-case (250,000 liters/year). Decision variables are set to the optimum values for the zinc-air system from Table 3a.

Technical Information Department **• Lawrence Livermore National Laboratory**
University of California • Livermore, California 94551