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UNIVERSITY OF ALASKA, FAIRBANKS ENERGY CENTER PARTICIPATION IN THE RURAL ALASKA POWER PROGRAM

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Abstract

In this paper we discuss the motivation and program structure for the Remote Area Power Program for Alaskan Villages. Rural Alaskan Villages are typified by small populations (many of less than 100 people), no road access to places outside the village, no access to the national (or even an Alaskan) electrical grid. Most of the Villages have electrical power typically generated by diesel generators providing power to each dwelling by a small very local micro grid. This system is difficult to maintain, very inefficient, and subject to frequent outages. To protect against power outages due to mechanical breakdowns, redundant generators are frequently in place, resulting in higher capital costs. Maintenance work is most often done by skilled workers from outside the village. Fuel must also be transported to the village. All of this results in a very high cost of power (up to 80 cents a kilowatt hour), currently subsidized by the state government to about ten cents a kilowatt for residential users through "Power Cost Equalization".

Recent advances in Proton Exchange Membrane (PEM) fuel cell technology have created the hope that these devices can be used in reliable, affordable remote power applications. However, verification of system efficiencies by independent parties has been sorely lacking. This work describes test benches developed to measure systems efficiencies of two fuel cell systems (additional work on other fuel cell systems will be reported later) designed and built to different criteria. Our results indicate that design decisions, such as humidification schemes, stack operating pressure, and hydrogen impurity management, can have a profound effect on systems efficiencies. By a careful systems analysis, component performance is characterized enabling whole system optimization. Appropriately optimized systems can exhibit excellent efficiencies. If wise decisions are made, parasitic losses can be reduced, and fuel cell systems efficiencies can be excellent. If heat recovered is included in the bottom line, efficiencies become impressive, especially if waste hydrogen and water vapor in exhaust streams can be recovered and converted to usable heat. This program is designed to address this issue while at the same time accelerate the development of hydrogen technologies needed to build the hydrogen economy of the future.

Background

Utility services such as electricity, water and sewer vary greatly within Alaska, and depend largely upon the type of community. Urban communities have utilities much like the lower 48 states, with electricity inexpensive and dependable, and water and sewer lines to most homes. Smaller communities such as

Kotzebue and Barrow are large enough to have functioning utilities, albeit at higher cost to the users, and some problems with service outages. The smaller communities, in general, are much less likely to have independent functioning utility companies. Many villages have electricity, provided by diesel generators and managed by Alaska Village Electric Cooperative (AVEC) which is headquartered in Anchorage. Many villages do not have running water or sewer services to most residences.

In addition to the vast distances between villages, climate also plays a significant role in the provision of utilities to remote villages. Alaska is a cold climate, with very short periods of warm weather during the summer months and long periods of cold weather during the late fall, winter and early spring months. Permafrost is present in much of the state.

Climate also affects the energy requirements of communities. The largest energy requirement is for space heating, which consumes about 60% of the total energy used in a remote village. Virtually no energy is used for air conditioning. Electrical loads fall in the summer when sunlight is present virtually all the time, and rises during the dark winters.

Diesel electric generators currently provide electrical power in remote villages. These generators are reliable if properly maintained, and the low cost of oil make them relatively economical. In their most efficient use, the waste heat is recovered and used for space heating (usually for a large building, such as a school) with total system efficiencies of about 60%.

The cost of producing electricity is high in the villages for several reasons. The cost of transporting diesel fuel to the village is the most obvious cost. Since there are no roads, fuel must be barged or flown into the village. Building and operating an electrical utility also requires skilled labor, both for linemen to string wires between houses, and also for mechanics to maintain the diesel engine. As the villages grow smaller, it becomes less and less likely that a person with these skills will be found in the village, so technicians must be brought in from outside, at considerable expense. Since each village is isolated and not connected to a grid, backup power must be provided within the village by redundancy in the diesel units, resulting in high capital costs. And furthermore, as the villages become smaller and smaller, the per residence cost rises simply due to the reverse of the economies of scale: fixed costs can be distributed over fewer users. In addition, because the generators need to be sized for peak demand the generators are most frequently operated significantly below the optimal efficiency.

Rural electrification occurred in Alaska during the 1970's and 1980's when oil money was flooding the state. The cost of electrical power in Alaska varies from about ten cents a kilowatt hour in Anchorage and Fairbanks, to twenty cents in Kotzebue, to forty cents in a village of a few hundred, and to eighty cents per kilowatt hour in a village of a few dozen people. The true cost to the rural residential consumer has been masked by the Power Cost Equalization (PCE) program, which, until now, has leveled the cost of the first 700 kilowatt hours to a rate equal to that of urban areas in Alaska. However, declining revenues from the oil industry to the state have left the state legislature less and less able to fund this program, and have cut the PCE to include only the first 500 kilowatt hours per month per residence. The threat of the elimination of the PCE program is a cause for concern for rural residents in Alaska. Various strategies have been proposed for reducing the cost of producing power in villages. Conservation is the simplest and most useful short-term solution, but does not address the longer-term issue of high fixed costs, depleting resources and increased emissions.

The University of Alaska, Fairbanks (UAF) has formed an Energy Center to evaluate possible technologies that could reduce the cost of producing power in remote villages. There have been numerous attempts to provided remote villages in Alaska with alternatives to diesel power, but most have not provided significant amounts of power at significant reductions in cost.

In order for a technology to successfully challenge the current status quo, it must be cost competitive with the total cost of living. Because of the extremely high cost of maintenance if skilled labor must be flown into the villages, this means that the technology must be extremely reliable while operating in an arctic environment. Reductions in capital and fuel costs would also be helpful, but will not alone be enough to overcome the expense of maintaining a system that requires more logistical support than the diesel generators.

The role of the UAF Energy Center is to experiment with potential technologies in an environment where technical support is readily available, and to assure that the technology is sufficiently robust to survive in Arctic conditions.

Program

This program was originally initiated as part of the Russian American Fuel Cell Consortium (RAFCO). It was envisioned to be a research and technology validation program to develop distributed technologies suitable for arctic climates common to Russia and Alaska. Having its funding roots in the Department of Energy managed out of the Hydrogen Program Office, synergism between the needs of this Alaskan program and that of the hydrogen program quickly grew. A technology of particular interest to the hydrogen community and one that is being aggressively pursed by industry for distributed power applications is a small Proton Exchange Membrane Fuel Cell (PEMFC). A research development and deployment program to promote PEMFC technologies suitable for use in Alaska provided the opportunity to accelerate its deployment as a technology for use in remote distributed applications in the lower 48 states while addressing the severe needs of the rural Alaskan and Russian population.

The Alaskan Remote Area Power Program is structured to address the unique issues that one faces when operating in a truly remote location and under extremely harsh environmental conditions. Any technology that is introduced into this or any other environment must compete on economic terms. The measure of merit to the consumer is the cost of establishing an acceptable standard of living. In this case, the cost of providing energy in a useful form (electricity and heat) to a single dwelling is the measure of merit. Hence, this PEMFC program is designed with the expectation of significantly increasing the fuel utilization and hence, dramatically reducing overall fuel use seen by an individual. Secondary benefits of the program should be to increase reliability with a commensurate increase in security. As discussed, redundant diesel generators most commonly produce electrical power with the waste heat possibly being used by a local school or other nearby large building. This forces the individual dwelling owner to purchase very expensive electrical power produced by the diesel generators and to supply heating for the dwelling separately adding to the energy cost for the individual. This program is designed to develop and deploy systems hardware that should supply electrical energy for a dwelling while at the same time satisfy the heating requirements. With a total energy systems approach we expect the total fuel utilization to improve from the nominal 20% electrical to upwards of 80% for electrical and heat. This not only will significantly reduce the cost to the dwelling owner but it also eliminates the need for a separate heater and heating oil supply. (In reality, one would keep a backup heater in case the unit in the dwelling was in disrepair. This is already standard practice in many parts of Alaska.) In other words, for the same cost paid to the local utility for electrical power, the individual will also be able to heat the home, provide hot water, reduce emissions, and increase the reliability of the overall system.

The PEM Fuel Cell as envisioned for this application is actually a system composed of a reformer to convert diesel fuel (already available in villages) to hydrogen, a PEM fuel cell to convert the hydrogen into electricity, and an AC inverter. The overall system will be a hybrid of technologies including energy storage (most likely batteries) to supply peak power requirements, with hydrogen storage for rapid start up of the entire system. In addition to the electrical energy produced, waste heat from this system will be used for residential space and water heating.

The PEM Fuel Cell Project is being funded through the US DOE Hydrogen program. The project currently involves nine team members: Plug Power (fuel cell development, systems integrator), Northwest Power (reformer development, system integrator), Schatz Energy Research Center (fuel cell development), Hydrogen Burner Technology (reformer technology), Energy Partners (fuel cell technology), and Teledyne centralized power generation already in existence in the Alaska villages a micro-grid is already in place.

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National Laboratories (system integration, reformation reacting flow, and program management), University of Alaska Fairbanks (arctic engineering, test and evaluation

This program is designed in three phases with each phase completion scheduled at the end of a calendar year.

Phase I was initiated July 15, 1998 and had two principle components
1) Delivery of a 3 to 5 kW PEMFC made operational with hydrogen by September 30, 1998.
2) Delivery of diesel reformer and made operational by December 30, 1998.

Phase I has been successfully completed by some but not all of the team players.

Phase II was initiated February 1, 1999 with the following three principle components
1) Test and evaluate the performance of the fuel cells and the reformers delivered as part of Phase I. The evaluation of these system components is designed to determine system compatibility, system design parameters needed to provide grid quality power, emissions and overall thermodynamic first law system efficiencies
2) Based on information obtained from Phase I systems, design and build Phase II components (reformers and fuel cells) that are compatible with one another. Operate the fuel cell on the hydrogen from the diesel reformer in the May-June 1999 time frame.
3) Create all the systems control algorithms and logic to permit this system to provide the end-user "grid" quality power. The performance of this system must be analogous to or better than operating off a national grid. It must be transparent to the end-user that the energy services in use are delivered by a local distributed system. This phase is to be completed in December 30, 1999

Phase III is to be initiated January 1, 2000 with the following deliverable
1) The system designed in Phase II is to be field tested and delivered to a remote arctic location for standalone alpha field-testing. This system will experience an Alaskan summer and winter cycle. Data from this test will be used to improve the systems for a Beta test and deployment into the field.

This program helps us move toward an environmentally benign, carbonless and sustainable society in the following ways:
1) It accelerates the development of hydrogen end-use technologies, specifically the PEMFC integrated system for utility applications.
2) It helps to establish integrated distributed power generation systems that significantly increase the overall efficiency of energy utilization and system reliability.
3) It significantly reduces the use of fossil fuels today while putting in place the systems necessary for eventual shift away from fossil fuels to renewables. For example, the only part of this system that is fossil fuel specific is the reformer. When renewable energy resources become developed the reformer is replaced with pure hydrogen as the energy carrier. One discards only the reformer everything else remains in place.

Work completed to date

Proton Exchange Membrane (PEM) Fuel Cells are a potential technology for remote distributed power generation. The virtues of fuel cell stacks have been widely advertised: they are quiet, have high efficiencies, and have no moving parts to wear out (although there is still a significant balance of plant for handling mass flows of air and cooling water that involves moving parts, such as blowers, compressors, humidifiers, and pumps). Some companies have predicted that small residential sized power generators built around PEM fuel cells will be commercially competitive with conventional power generation for remote sites within a few years.

To provide an impartial evaluation of PEM fuel cells, the Energy Center at the University of Alaska, Fairbanks (UAF) and Sandia National Laboratories (SNL) measured a total system energy balance for three fuel cell systems. As currently envisioned, a residential PEM fuel cell system will include a reformer to convert diesel or kerosene fuel to hydrogen, a PEM fuel cell to convert hydrogen into DC electrical energy, and an inverter to convert DC power to grid-quality AC power. However, the scope of the work completed to date is focused only on the PEM Fuel Cell and its required auxiliaries. Our work does not attempt to analyze the performance of the stack other than as part of the system, as a device that converts fuel into electrical power and heat. The bottom line is this: how well does this system convert fuel into electrical power, and how does this system compare with other available technologies.

In addition to electrical power, PEM fuel cells also produce heat. In Alaska, the largest power requirement is for space heating. This requirement provides a direct use for the heat generated by the fuel cell. Some heat produced by the fuel cell will be transferred directly to the surroundings by radiation and convection, but this heat is harder to capture, and will not be considered "useful" heat. Our evaluation of fuel utilization, therefore, will consider usable heat to be heat transferred out of the fuel cell with mass flow (in the cooling loop and in the air exhaust) as a useful product.

Description of fuel cell systems received

Design decisions such as operating pressure, hydrogen impurity management, and humidification schemes have profound effects on fuel cell systems. These differences dictate the different auxiliary devices needed to run the fuel cell, and affect the efficiency attained by the system.

This work is intended to evaluate fuel cell systems designed for use in distributed applications where both electrical power and heat are to be used. In order to evaluate the impact of individual design decisions, a fuel cell purchased from Energy Partners was used to build a test bench to evaluate components, such as humidification systems, air supply devices, and heat exchangers. In the future, this stack will be used for initial testing of reformer technologies. This stack is a 26-cell pressurized stack, designed to be operated at 30 psig on both the air and hydrogen side. The hydrogen side of the fuel cell requires flow-through for water and impurity management, nominally at 1.5 times stoichiometry. Nominal power from the stack is 3kW. The system built around this stack was not optimized for stationary power generation, and therefore no efficiencies will be reported for this system.

The second fuel cell was built by the Schatz Energy Research Center (SERC) and is designed for use in remote power applications. It consists of a 60-cell stack, with an internal humidification section that uses part of the heat generated by the stack for evaporation. The hydrogen side is run dead-ended, using pure, dry hydrogen, with periodic purges to remove accumulated liquid water and other impurities. The fuel cell system is designed to be run at near atmospheric pressure, with a variable speed blower. The stack is designed to be operated at about 3kW.

The components used on the SERC bench (blower and pumps) were purchased based on the recommendation of SERC, and the system is a good indication of the performance that can be expected from a well designed stationary power generation system.

A fuel cell system supplied by Plug Power was also evaluated as part of this work, but at the request of Plug, these results are not reported at this time.

Test Bench design

Fuel cell system efficiency can be measured in several ways, depending on the application and the overall system design. The challenge is to design a test bench to accurately and independently record all of the mass and energy flows through the system under a range of test conditions.

Total energy input to the fuel cell may be broken down into two forms: the energy value of the hydrogen fuel and the electrical or other energy supplied to the parasitic devices such as pumps and blowers, and humidifiers. Power output comes in the forms of electrical power, heat in the de-ionized (DI) cooling loop, heat in the air exhaust (including the latent heat of condensation of water vapor) and the energy content of the stream of waste hydrogen.

We constructed three test benches, each equipped with an array of thermocouples, pressure gauges, flowmeters, power meters and other miscellaneous devices. Wherever possible, calibrations were performed under actual operating conditions. Measurements were cross checked by redundant instrumentation, and by comparison with calculated values. All signals were interfaced through a modular signal conditioning system and fed to a desktop computer. Software was developed for each fuel cell system to provide control of the reactant flows, to automatically shut down the stack if an unsafe operating condition is detected, to display the status of the system, and to continuously log the data. The software can be readily adapted to accommodate the requirements of other fuel cells.

Results:

In order to calculate a system efficiency, the parasitic loads required by necessary auxiliary devices such as blowers, pumps, and solenoid valves must be measured and subtracted from the electrical power output. However, these parasitic loads are strongly affected by design parameters such as operating stack pressure, humidification, and hydrogen exhaust schemes. These design decisions make direct comparisons between the systems difficult, as system boundaries cannot be drawn in the same way for each system.

Two different types of efficiencies, first-law and second-law, are reported. First-law efficiency can be simplistically described as the ratio of energy out divided by energy in. The second-law of thermodynamics imposes an upper limit on the amount of work that can be extracted as energy changes from one form to another. A second-law efficiency is therefore simplistically described as "what you get vs. what you *can* get". We report two second-law efficiencies but the goal of this work is to evaluate the efficiencies of fuel cell <u>systems</u>. In order to do that, first-law efficiencies must be determined. There are several ways to calculate the first-law efficiency, based mostly on how one defines the system, and what products are considered useful. The preferred efficiency for our purpose includes the net electrical power generated plus the useful heat recovered. In order to simplify analysis, we report efficiencies based on steady-state values measured at stack operating power level of about 2700 Watts. Data reported here is based on average values measured during a 30 minute run at steady state.

Since the electrical power is the most valuable product created by the fuel cell system, we elected to convert all energy flows into units of watts. This provides a direct method of determining where the energy is coming into the system, and how it is leaving. Hydrogen mass flow into the system was measured in units of standard liters per minute (slm). Converting thermodynamic data to Watts gives a conversion factor of 212.7 W/slm for the higher heating value of hydrogen, or 179.9 W/slm for the lower heating value of hydrogen. Efficiencies using both values were calculated for purposes of comparison with other results in the literature.

Fuel Cell efficiencies

3) Voltage efficiency at open circuit

One popular measurement is to set the system boundary to include only the fuel cell membrane, and to compare the open circuit voltage across a single cell with the ideal maximum voltage as dictated by the second law of thermodynamics. (Appleby, 1989) This measurement gives an indication of the performance of the cell membranes and catalysts, but is not an indication of total system efficiency.

$$\eta_V = V_{Stack\_open\_circuit} / V_{ideal}$$

Where $V_{Stack\_open\_circuit}$ is the measured stack voltage at open circuit, and V_{ideal} is the number of cells times the ideal voltage of 1.23 volts per cell. This value is based on the Gibbs free energy change available during the reaction, so this represents a second law efficiency.

4) Voltage efficiency under load

$$\eta_V = V_{Stack} / V_{ideal}$$

The voltage efficiency can be calculated by comparing the cell voltage to the ideal voltage but measured under conditions of a working load, as shown above. This number should be a measure of the ratio of the power out to the power into the system delivered by the energy content of the hydrogen consumed. Since this number ignores the parasitic losses in the system and the hydrogen purged, it is not a measure of the total system efficiency. However, it is an indication of how the fuel cell membrane is acting under conditions of an actual load. This value is dependent on the current density of the membrane, and will decrease as the current density increases.

3) Gross electrical power output versus fuel power in (lower heating value).

This measurement is a convenient way of comparing rough fuel cell performance. However, it ignores the parasitic loads.

$$\eta_{GE} = I_s V_s / \dot{E}_{H2in(low)}$$

and

$$I_s V_s = \dot{E}_{Gross\_Electrical\_out} = P_{Gross\_Electrical\_out}$$

Where I_s is the fuel cell stack current, V_s is the fuel cell stack voltage, and $\dot{E}_{H2in(low)}$ is the flow rate of the energy value of the incoming hydrogen fuel per second, (given by the mass flow rate of hydrogen multiplied by the lower heating value of hydrogen, which results in a value of 179.9 W/slm). Not all of the hydrogen is consumed by the fuel cell, so this value includes waste hydrogen exhausted from the system. Use of the lower heating value assumes that the water formed during the reaction will exit the system as water vapor (a good assumption for applications where heat needs to be removed from the system).

4) Net electrical power out versus total power in (lower heating value for hydrogen)

$$\dot{E}_{in} = \dot{E}_{H2(low)} + \dot{E}_{other}$$

$$\dot{E}_{out} = \dot{E}_{Electrical\_out} - \dot{E}_{Parasitic}$$

$$\eta_{Net(low)} = \dot{E}_{out} / \dot{E}_{in}$$

Where $\dot{E}_{Parasitic}$ is the parasitic electrical power in, $\dot{E}_{Other}$ is any other form of power in, such as heat or natural gas, and $\dot{E}_{Electrical\_out}$ is the gross electrical power out of the fuel cell. This number is a good measure of efficiency in many applications, where the electrical energy is the only useful product, and heat is discarded.

5) Net electrical efficiency versus total power in (higher heating value of 212.7 W/slm)

$$\dot{E}_{out} = \dot{E}_{Electrical\_out} - \dot{E}_{Parasitic}$$

$$\dot{E}_{in} = \dot{E}_{H2(High)} + \dot{E}_{in\_other}$$

$$\eta_{Net(High)} = \dot{E}_{out} / \dot{E}_{in}$$

This efficiency is the same as in the previous calculation, except the higher heating value for hydrogen is used. Since part of this application is heat recovery, condensing the water in the air exhaust is one way of recovering the heat produced by the system, and this is the more useful efficiency for this work.

6) Net electrical efficiency plus useful heat versus total energy flow (higher heating value)

$$\dot{Q}_{net} = \dot{Q}_{out} - \dot{Q}_{in}$$

$$\eta_{system} = (\dot{E}_{out} + \dot{Q}_{net}) / \dot{E}_{in}$$

Where $\dot{Q}_{out}$ is the heat energy carried out of the fuel cell system by the cooling loop and recovered in the heat exchanger. $\dot{Q}_{in}$ is heat energy added to the system, required for humidification. $\dot{E}_{out}$ is as given above, and refers to the net electrical energy out.

Since net recoverable heat energy is considered a useful product, this system efficiency is the preferred measurement for purposes of comparison between systems in this work.

7) Net electrical efficiency plus useful heat plus other calculated recoverable heat sources versus total energy flow (higher heating value for hydrogen)

$$\eta_{Potential} = (P_{NE} + \dot{Q}_{out} + \dot{E}_{H2\_waste} + \dot{Q}_{Air\_Exhaust}) / \dot{E}_{In}$$

Where $\dot{E}_{H2\_waste}$ is the recoverable energy flow value of the hydrogen waste stream, measured by capturing the hydrogen exhausted during a purge cycle, and $\dot{Q}_{Air\_Exhaust}$ is the heat energy in the air exhaust. Most of the energy in the air exhaust comes in the form of water vapor that can be condensed. This value can be calculated based on the assumption that the air leaving the fuel cell is saturated with water vapor at the air exit temperature and cooled to ambient temperature, releasing the latent heat of condensation of the vapor.

It should be noted that we have not yet completed a measurement of the heat that can be extracted from the air exhaust. This value is reported for two reasons: 1) it shows that our test bench accounting is reasonable, and 2) additional heat energy is available from the system if recovery hardware is developed.

Discussion:

The goal of this work is to evaluate the suitability of fuel cell systems for remote power applications, specifically to determine if the thermodynamic efficiencies are sufficiently high to pursue this technology. This differs somewhat from the goals of fuel cell suppliers who frequently report only fuel cell stack efficiencies. A fuel cell system includes the fuel cell stack, an air supply device (blower or compressor), humidification system, a hydrogen management system, and a pump and heat exchanger for heat removal.

For the purposes of comparison with existing values in the literature the voltage efficiency have been calculated for the fuel cell under both open circuit and operating currents. These values are included primarily to demonstrate that the fuel cell stack is operating as advertised by the fuel cell supplier. During operation, the SERC stack operated very smoothly, with very little variation in cell to cell voltages. The SERC stack also did not require a warm up period, as a load of 2.7 kW was applied while the stack was at ambient temperatures.

The gross electrical out versus hydrogen in efficiency provides a measure of the hydrogen management system. In the case of the system evaluated here, the hydrogen is dead-ended except during periodic purges, so the hydrogen exhausted from the stack is only about ten percent of the total flow. Discussions with the supplier indicated that this purge volume could probably be reduced somewhat, increasing the total system efficiency, but it is not clear what the necessary purge rate is for sustained operation.

The fourth efficiency number is based on a net electrical efficiency using the lower heating value of hydrogen. This number is useful for applications where the electrical power is the only useful product from the fuel cell, such as in transportation applications. This number is the first that considers the parasitic loads in the system. Since the stack evaluated here is designed to work at atmospheric pressure, it has very low parasitic loads for the air supply system. Since humidification is internal, there are no additional energy forms that must be added to the system.

The net electrical power efficiency (number 5 in the table) is based on the higher heating value of hydrogen assumes that the water created during the reaction will leave the system as a liquid rather than as a vapor. Since heat recovery is a goal of this work, this is the preferred value for hydrogen energy.
Calculating efficiencies based on the higher heating value of hydrogen will result in lower values than those calculated on the lower heating value.

From the point of view of using a fuel cell system for both electrical power generation and heat production, efficiency calculated as item number 6 is actually the most useful. In this calculation, we treat both net heat and net electrical power as useful products. Based on this value, the overall efficiency of the system evaluated here rises to nearly 70%. This number is quite encouraging. This number weights electrical power and the heat equally, but the heat is of a relatively low quality, and cannot be easily transformed into other forms of energy.

The last efficiency calculated is a theoretical efficiency, in that we can identify two products exiting the fuel cell that have recoverable energy. The first is the hydrogen waste stream, which might be used by the system, either recycled back as fuel, or burned for heat. The second is the air exhaust stream, which is saturated with water vapor. Just as it requires a considerable amount of heat to humidify the incoming air, this heat can be recovered if the water vapor is condensed out of the exhaust. Since we have not directly measured or recovered either of these energy streams at this point, we are reporting these values as estimates. However, the bottom line becomes very attractive at this point. Efficiencies of over 90% may be attained if the energy in these discard streams is recouped. If remote power using fuel cells is ever to be a viable commercial technology, this energy recovery is critical.

Conclusions:

This work demonstrates that an integrated systems approach must be used when attempting to optimize the fuel cell system for a particular performance criterion. PEM fuel cell systems, when designed to minimize parasitic losses, are efficient devices. A total measured system electrical efficiency of 48% (based on the lower heating value of hydrogen) as seen with the SERC system is an excellent result from the point of view of thermodynamic efficiency. However, it must be noted that the final system as envisioned in this work includes a reformer and an inverter, both of which involve losses. If we estimate the overall efficiency of the reformer at 75% and the efficiency of the inverter at 90%, the total system efficiency drops to 31%. Diesel electric generators can attain similar efficiencies when they are operating under optimal conditions (efficiencies as high as 40% have been reported recently). Fuel cells tend to perform better at low loads, while diesel efficiencies are highest at higher loads.

If the heat generated by the system can be managed and put to good use, the overall system efficiency rises to impressive levels. Most of the energy put into the fuel cell exits the system in some usable form, either as electricity, usable heat or as waste hydrogen that can be converted to heat. Our results indicate that this efficiency may be as high as 90% (though we must note that this number has not been yet measured). This number is only for the fuel cell part of the system. It is not clear what the overall energy recovery will be from the reformer, except that some energy will likely be lost due to the combustion exhaust that might need to be vented from the system.

This work reinforces that electrical efficiency alone can not be the single driving motivator for the use of fuel cells in the systems considered here. The ability to operate with diesel-like efficiency in a small package suitable to be located at a single dwelling where one can make maximum use of all forms of energy make fuel cells in this application <u>very</u> attractive.

The final observation is that while the thermodynamics look encouraging, we are still a long way from proving that this system is capable of competing with diesel electric generators for remote power applications. Capital costs, installation costs, and maintenance costs affect the overall price of power generation as well as fuel costs. In remote Alaskan villages, the reliability of the system is paramount: if extensive technical support is needed, fuel savings will be quickly overwritten by maintenance losses. This requirement favors simplicity in design, and demands high quality components and assembly. The need for extremely high systems reliability cannot be overstated.

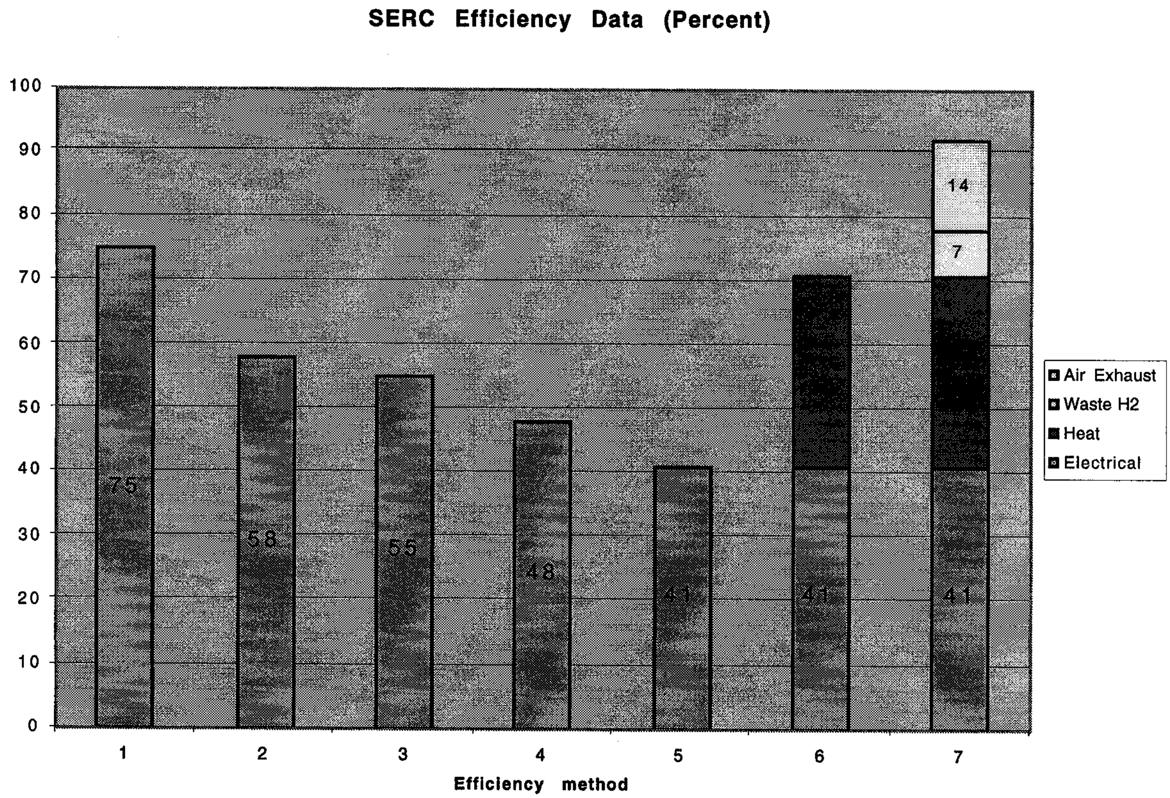

Figure 1. Results of calculating efficiencies in various ways for the SERC bench. See text for discussion of methods.

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