INTEGRATED RENEWABLE HYDROGEN/UTILITY SYSTEMS

Final Report
Phase1
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Executive Summary

The Desert Research Institute (DRI) has completed Phase 1 of a Department of Energy contract to employ hydrogen as an energy storage medium for remote, renewable utility applications. The goal of this two-phase project is to bring about technologies to accelerate the use of clean, renewable energy worldwide in an economically feasible and technically viable way. The goal is being met through the development of design and analysis tools, assembly of a test system, and ultimately, installation of a full prototype system in Phase 2 of the project. This approach takes advantage of hydrogen's ability to store large amounts of intermittent energy in a dispatchable and cost effective way The design and control system tools developed from this project will provide the basis for smart control technology critical for future distributed power systems. The test and full prototype systems will serve as pathfinders for using hydrogen as a utility energy storage medium. The expected location of the prototype system is Kotzebue, Alaska, a village with a remote yet growing wind farm as well as realistic loads and environmental conditions.

Technology has evolved during the past two decades allowing us to take this first step in combining components from diverse technical areas into independent, renewable power systems. These on-demand power systems require only a renewable power input and can range in size from a few watts (small enough to power weather monitors) to hundreds of kilowatts (large enough to power villages, buildings, or off-grid neighborhoods). We are pursuing the first applications of these systems in remote regions where wind or solar power is integrated with adequate storage to provide a steady supply of electricity to communities or any other load requiring on-demand power. The energy storage component will provide power to the community when the renewable source is quiescent.

Phase 1 of the project had three primary objectives:

1. To begin the modeling process for generalizing ways to bring about integrated hydrogen power systems in the most timely way;

2. To design and install a renewable hydrogen test system of a useful scale and begin evaluation of various system designs and controls; and

3. To evaluate the possibility of deploying a remote hydrogen power system, and, if reasonable, to complete a conceptual system design.

The first objective has been completed and is based on TRNSYS integrated system software. The use of models developed by DRI and Stuart Energy Systems has shown the benefit of the research direction planned under this project. The second objective has also been met through the installation of a test system at the DRI Northern Nevada Science Center in Reno, Nevada. This system is capable of performing as a flexible, physical model of a renewable power system using hydrogen or any other energy storage. Since the originating DOE solicitation excluded any new renewables as part of the project, and DOE expressed the desire to consider Alaskan possibilities, the Village of Kotzebue, Alaska was selected as the location for the first system design and evaluation, and is the subject of objective 3. The Kotzebue Electric Association (KEA) is a forward looking local utility intent on successfully employing clean energy technologies while benefiting the community economically and environmentally.

Introduction

Project Background

Fundamental to this project are two principles. First, without energy storage, renewable power from intermittent sources cannot provide a base load supply or completely penetrate a power grid. Given the cost and performance of the storage technologies, however, global availability of these systems is many years away. Second, the current and near-term states of renewable power and energy storage technologies permit niche opportunities to deploy small-scale renewable hydrogen utility systems in high-value applications, usually for the production of remote power. The first principle relates to the long-term opportunity for hydrogen and other utility energy storage methods to provide increased growth of renewable power throughout the world. The second principle relates to the near-term opportunities for hydrogen and other energy storage methods to be employed with existing renewable energy sources. This project is intended to accelerate the hydrogen, fuel cell, and renewable energy opportunities based on the second principle.

The project is a collaboration with team members from industry, university, utility, and government sectors. The team members, their capabilities, and the nature of their participation are described later in this report.

A study of existing modeling resources was performed, and the platform TRNSYS was chosen as the basis for the system modeling necessary for this project. A spreadsheet model was assembled at DRI, and a model at Stuart Energy Systems (SES) specific to hydrogen systems was run to validate the general direction of the project. Analysis with the spreadsheet and SES model validated the rationale for renewable hydrogen utility power systems. The progress in developing the detailed models is described later in this report. As a project activity supporting the final design and decisions for the Phase 2 utility system planned for installation in Alaska, additional modeling and analysis for system designs and performance are planned. These models are expected to complement the suite of models available for renewable and integrated power systems. The models derived in this project will be specific to systems that use energy storage in the form of hydrogen, later generalized to other storage devices. Additional features will be added to the TRNSYS-based model will be completed and used to fully test the design scenarios for Alaska system configuration during Phase 2.

Hydrogen Storage Systems

Hydrogen is one of several candidates that can be used as a utility energy storage medium in non-grid applications. Examples of storage mediums include batteries, pumped hydroelectric, flywheels, compressed gas, and zinc or halogen electrochemical systems. As part of this project, we have developed tools to analyze hydrogen storage systems that can also be used to analyze the cost and performance expectations of all the other potential energy storage systems. For any application, there is an optimum method of energy storage based on cost and performance criteria, recognizing that the cost and performance parameters will evolve over time. The general format for these systems is depicted in Figure 1, with the options for components from source to load.

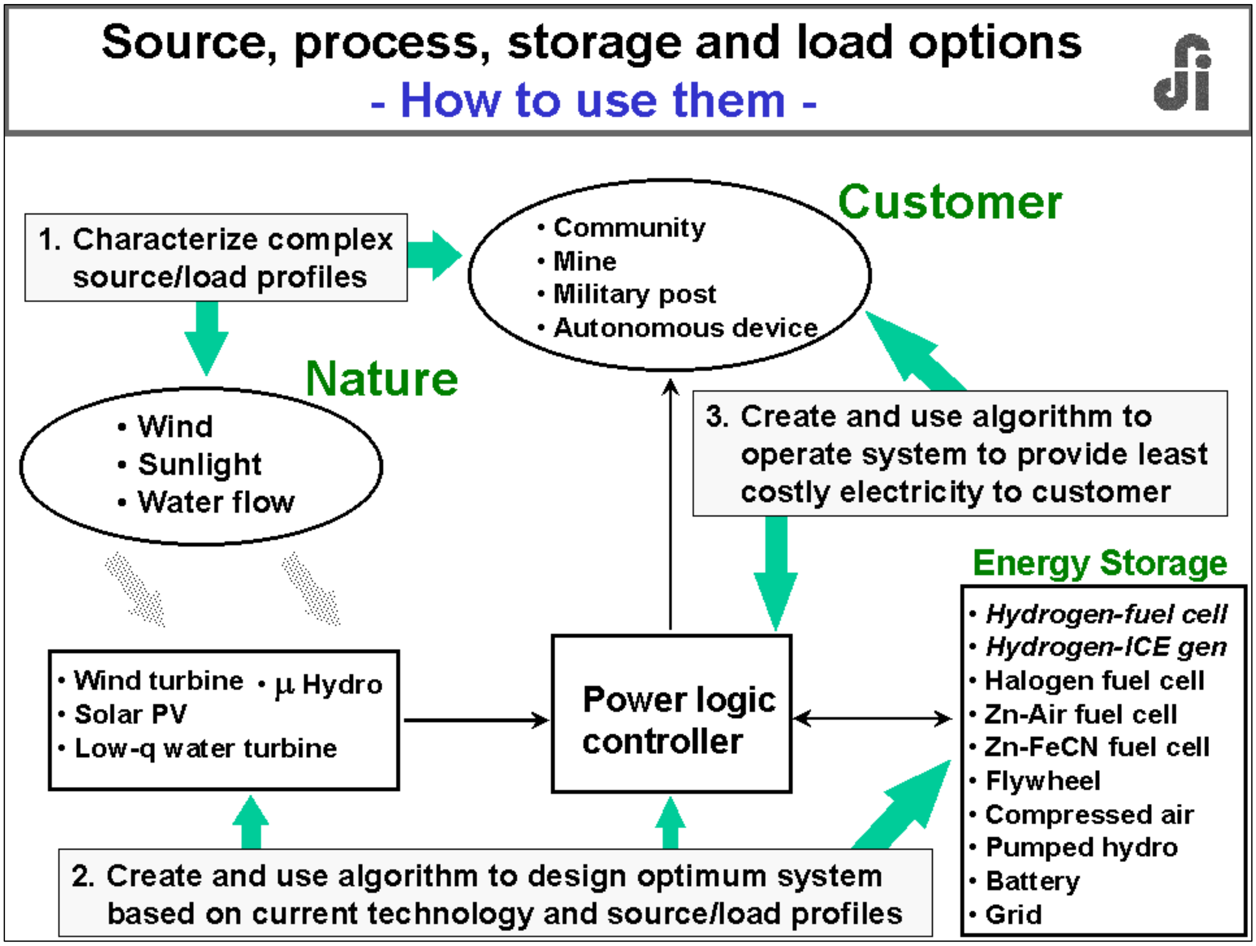

Figure 1 - Source, Process, Storage, and Load Options for Remote, Renewable Power Systems.

Under conditions where pumped hydroelectric is feasible, that method will usually be the most efficient and cost effective for storing renewable energy. For short periods of stored energy use, batteries are usually more cost effective than other options. For conditions where credible periods of renewable power unavailability exceed two to three days, however, hydrogen energy storage is expected to compete with batteries based on component capital cost. In remote, renewable energy systems, the energy storage medium is required to buffer the intermittency of, and phase differences between, the time-varying renewable resource and the load. As in the application of any new technology, the use of hydrogen as a storage medium will have its earliest market in high-value applications, such as premium power or in niche applications in isolated locations.

The energy storage element of hydrogen systems is more complex than either battery storage systems or fossil-fueled fuel cell systems. For a battery system, the battery is both the energy storage and the power input and output element. In a fossil fuel system, there is one energy storage element, the fuel tank, and one power element, the internal combustion generator set or the fuel cell, reformer set. A hydrogen energy storage system is comprised of an input power electrolyzer, a hydrogen storage vessel and compressor, and an output fuel cell or internal combustion engine generator. Single-component systems such as batteries cannot separate the power and energy elements for optimization, and fossil-fueled systems still require a fossil fuel delivery infrastructure serving remote locations. A hydrogen system permits optimization of input and output power as well as energy storage elements for any given application and, ideally, will never require a fossil fuel delivery infrastructure.

We have included the option of hydrogen-fueled, optimized, internal combustion (ICE) generator sets as a possible choice for the output power element. For several years, optimized ICE generator sets have been considered as a transition power plant for the fuel cell. They can have similar efficiency and emission performance as a fuel cell and can be significantly less expensive in today's marketplace. However, here are still no manufacturers of ICE hydrogen generators, while the performance and cost of fuel cells are evolving rapidly. As a result, we expect that the output power element for hydrogen systems will shift toward fuel cells almost exclusively during the next decade.

Fuel cell systems using diesel fuel or other fossil fuels still require a fuel delivery infrastructure, as well as a water supply for the CO shift reactor. The presence of a reformer for the primary hydrogen supply also reduces the efficiency of the power system to the range of a conventional diesel generator. While reducing the air pollution impact, fossil fuel cell systems do not significantly reduce the fuel supply needs or environmental risks of fuel storage and shipping. A renewably powered system provides pure, electrolytic hydrogen to the fuel cell, eliminating concern for contamination of the fuel cell anode catalyst.

Project Overview

For the past six years, DRI faculty have recognized that the remote villages in Alaska and Native American communities in the West and Southwest are the best locations in the United States to test the market for fuel cells and integrated, renewable power systems. Nevada utilities have more than 10,000 customers without access to the central power grid; New Mexico has a greater number. The state of the technology today allows us to provide renewable electricity to locations currently without it. These systems can also provide on-demand electricity to pristine environments with no emissions.

Power systems employing fuel cells can be configured in several ways, all of which require the delivery of hydrogen to the fuel cell power generator. The hydrogen can be supplied from several different sources and there are five different fuel cell technologies that can be employed to produce power from the hydrogen. The options for power system configurations is shown in Figure 2. The top two hydrogen delivery options in Figure 2 are the "linear systems" described elsewhere in this report. In comparison, the presence of an alternative power path in the renewable hydrogen option is the source of the optimization opportunities also described in this report.

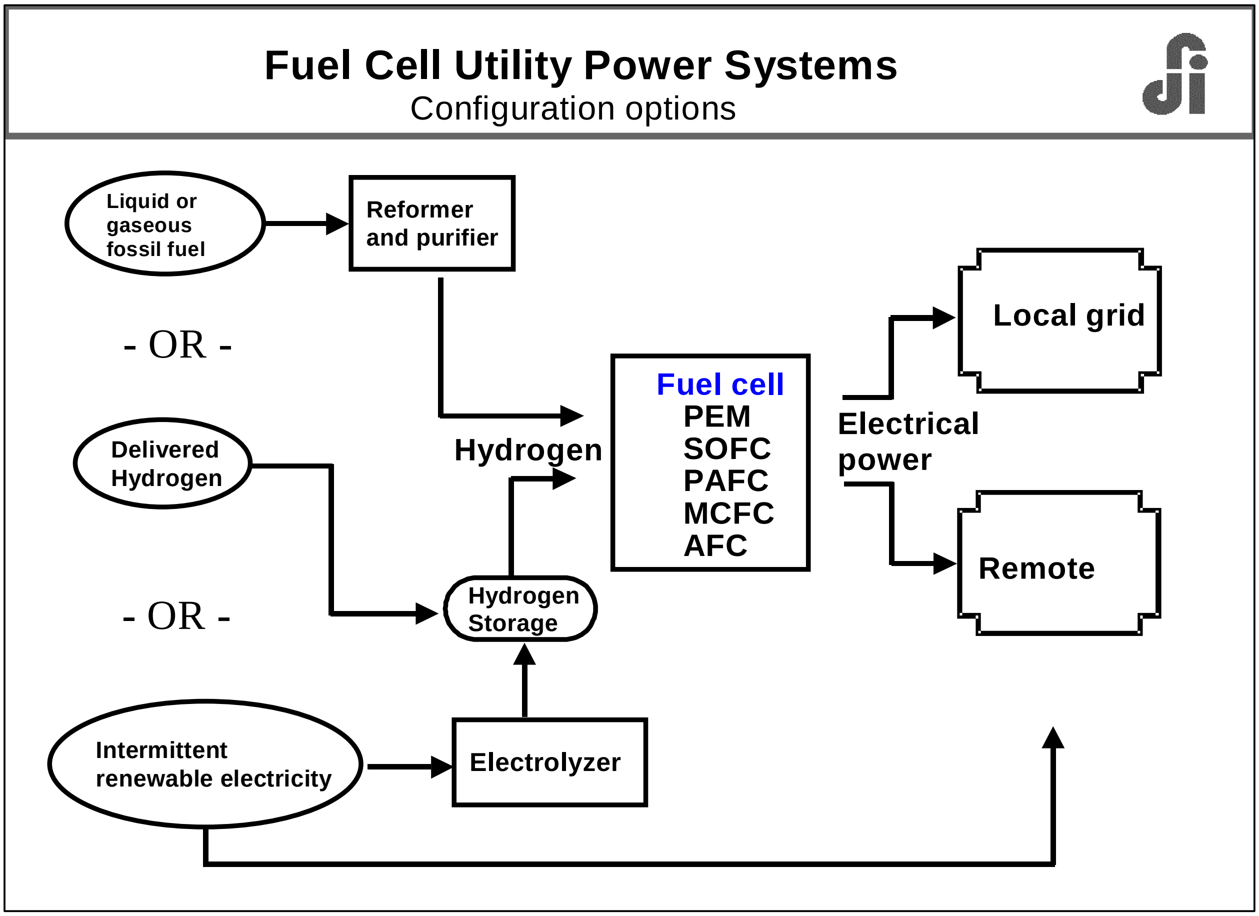

Figure 2. The possible configurations for fuel cell utility power systems, showing the source options for hydrogen. The five fuel cell options are: PEM (proton exchange membrane) SOFC (solid oxide fuel cell) PAFC (phosphoric acid fuel cell) MCFC (molten carbonate fuel cell) and AFC (alkaline fuel cell).

The products from this project will significantly benefit the U.S. industries that have carried the key technologies to the point of commercialization. The successful development of commercial, integrated power systems will expand the market for each component technology. This is particularly true for the fuel cell, solar, and wind power industries. New industries will evolve to supply renewable power systems to the one-third of the world that currently has no access to utility electricity. These industries will also increase the ability of wind and solar power to penetrate the central power grid market. A key objective of this project is to integrate the hydrogen energy storage system with stand-alone wind turbines in realistic, isolated situations independent of a power grid.

The industry, utility, and university team assembled by DRI is engaged in several parallel efforts to identify pathways for successful commercialization of these power systems. We are accomplishing this goal by employing a physical model of a complex system for the purpose of performing system analysis of potential design and control scenarios as well as systematically developing approaches to remove technical and economic barriers.

This project goes beyond the use of fuel cells, or internal combustion generator sets, and fossil fuels for power production in isolated utility applications. Instead, we are seeking to develop a system that provides for the long-term use of hydrogen as a storage buffer for utility energy. Systems integrated to do this are significantly more complex than the linear systems using reformed fossil fuel and fuel cells. This complexity creates a design and control challenge but also offers several coupled parameters for optimization of the design and control methods. Renewable systems with storage will provide on-demand power without the need for a fuel supply infrastructure, something that is very important in the isolated locations of the world.

This project was designed to be implemented in two phases. The purpose of Phase 1, which has been completed, was to identify some of the numerous system configurations, applications, and market approaches for renewable, hydrogen utility systems. Phase 2 involves completion of the system testing, design and control system method development, determination of codes and standards, and water management design necessary for successful installation of a utility system in Alaska. This phase of the work has yet to be undertaken.

Phase 1 Project Description

Phase 1 had three primary objectives:

1. To develop models that are specifically designed to optimize hydrogen storage systems for remote, renewable applications. The intent was to use the models to compare hydrogen systems with all other storage systems and to permit rational selection of the best system for a given application. The models were intended to be used to optimize the system design for a specific application, and once the system was designed, to optimize control to provide the most reliable and lowest cost electricity to the customer. Note that models have yet to be developed for optimization of design and control of a hydrogen system. DRI is developing these models and relating them to available models for similar systems.

2. To design, purchase, and construct a small-scale, complete hydrogen renewable energy system. The system was to be sized appropriately to realistically test out any design and control models and methods. The purpose was to enhance understanding of design, control, and interface issues.

3. To design and cost out a complete prototype system for a remote village in Alaska. Such a system would be finalized, purchased, and installed in the Phase 2 of this project.

Two additional objectives in Phase 1 were:

1. To identify and discuss any codes and standards appropriate to the deployment of integrated renewable hydrogen utility systems and provide recommendations that can aid in their commercialization. develop a business plan.

2. To develop a business plan indicating how this project would lead to the development, financing , operation and growth of a business that markets and deploys integrated renewable hydrogen utility systems.

Phase 1 Implementation

Economic Evaluation/Systems Analysis

We needed a robust, simulation software system for this analysis activity. To meet our objective, we had to be able to model the behavior of the individual components of a system as well as their complex interactions. The simulation platform software also had to be able to model electrolyzers, hydrogen storage, and fuel cells directly. With these as our criteria, we chose TRNSYS as the system simulation software platform on which to base our models.

Before selecting TRNSYS, we considered other similar software packages including HOMER, ViPOR, and HYBRID2. HOMER is designed to determine optimum system configurations, but it is not able to model the behavior of individual components of the system and their complex interactions. ViPOR is primarily focused on optimizing a grid layout. Although we concluded that HYBRID2 can approximate the operation of our renewable hydrogen system and examine the behavior of individual components over time, it currently models only wind, photovoltaic, diesel, and battery systems and is not capable of modeling electrolyzers, hydrogen storage, or fuel cells directly.

Economic modeling and analysis of system costs were accomplished by Stuart Energy and a summary of results are provided in Attachment 2. DRI established a model based on a first-order operating optimization where the power to the load can simultaneously come from the renewable and the fuel cell. This begins to reduce the renewable power requirement. Since, the electrolyzer is also sized to the renewable peak source, this reduction is important in lowering the capital cost of the full system. Improvements in the model, and in resulting physical systems, are expected in the second phase of this project.

The first-order model uses an electrolyzer with a peak power the same as the renewable resource:

$$P_E = P_R$$

When the renewable is available, as much renewable power as possible is directed to the load; and the excess is sent to storage, ranking batteries higher than electrolysis. The renewable capacity factor Cf_R defines the fraction of time that is possible. As a result, the total power required, then, to assure renewable power with a direct and storage route is a function of the average load power Pl_{AV}; the renewable capacity factor; and the conversion efficiencies for the electrolyzer, the fuel cell, and the compressor (η_E, η_F and η_C).

$$P_E = P_R = \frac{(1 - Cf_R)\, Pl_{AV}}{Cf_R\, \eta_E\, \eta_F\, \eta_C}$$

The above relationship is a part of the complex description of the combined design and control algorithms that are necessary to assure the best opportunity for deployment of renewable hydrogen utility power systems. The development of this complex modeling capability will also support the intelligent systems necessary for more general integrated and distributed power systems. Figure 3 shows a partial set of interrelationships that are necessary to optimize the design of an integrated, remote, hydrogen power system. The system interrelationships necessary to optimize the control system that will be used to operate an integrated hydrogen power system can be described in a similar way.

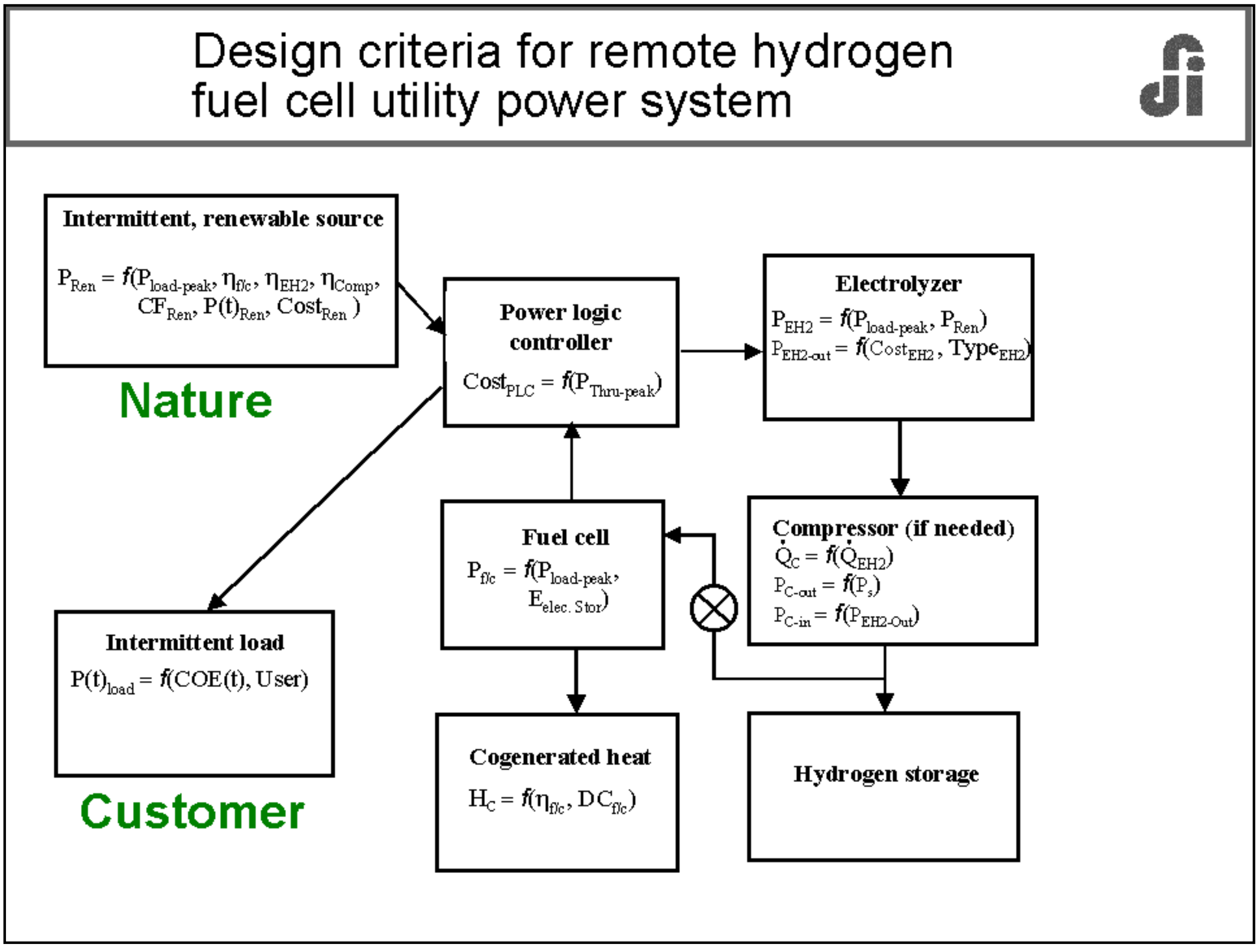

Figure 3. A sample of the relationships necessary for optimization of the design of a renewable, hydrogen power system.

One important modeling improvement that will be made in Phase 2 is the addition of mesoscale climate modeling and data analysis. The addition of the information provided by mesoscale modeling can assure a given confidence integral for expected wind availability for some forecasted period of time. The confidence integral-projection time relationship is site dependent and, once known, can be employed to reduce both the system capital cost and the operating cost.

Examples of economic and systems analysis for potential installations in Alaska are included in this report (Figure 8). These analyses indicate that the concept of hydrogen storage can be economically viable and is technically feasible. Early trade studies have shown that the system cost can be reduced with the addition of standby fuel or power. This can be a separate diesel generator, or fuel supply and reformer connected to the existing system fuel cell. Operation of the standby power is not necessary; but, as an option, it softens the engineering constraints on the full system.

We have evaluated the component cost range for the return power components within a hydrogen system specifically designed for an application in Alaska (powering the local radio transmitter). The load would vary from 13.5 to 20 kW. The hydrogen-fueled power sources evaluated included PEM fuel cells, alkaline fuel cells, and internal combustion (ICE) generator sets. We received cost estimates for each technology, and the costs ranged from $60,000 to $600,000. The lowest cost was represented by an alkaline and PEM fuel cell option. The ICE was approximately $120,000 for a first developed prototype, and a first developed prototype PEM fuel cell was the highest at $600,000.

Small-Scale, Complete Hydrogen Renewable Energy System

To test our models and others, such as HYBRID2 and HOMER, we have designed, purchased, and installed a complete, small-scale, renewable, hydrogen, fuel cell power system. This effort was accomplished using funds appropriated by the Nevada Legislature in a program (Applied Research Initiative) designed to encourage economic development in the state. The system includes the following:

- two 1.5 kW wind turbines
- 2 kW of solar PV on trackers
- a 2 kW PEM fuel cell stack
- a 5 kW unipolar electrolyzer
- a hydrogen storage tank and compressor
- a 5 kW computer-programmable load, a data acquisition system,
- a computer-based control system with analysis software

Because the output of the system is sufficient to power the average home, this system is classified as a residential-scale, renewable hydrogen fuel cell utility system (RRHFUS). The system configuration is shown in Figure 4.

All of the components for the RRHFUS were purchased in early FY 99. The wind turbines were installed on 80-foot tall towers in June 1999 and are operational. The rest of the system was completed in October 1999. The wind turbines have anemometers associated with them, and the solar panels will have pyrenometers so that the system performance can be related to the actual input of solar and wind power.

This system also permits the interchange of individual components, allowing performance analysis and comparison of these components in a system environment, critical for future system designs. The intent is not to validate product performance of specific vendors as much as it is to identify which components are best for specific applications, recognizing that the breath of applications covers the specifications of all vendor products.

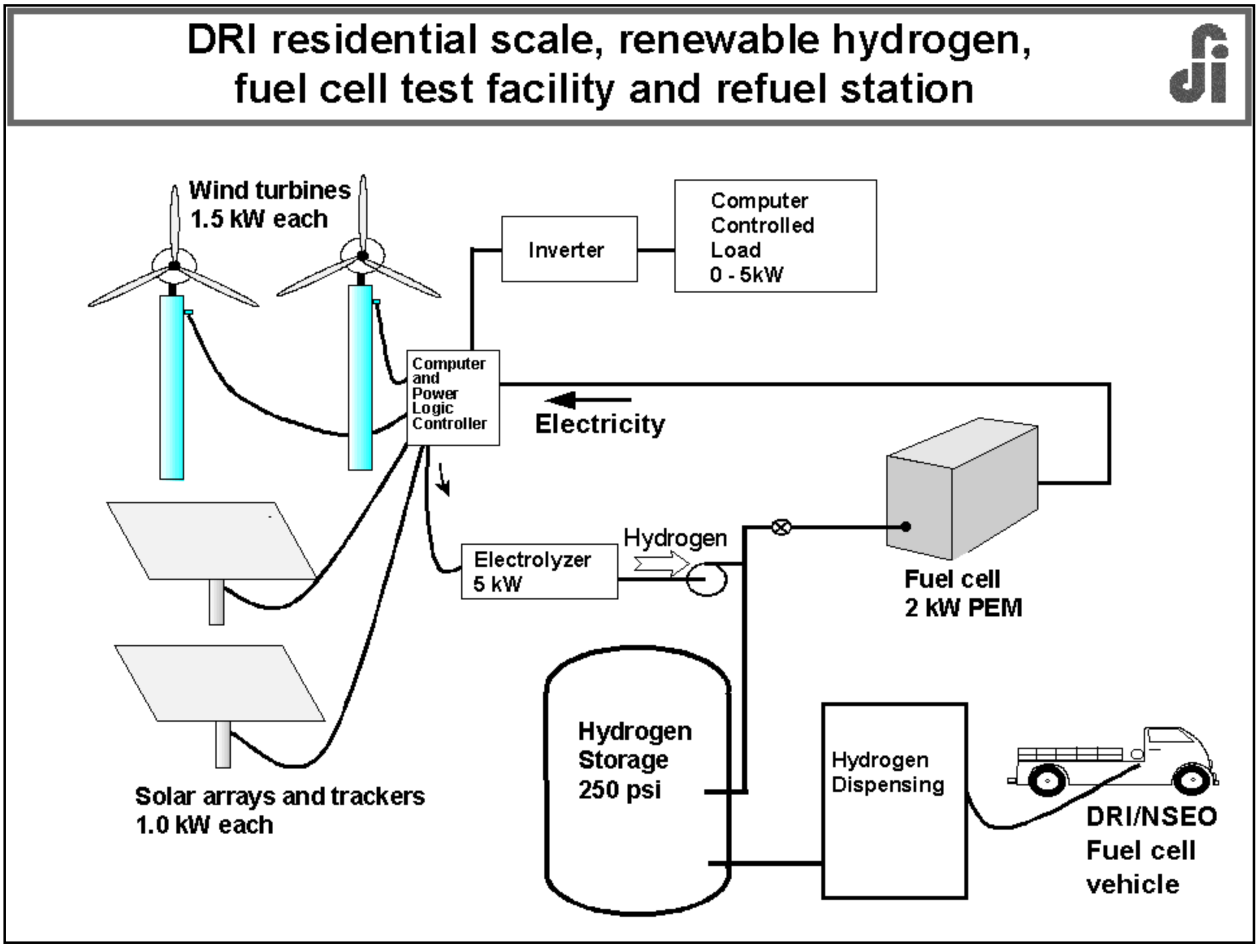

Figure 4. Schematic showing completed test facility and refueling station at DRI's Northern Nevada Science Center.

Separate, high-current power lines from each of the two solar arrays and each of the two wind turbines run into the laboratory so that any combination of wind or solar renewable resource can be connected to the power control system. All of the renewable power input, the power to the electrolyzer, the power from the fuel cell, and the power to the inverter and load are connected in common to a 24 VDC bus bar. The configuration for this is shown in Figure 5, with photographs of the primary components.

The following is a detailed description of the system and each primary component:

System Design Concept: The system is designed around a DC bus bar. The bus bar allows electricity to come from multiple sources and go to multiple sinks all from one point (or electrical "node"). Electricity produced by the solar photovoltaic panels and wind turbines flows to the bus bar. A continuously variable, resistive electric load draws electricity off the bus bar. If the amount of power being produced by the renewables is greater than the amount being drawn by the load, then the computer control system turns on the electrolyzer. The electrolyzer draws electricity from the bus bar and uses the power to electrolyze water into hydrogen and oxygen. The oxygen is vented to the atmosphere, while the hydrogen is compressed to 125 psi and stored in a tank. If the amount of power being produced by the renewables is less than the amount being drawn by the load, then the computer control system turns off the electrolyzer and turns on the fuel cell stack. Hydrogen flows from the storage tank to the fuel cell stack, producing electricity. That electricity goes to the bus bar and then to the load. A small set of batteries is connected directly to the bus bar to help regulate the bus bar's voltage and to provide "peak power" during the brief periods when the load draws more power than the fuel cell can produce. With this system design, the load is always supplied with renewable electricity.

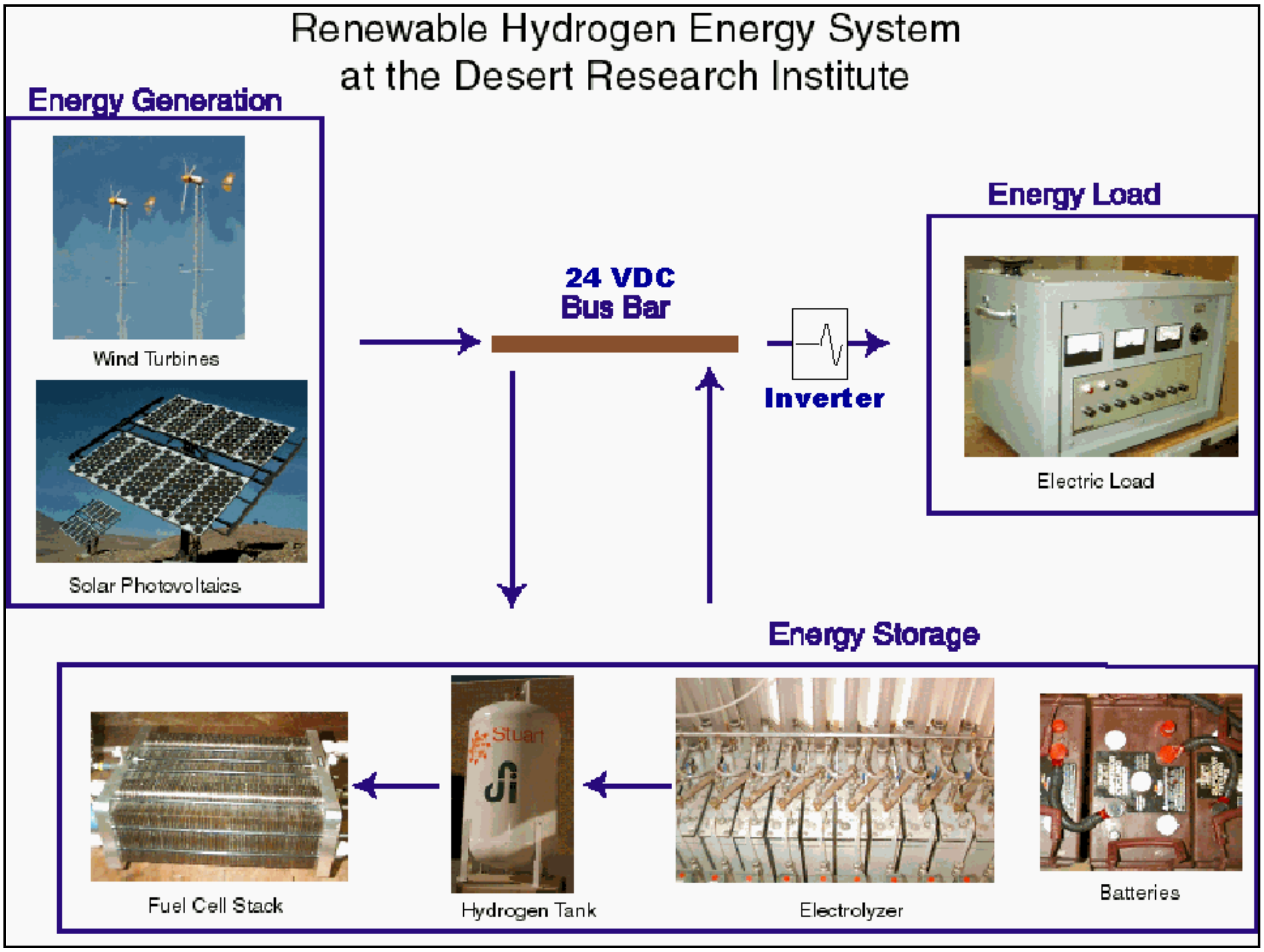

Figure 5. Interrelationships of primary components in RRHFUS

Wind Turbines: Two Bergey Wind Corporation BWC1500 wind turbines produce a total of 3,000 watts of electricity in full wind. Each turbine is mounted on an 80-foot tall Rohn 25G lattice tower. The turbines produce unregulated AC electricity, which is conditioned and regulated by a rectifier before it is sent to the DC bus bar.

Solar Photovoltaic Panels: Two arrays of PV panels produce a total of 2,000 watts of electricity in full sun. Each array consists of ten Siemens SR-100 single crystal modules mounted on a Zomeworks passive tracker. The trackers use refrigerant in tubing to track the sun throughout the day, allowing the PV panels to receive more insolation than if they were fixed on the ground, but with a simpler mechanism than a computerized, motor-driven tracking system. A battery charger regulates the electricity from the PV panels before it goes to the bus bar.

Load Simulator: The load simulator is a Simplex Swift-E test load bank. The simulator can draw a maximum of 5,000 watts of AC electricity and is meant to simulate a house. The load bank contains six resistors that draw different amounts of power when switched on. The resistors are controlled by solid state relay switches, which are in turn activated by the system's control computer. In this way, the test load can be used to simulate the varying amounts of electricity drawn over time by a real load, such as a house. Between the bus bar and the load is an inverter, which converts the 24VDC electricity from the system into 120VAC electricity for the load.

Electrolyzer: The electrolyzer is a Stuart Energy SunFuel 5000. It can draw a maximum of 5,000 watts of power and uses that power to produce up to one normal cubic meter of hydrogen per hour. It produces the hydrogen in 13 potassium hydroxide (KOH) cells. The cells with their "balance of plant" (e.g., water seal, compressors, pumps, plumbing, etc.) are housed in a modified ISO shipping container, similar to those transported on 18-wheel trucks. The electrolyzer's operations are controlled by its own "programmable logic controller," or PLC built in by the manufacturer.

Fuel Cell Stack: The system uses an Analytic Power FC-3000 proton exchange membrane (PEM) fuel cell stack. It has 64 cells and can produce approximately 2,000 watts at full power. The stack requires "balance of plant" equipment to operate including a coolant pump, heat exchanger, fan, and an air compressor.

Batteries: Four Trojan L-16 deep cycle batteries are used for peak power.

Data Acquisition and Control Computer: National Instruments' LabVIEW software runs on a personal computer to collect data from the system and control the fuel cell stack and electrolyzer. The computer is ruggedized to allow it to be uses in cold climates. National Instruments' FieldPoint hardware is used to process the incoming and outgoing signals.

Simulation Software: All the system simulation work will be accomplished using TRNSYS 14.1. This software was developed by the University of Wisconsin and is used worldwide for simulation of energy systems.

Prototype System for a Remote Village in Alaska

The concept of a remote hydrogen renewable power system in Alaska originated with DRI faculty in 1993. Motivation for installation and use of such a system in Alaska includes the following:

- Alaska has about 200 separate utilities, 95% of which use delivered diesel fuel.
- Power costs outside the large Alaskan cities is \$.25–\$1.00/kWh.
- Federally mandated cleanup of diesel fuel sites is estimated to cost more than \$700 million.

- The components necessary for an integrated renewable hydrogen power system are available and financially viable for use in remote applications.
- Rural Alaska exhibits important characteristics common to a large fraction of the world where natural energy sources and local economics favor remote, renewable power.

DRI, in conjunction with the Kotzebue Electric Association (KEA), has begun exploring the opportunity to install a renewable hydrogen power system for practical use in Kotzebue, Alaska. Working with the KEA, we have developed a plan for the installation of this first system in conjunction with an already operating wind turbine array. KEA has led the world in demonstrating viable, renewable energy options for remote regions by installing ten 65 kW wind turbines and displacing a significant quantity of more costly and polluting diesel fuel. Currently, diesel generators are still required to provide power when the wind turbines are not operating. DRI and KEA have agreed in principle to install a hydrogen energy storage system in conjunction with the wind turbines. This will power a load in Kotzebue, independent of the diesel generators and regardless of the wind.

Kotzebue exhibits the characteristics of numerous remote communities worldwide where integrated renewable energy systems have yet to be deployed. First is the existence of an operating and abundant renewable wind source. Second is the presence of a well-trained workforce as well as physical plant and operating resources within KEA. Another important consideration is that the Village of Kotzebue has at least one commercial load whose management has agreed to isolate the load from the local grid to test the system under real conditions.

A team of representatives from DRI and DCH Technology met with the KEA, local permitting authorities, and other Alaska entities in June 1998. A complete discussion of that visit is included in the September 21, 1998 Status Report included as an attachment to this report. We developed a plan to integrate a 20 kW hydrogen power system with the output of three 65 kW wind turbines and a local utility load. Initial options and specific designs have been completed and are described in Figures 6 and 7, which show two of several different system designs for remote Alaska.

Additionally, we considered two other villages (Kivalina and Wales) which are also serviced by KEA. Both have greater wind capacity than the Village of Kotzebue. Discussion on the issues associated with these two villages is in the attached September 21 report.

In the first Kotzebue example (Figure 6), the complete hydrogen storage power system is geographically located at the wind turbine site, approximately three miles from the village. Adjacent to the wind turbines is the transmitter for the local commercial radio station KOTZ, which has a power requirement of approximately 14 kW. In this system, a 20 kW fuel cell is used to power the transmitter and heaters used periodically to maintain temperature within the transmitter shack. The electrolyzer will draw power from the equivalent of three wind turbines, proportional to the wind turbine output at any time. This design is a self-contained, remote, renewable power system using hydrogen storage supplying a variable utility load.

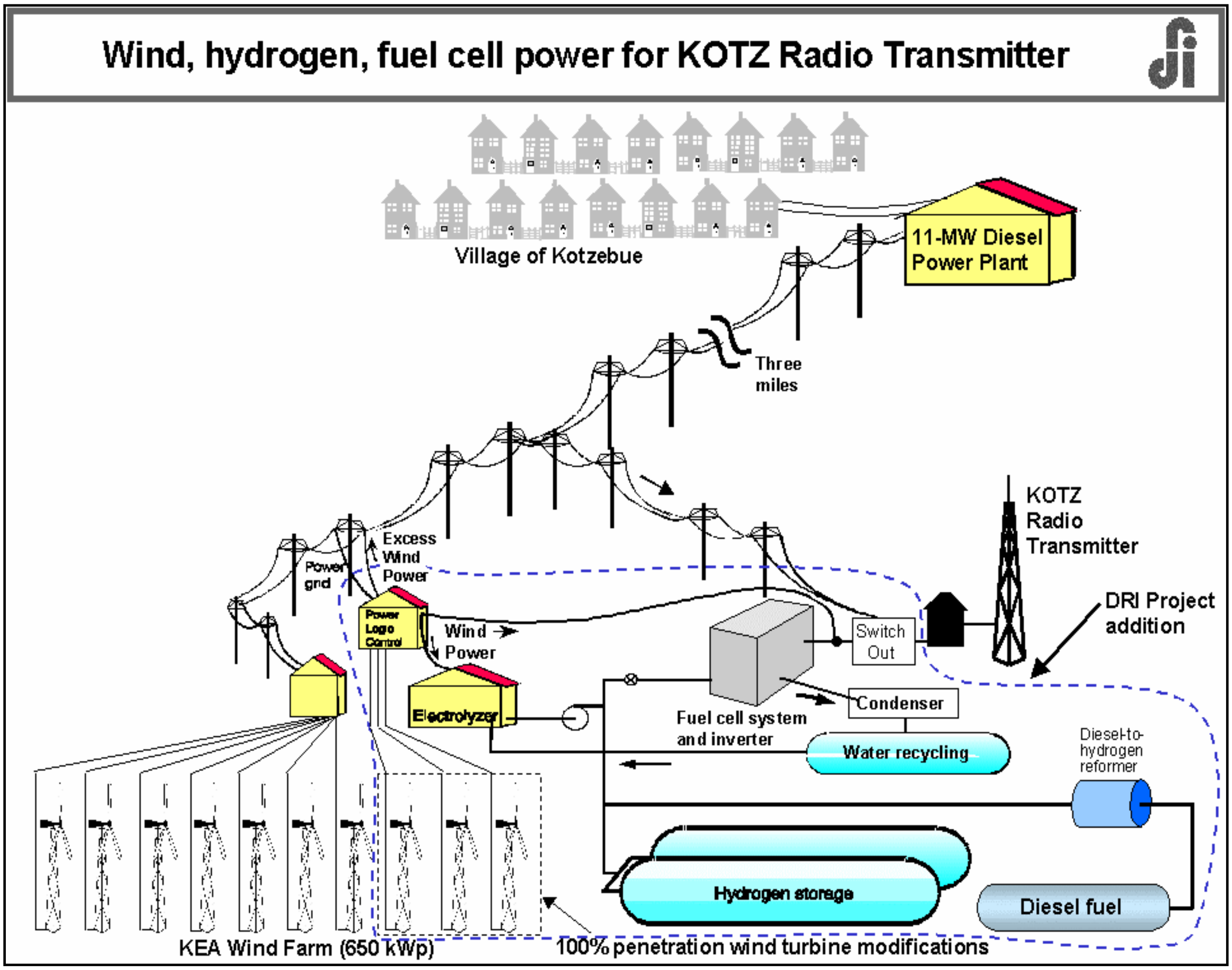

Figure 6. Wind-hydrogen scenario for powering KOTZ radio transmitter.

The second example (Figure 7) has the hydrogen production and storage located at the wind turbine site while one to four fuel cells are located in the village powering independent loads. A small, low-pressure gas line would carry the hydrogen from the storage site to the fuel cell in the village. This system uses the lower incremental infrastructure cost of a hydrogen gas line to transmit power from its production location to its point of use.

In both examples, the option of modifying the wind turbines is being considered. Most wind turbines today are designed to be grid-connected using synchronous generators that require external excitation power to provide the field for power production and the signal for frequency synchronization. Wind turbines with permanent magnets that permit grid-independent operation are available, but they are limited in size to a few kilowatts. The modification option for turbines with synchronous generators currently requires the addition of a synchronous condenser (basically a rotating generator) to provide the excitation during start up. These can derive their rotation power from a separate wind power shaft or from a fossil-powered generator. For high power wind turbines to become truly grid-independent in a large marketplace, some alternative excitation scheme is necessary.

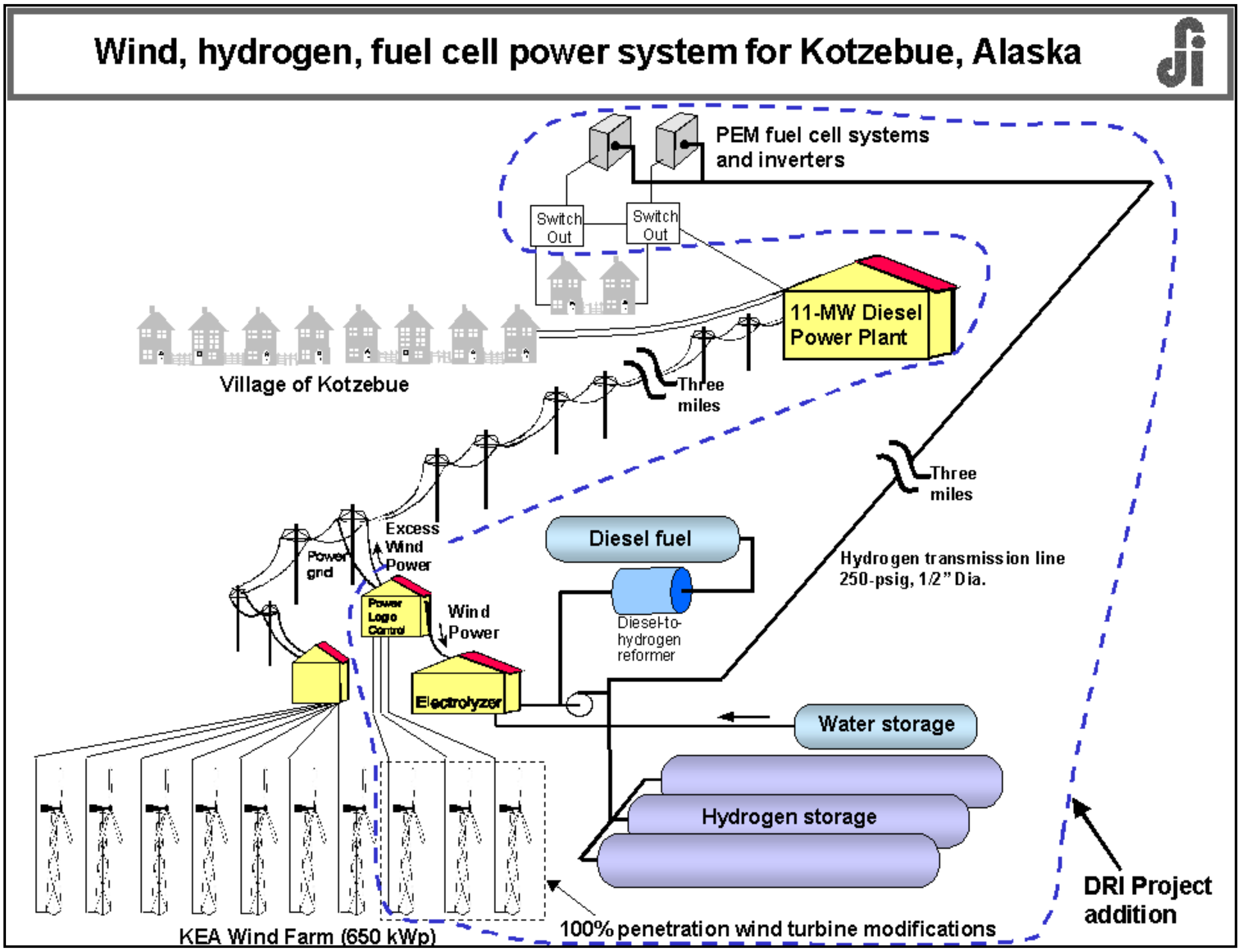

Figure 7. Wind-hydrogen scenario for piping hydrogen into Kotzebue Village for powering independent loads with fuel cells

The use of a fossil fuel storage system, such as propane, and a reformer to soften the design requirements on the system is shown in both figures 6 and 7. The use of fossil fuel back-up may not need to be employed in either of these two examples however. Instead, in the KEA prototype systems, the use of a switchover to the main village diesel power grid can simulate the use of a standby fuel reservoir and a reformer attached to the fuel cell.

Costing of System Options in Kotzebue

Cost estimates for the installation of the system configuration for powering the KOTZ radio transmitter were obtained using a model that does a first-order optimizing of the renewable resource power and electrolyzer power required based on the system efficiencies. The operation that provides parallel power delivery to the load and the electrolyzer was considered to reduce the peak power requirements. The model provided the system capital, installation, and permitting costs.

Three other examples of capital and installation costs (Kivalina Village, St. George Island and Kotzebue Village) were considered to show the effects of economy of scale and situational opportunities, such as renewable capacity factors.

Sixty miles north of Kotzebue on a barrier island is the Village of Kivalina, Alaska. Kivalina has a 125 kW average load and is currently powered by diesel generators. Recently, Kivalina residents elected to move the entire village and power system several miles to the mainland. An early estimate of the cost for this move is $50,000,000. Kivalina is in a very good wind regime, so we looked at the possible cost of a completely autonomous, non-fossil power system for the village. Since there are no pre-existing wind turbines in this case, we included the cost of a wind turbine array in the model. This estimate shows that the entire town can be powered with wind energy and a hydrogen fuel cell with the system cost that adds approximately 10% to the cost of the move of the village.

Three hundred miles north of the Aleutian Islands are the two Pribilof Islands of St. Paul and St. George. Several years ago, we studied the possibility of deploying a wind-hydrogen power system to that community. The Village leaders and the local Aleut Corporation were supportive of the concept. The wind capacity factor there is well in excess of .35 and there are several local advantages to the addition of new and independent power. The community load averages 125 kW with a 195 kW peak.

The Village of Kotzebue has a population of approximately 3200, and has an average power consumption of 3,300 kW. The utility (KEA) has 11,000 kW of installed diesel generating capacity with a 4,200,000 gallon diesel fuel supply in the village. KEA recently installed ten 65 kW Atlantic Orient wind turbines in an area approximately three miles from the village. Power from the turbines is sent to the village on a 7000-volt transmission line and interconnected to the grid.

Model simulations were run for the four examples in three different time frames: today, the near-term (approximately 5 years out), and the far-term (approximately 10 years out). The expected capital costs of the major components were used in the out-year examples. These cost projections are based on statements from the electrolysis and fuel cell industries, and we believe the projections are reasonable. The results are plotted in Figure 8. The tabular information is shown in detail in Attachment 1, with key parameters highlighted in gray. For the example of the KOTZ radio transmitter, Table A1-1 includes two examples of the amount of energy storage. The data shows that increasing the energy storage by 200% only increased the installation and capital cost by 41%. This is a major advantage of hydrogen storage over battery energy storage for time periods greater than a few days, because with hydrogen the energy storage can be optimized separately from the power delivery.

Two significant variants, illustrated in Table A1, are the cost of the fuel cell and the amount of hydrogen storage capacity. For a 20 kW fuel cell stack,, meeting predetermined performance standards, we have found that the price varies from $60,000 to $600,000 depending on the manufacturer. The large variation in fuel cell cost is an indicator of the youth of the industry, leading to the conclusion that near-term reductions will permit integrated hydrogen systems to be competitive. The 20 kW fuel cell cost chosen for the KOTZ transmitter scenario in today’s time frame was $180,000.

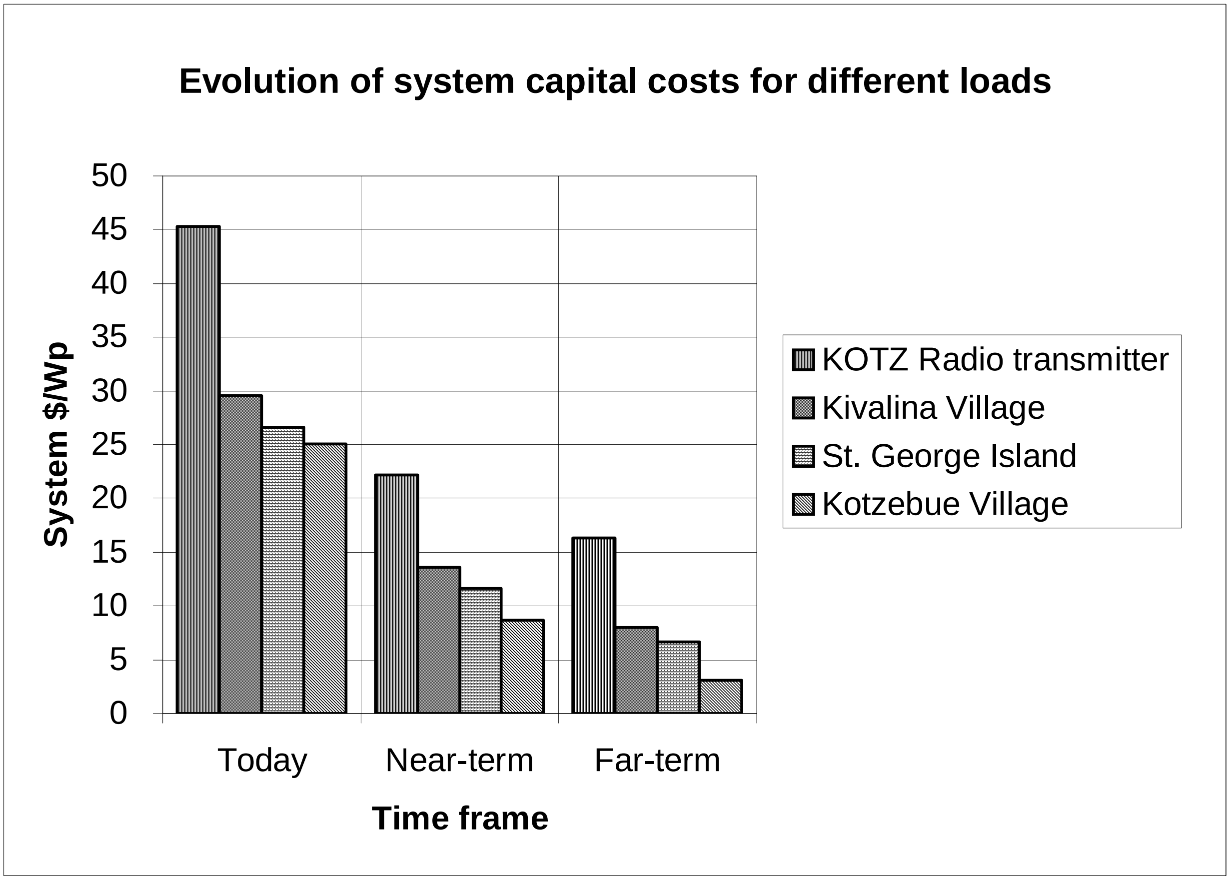

Figure 8. Model results for system capital cost scenarios at four possible locations. Each scenario was run for three different time periods to show the effects of expected cost reductions on the market possibilities for renewable hydrogen power systems. In all the examples other than the KOTZ radio transmitter, the model included the cost of renewable power production (wind energy in these examples).

In all the examples, (except for the Kotzebue radio transmitter) the installed capital cost projections for the near-term (less than $15/W) and far-term (less than $10/W) look favorable for isolated locations. One comparative example is a new diamond mine in Northern Canada that recently installed a 25,000 kW diesel power plant at approximately $25/W.

It is expected that several factors will influence a reduction in the installed costs. Refinements in the integrated hydrogen system designs and the control methods are expected to play a major role in that cost reduction. Those refinements will be facilitated as more model improvements occur and as the operation of the RRHFUS physical system model shows the behavior of realistic, integrated systems.

Participation of Team Partners

The project team is made up university, industry, utility, and government participants. The partners, their capabilities, and the nature of their participation are described below.

DCH Technology (DCH)
DCH is a leader in advanced hydrogen sensors and safety system engineering. DCH has recently acquired rights to manufacture a PEM fuel cell design from Los Alamos National Laboratory (LANL). The new performance characteristics of this PEM stack are specifically beneficial to remote and arctic applications. DCH's contributions will include:

- Hydrogen sensor and safety systems
- Hydrogen safety engineering
- Hydrogen codes and standards development
- Adiabatic, 5 kW PEM fuel cell stack(s) licensed from LASL - with proprietary design features favorable for remote power systems
- Hydrogen safety training

Nevada State Energy Office (NSEO)
NSEO has been a major supporter of renewable, hydrogen, and fuel cell development in Nevada. The office is providing additional funding support for this project and isalso experienced in the identification of market niche applications for distributed and remote power (Nevada currently has approximately 10,000 remote (non-grid) utility customers). NSEO has recently begun supporting DRI in project management related to advanced utility and transportation energy issues. Their contributions will include:

- Project management support
- Energy system site analysis - western U.S.
- Hydrogen energy system codes and standards development

Los Alamos National Laboratory (LANL)
LANL and DRI have been working together identifying applications for distributed power and isolated, renewable power systems for the western U.S. LANL is currently working with several near-term developers of remote neighborhood, reservation, and community power systems in New Mexico. We have met on several occasions with interested business and financial parties to understand the potential for hydrogen storage in the desert Southwest. LANL is also a major developer of PEM fuel cell technologies. Their adiabatic stack is a prime candidate for remote applications. Their contributions will include:

- Definition of reasonable, early sites for renewable, hydrogen utility systems in New Mexico and the desert Southwest.
- Design and development for a site in the Southwest.
- Strategic planning for distributed power systems worldwide
- Fuel cell system support

Stuart Energy Systems, Ltd. (SES)
Stuart has been a manufacturer of unipolar, potassium hydroxide electrolyzers for several decades. The company is currently developing a new design with acquisition costs low enough for use in utility power systems. Stuart was also the first U.S. electrolyzer company to

participate in the development of renewable, hydrogen utility systems for Alaska and remote locations. Company engineers began developing a model for remote, renewable, hydrogen, fuel cell systems in 1993 in support of our first approach to deploying such systems in remote Alaska. Stuart's contributions will include:

- Assisting in model development and running model alternatives
- Providing an electrolyzer for KEA with the same performance as the electrolyzer at DRI.
- Supporting of codes and standards development
- Developing of integration scenarios

Proton Energy Systems (PES)

PES is a developer of solid polymer electrolyzers and unitized regenerative fuel cells (URFC). The URFC is a single electrochemical component with potential for reasonable reversibility permitting both electrolysis of water and power production from hydrogen. PES's contributions will include:

- Providing a URFC to the DRI Reno facility to compare performance with conventional electrolyzers and fuel cells
- Providing a solid polymer electrolyzer for DRI's system to compare its performance to KOH electrolysis
- Offering a candidate electrolyzer for KEA system.

Kotzebue Electric Association (KEA)

KEA is a world leader in the use of wind power in small utility applications. The Association has a 3MW village load and currently have 0.65MW of wind power installed, with plans for an additional 1MW. KEA is a remote Alaska utility with a workforce capable of operating and maintaining a complex utility system with energy storage, something critical to the success of new systems such as the one planned in this project. KEA's contributions will include:

- Arctic engineering for the KEA system
- System engineering support
- Logistics support for system implementation in Kotzebue
- Provision of protective shelters for equipment
- Providing lodging for team members while in Kotzebue

Northern Power Systems (NPS)

NPS is a contractor to KEA and has extensive experience in designing, building, and deploying isolated power systems. The company is a wind turbine manufacturer with a product for small and isolated power markets. Company engineers have designed modifications of grid-connected wind turbines to permit grid-independent operation. NPS's contributions will include:

- Design of modifications for grid-independent operation of AOC 15/50 wind turbines.
- Power system integration
- Installation of grid independent modifications in KEA system

Northwest Power Systems (NWPS)

Northwest Power Systems is a developer of fossil fuel reformers capable of providing hydrogen for fuel cells with very low CO concentrations. This is the result of employing their palladium-silver membranes as hydrogen separators in the output stage. The presence of a diesel supply and adequate reformer reduces the cost of the rest of the renewable hydrogen system and still permits it to be a renewable system. The company's contributions will include:

- Providing a 10 kW reformer as a hydrogen supply backup.
- Training in system operation and maintenance

NRG Technology

NRG is an energy system development company with experience in hydrogen engines. The company has completed a design for a high efficiency, hydrogen-specific ICE genset. NRG will provide a candidate hydrogen-specific ICE genset to operate in the same capacity as a fuel cell in the DRI Reno system or in the Alaska system, if selected

University of Nevada, Reno (UNR)

The Mechanical Engineering Department of UNR will provide engineering support for the thermal integration of renewable systems employing hydrogen production and power production from hydrogen. This support will be extended to the KEA system design. The Department will also provide engineering support for closed loop water management systems for hydrogen electrochemical systems.

Bergey WindPower Company (BWC)

BWC is a manufacturer of small wind turbines with thousands of turbines deployed worldwide. Their BWC-1500 turbines are used in the DRI test facility and are designed to be grid independent or intertied. The grid independence is important to future remote hydrogen installations. BWC will provide a 10 kW turbine for use in the wind profiler.

Codes and Standards:

Given the innovative nature of renewable hydrogen energy systems, it is not surprising that codes and standards for these systems are in a formative stage of development. The leading authority for development of these standards is the Organization for International Standardization under ISO TC197. As it stands today, project approval agencies considering a hydrogen energy project proposal would refer to the different component-specific codes which exist for industrial hydrogen applications and to the natural gas energy applications which form the precedent base for hydrogen energy standards currently under development. The relevant codes for reviewing the major components of the system proposed for Kotzebue are as follows:

Wind Turbines: The wind turbines would be constructed according to applicable building codes and would be designed for the applicable wind loading and temperature range. Underwriter's Laboratory (U/L) is developing a certification procedure for stand-alone inverter grid interconnect protection. The Society of International Electrical and Electronic Engineers is developing distributed power systems grid interconnect standards – IEEE SC 21.

Electrolyzer: Although no electrolyzer-specific codes exist, the electrolyzer would be built according to well-established hydrogen plant design principles. Electrolytic hydrogen plants have a "100 plus year" history of industrial operation. Stuart Energy, through its parent company, The Electrolyzer Corporation, has been supplying industrial hydrogen plants for more than 50 years.

In general, considering the design of an electrolysis plant, the interior of the plant is a Class 1 Div 2 Group B area for purposes of electrical classification and occupancy. For smaller plants, a certified hydrogen gas detection area sensor coupled to a continuous ventilation system of adequate capacity (at least five air changes per hour) could be installed to allow the occupancy to be de-rated to normal occupancy according to provisions in the National Electrical Code (NEC). Piping would comply with ANSI/ASME B31.3. Components, including valves are certified to meet or exceed working pressures in the system. The hydrogen produced should meet the purity specified in ISO/TC 197 "Hydrogen Fuel-Product Specification." Hydrogen vents from pressure relief devices would have to be directed outdoors in compliance with NFPA 50 A.

In the long run, electrolyzers may become standard energy appliances; and development of product specific standards for manufacturing may evolve, whereby the electrolyzer will obtain product class approval by U/L or Factory Mutual (F/M).

Storage: The storage would be sited according to NFPA 50 A. The vessels themselves would be certified for the range of working pressures and temperatures and constructed according to the ASME Boiler and Pressure Vessel Code Section VIII. Following convention and given the remoteness of the site, a flame sensor would be used to detect if a fire is present.

General Piping: General piping would comply with ANSI/ASME: B31.3 Process piping standards, B31.8 Gas Transmission and Distribution Piping Systems, and B31.2 Fuel Gas Piping. A key issue to approval will be detection of leaks. In the case of residential piping for natural gas, an odorant is injected into the gas. As yet, no odorants have been identified for hydrogen as sulfur-based compounds used in natural gas (such as Mercaptans) are incompatible with PEM fuel cells. Electronic area detectors for hydrogen have been approved on a project-by-project basis. Generally speaking, detectors need to be certified for the application by a certification agency such as Underwriters Laboratories (U/L) or Factory Mutual (F/M).

Fuel Cell: Fuel cell codes and standards are under development including International Electrical Code (IEC 105) and domestically under the International Electrical and Electronic Engineers (IEEE SC21). The operation of the natural-gas-fueled ONSI Phosphoric Acid Fuel Cell provides a precedent for hydrogen fuel cells. One of the key issues in operating hydrogen fuel cells will be leak detection as indicated in the General Piping section. As with small electrolyzers, it seems likely that a product class certification will evolve for these systems.

Phase 2 System: The project at Kotzebue—as one of the first systems incorporating wind, electrolysis, compressed gas storage, and fuel cells in an arctic climate—will be an important precedent for acceptance of future systems. As part of design acceptance by the customer, the safety of the project will likely be considered through a structured safety design review process such as a system HAZOPS. Phase 2 of this project will involve a safety review as well as a review of codes to ensure adequate protection at reasonable cost in order to expedite approval of future projects of this type.

Conclusions

Existing models for analysis of remote power systems were studied, and the modeling package TRNSYS was purchased. It is being modified for use with remote, hydrogen, fuel cell power systems. Other first-order modeling has shown a reduction of approximately 30% for renewable and electrolysis power when the control system permits simultaneous direction of power to storage and the load, as opposed to all the power being routed through storage. The peak power from the renewable and the peak power to the electrolyzer are the same. The peak power from the fuel cell or ICE generator is the same as the load peak.

An important refinement will result from the addition of mesoscale climate modeling, providing a known confidence integral for wind or cloud forecasting and softening the system engineering requirements. The system engineering requirements can also be softened and costs reduced by the addition of standby fuel or power. This can be a separate diesel generator, or fuel supply and reformer connected to the system fuel cell. Operation of the standby power is not necessary; but, as an option, it softens the engineering constraints on the full system.

A complete residential-scale, hydrogen, fuel cell system (RRHFUS) has been purchased and is currently operating at the DRI Northern Nevada Science Center location in Reno, Nevada. This system will be used to test models and control systems for future isolated renewable power systems. The system provides a unique opportunity for a wide range of experiments in integrated, renewable power system operation and can test system designs as well as individual component performances. The data from RRHFUS will help in designing and operating future distributed power systems.

Early system designs and cost estimates show that it is reasonable to consider hydrogen and fuel cell or internal combustion power systems for remote communities in Alaska and elsewhere. There is a significant economy of scale in installing larger systems and the expected cost reductions over the next decade will make renewable hydrogen systems competitive in many markets worldwide. Today there are competitive opportunities for renewable hydrogen systems of a scale greater than 125 kW in remote locations with wind capacity factors greater than 0.30.

Modeling of renewable hydrogen systems has shown that they technically can be accomplished and that they are economically viable under certain circumstances today and that viability should expand rapidly as the component technologies come down in cost. The synergies among the independent evolution of the component technologies are evident in the expected growth in the marketplace for the systems developed under this project.

DRI has begun exploring the opportunity to install a renewable hydrogen power system for practical use in Kotzebue, Alaska. This effort has been in conjunction with the Kotzebue Electric Association (KEA). A plan has been developed for the installation of a prototype system in conjunction with an already operating wind turbine array. In meeting with the Kotzebue Electric Association and local permitting authorities, the possibility of local barriers to building a system in the village was minimized. KEA also helped in identifying a willing customer for the power from a hydrogen power system, while agreeing to disconnect them from the local diesel-powered grid.

The initial capital cost for the proposed site is high because of the small average load of 16 kW. Four different sites were considered, two at 125 kW, one at 3300 kW and the 16 kW system at the radio transmitter.

In the long term, new methods of wind turbine excitation are going to be needed to permit turbines to operate independent from a power grid. This will help in increasing the market for wind turbines as well as total wind remote power systems

Acknowledgements

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Attachment 1. Tables for expected system capital cost scenarios for Alaska

Table A1- 1. Kotzebue KOTZ radio transmitter 16 kW average load

Kotzebue Alaska Renewable Hydrogen Power System for KOTZ radio transmitter				
	Today low storage	Mid-term	Far-term	Today high storage
Load average power (kW)	16	16	16	16
Load peak power (kW)	20	20	20	20
Fuel cell stack peak power (kW)	20	20	20	20
Fuel cell stack cost per kWp	6,000	500	100	6,000
Renewable capacity factor	0.35	0.35	0.35	0.35
Fuel cell average efficiency	0.40	0.45	0.58	0.40
Electrolyzer system average efficiency	0.69	0.71	0.75	0.69
Peak power renewable required (kW)	108	93	68	108
Electrolyzer peak power (kW)	108	93	68	108
Electrolyzer system cost per kW	2,500	750	250	2,500
Electrolyzer system cost	269,151	69,752	17,077	269,151
Fuel cell BOP cost per kW	1,000	200	100	1,000
Fuel cell cost	120,000	10,000	2,000	120,000
Fuel cell BOP cost	20,000	4,000	2,000	20,000
Storage tank volume (gal)	60,000	60,000	60,000	60,000
Storage tank quantity	3	3	3	9
Total storage volume (gal)	180,000	180,000	180,000	540,000
Single storage tank cost	52,100	35,000	20,000	52,100
Fittings	2,350	1,600	2,350	2,350
Saddles	2,150	1,500	2,150	2,150
Total storage tank cost	169,800	114,300	73,500	509,400
Controller and DAQ	15,000	10,000	8,000	15,000
Power electronics cost/kWp to load	700	500	300	700
Power electronics total cost	14,000	10,000	6,000	14,000
Compressor	10,000	7,000	5,000	10,000
Shipping elecytrolyzer	2,000	2,000	1,500	2,000
Shipping storage tanks	4,500	4,500	4,500	13,500
Shipping fuel cell	3,800	3,800	3,800	3,800
Shipping compressor	600	600	600	600
Site preparation	75,000	75,000	75,000	75,000
Fuel cell, electrolyzer housing	8,000	8,000	8,000	8,000
Water processing equipment	45,000	35,000	30,000	45,000
Switch out system at load	8,000	8,000	8,000	8,000
Storage batteries	1,000	1,000	1,000	1,000
System final design w/Arctic engr	65,000	65,000	65,000	65,000
System safety and permitting	15,000	15,000	15,000	15,000
Renewable power required (kWp)	108	93	68	108
Renewable installed cost per kWp	0	0	0	0
Renewable installed cost total	0	0	0	0
System component subtotal	$846,551	$443,452	$326,277	$1,195,151
Capital cost ($/Wp)	42.33	22.17	16.31	59.76
System performance				
Fuel cell system efficiency	0.276	0.320	0.435	0.276
Average load power consumption (kW)	16.00	16.00	16.00	16.00
Longest possible storage time (days)	22.02	25.49	34.71	66.06

Table A1- 2. Kivalina Village 125 kW average load

Kivalina Alaska Renewable Hydrogen Power System			
	Today	Near-term	Near-term
Load average power (kW)	125	125	125
Load peak power (kW)	200	200	200
Fuel cell stack peak power (kW)	200	200	200
Fuel cell stack cost per kWp	6,000	500	100
Renewable capacity factor	0.45	0.45	0.45
Fuel cell average efficiency	0.40	0.45	0.58
Electrolyzer system average efficiency	0.69	0.71	0.75
Peak power renewable required (kW)	554	478	351
Electrolyzer peak power (kW)	554	478	351
Electrolyzer system cost per kW	2,500	750	250
Electrolyzer system cost	1,383,857	358,633	87,803
Fuel cell BOP cost per kW	500	200	100
Fuel cell cost	1,200,000	100,000	20,000
Fuel cell BOP cost	100,000	40,000	20,000
Storage tank volume (gal)	60,000	60,000	60,000
Storage tank quantity	25	25	25
Total storage volume (gal)	1,500,000	1,500,000	1,500,000
Single storage tank cost	52,100	35,000	20,000
Fittings	2,350	1,600	2,350
Saddles	2,150	1,500	2,150
Total storage tank cost	1,415,000	952,500	612,500
Controller and DAQ	15,000	10,000	8,000
Power electronics cost/kWp to load	700	500	300
Power electronics total cost	140,000	100,000	60,000
Compressor	10,000	7,000	5,000
Shipping elecytrolyzer	2,000	2,000	1,500
Shipping storage tanks	37,500	37,500	37,500
Shipping fuel cell	10,000	10,000	10,000
Shipping compressor	600	600	600
Site preparation	275,000	275,000	275,000
Fuel cell, electrolyzer housing	10,000	10,000	10,000
Water processing equipment	45,000	35,000	30,000
Switch out system at load	8,000	8,000	0
Storage batteries	10,000	10,000	10,000
System final design w/Arctic engr	125,000	125,000	125,000
System safety and permitting	15,000	15,000	15,000
Renewable power required (kWp)	554	478	351
Renewable installed cost per kWp	2,000	1,300	750
Renewable installed cost total	1,107,085	621,631	263,410
System component subtotal	$5,909,742	$2,718,364	$1,591,613
Capital cost ($/Wp)	29.55	13.59	7.96
System performance			
Fuel cell system efficiency	0.276	0.320	0.435
Average load power consumption (kW)	125.00	125.00	125.00
Longest possible storage time (days)	23.49	27.19	37.02

Table A1- 3. St. George Village 125 kW average load

St. George Alaska Renewable Hydrogen Power System			
	Today	Near-term	Far-term
Load average power (kW)	125	125	125
Load peak power (kW)	200	200	200
Fuel cell stack peak power (kW)	200	200	200
Fuel cell stack cost per kWp	6,000	500	100
Renewable capacity factor	0.45	0.45	0.45
Fuel cell average efficiency	0.40	0.45	0.58
Electrolyzer system average efficiency	0.69	0.71	0.75
Peak power renewable required (kW)	554	478	351
Electrolyzer peak power (kW)	554	478	351
Electrolyzer system cost per kW	2,500	750	250
Electrolyzer system cost	1,383,857	358,633	87,803
Fuel cell BOP cost per kW	500	200	100
Fuel cell cost	1,200,000	100,000	20,000
Fuel cell BOP cost	100,000	40,000	20,000
Storage tank volume (gal)	60,000	60,000	60,000
Storage tank quantity	15	15	15
Total storage volume (gal)	900,000	900,000	900,000
Single storage tank cost	52,100	35,000	20,000
Fittings	2,350	1,600	2,350
Saddles	2,150	1,500	2,150
Total storage tank cost	849,000	571,500	367,500
Controller and DAQ	15,000	10,000	8,000
Power electronics cost/kWp to load	700	500	300
Power electronics total cost	140,000	100,000	60,000
Compressor	10,000	7,000	5,000
Shipping elecytrolyzer	2,000	2,000	1,500
Shipping storage tanks	22,500	22,500	22,500
Shipping fuel cell	10,000	10,000	10,000
Shipping compressor	600	600	600
Site preparation	275,000	275,000	275,000
Fuel cell, electrolyzer housing	10,000	10,000	10,000
Water processing equipment	45,000	35,000	30,000
Switch out system at load	8,000	8,000	0
Storage batteries	10,000	10,000	10,000
System final design w/Arctic engr	125,000	125,000	125,000
System safety and permitting	15,000	15,000	15,000
Renewable power required (kWp)	554	478	351
Renewable installed cost per kWp	2,000	1,300	750
Renewable installed cost total	1,107,085	621,631	263,410
System component subtotal	$5,328,742	$2,322,364	$1,331,613
Capital cost ($/Wp)	26.64	11.61	6.66
System performance			
Fuel cell system efficiency	0.276	0.320	0.435
Average load power consumption (kW)	125.00	125.00	125.00
Longest possible storage time (days)	14.09	16.31	22.21

Table A1- 4. Kotzebue Village 3300 kW average load

Kotzebue Village, Alaska Renewable Hydrogen Power System			
	Today	Near-term	Far-term
Load average power (kW)	3,300	3,300	3,300
Load peak power (kW)	6,000	6,000	6,000
Fuel cell stack peak power (kW)	6,000	6,000	6,000
Fuel cell stack cost per kWp	6,000	500	100
Renewable capacity factor	0.35	0.35	0.35
Fuel cell average efficiency	0.40	0.45	0.65
Electrolyzer system average efficiency	0.69	0.71	0.75
Peak power renewable required (kW)	22,205	19,182	12,571
Electrolyzer peak power (kW)	22,205	19,182	12,571
Electrolyzer system cost per kW	2,500	750	250
Electrolyzer system cost	55,512,422	14,386,318	3,142,857
Fuel cell BOP cost per kW	500	200	100
Fuel cell cost	36,000,000	3,000,000	600,000
Fuel cell BOP cost	3,000,000	1,200,000	600,000
Storage tank volume (gal)	100,000	100,000	100,000
Storage tank quantity	100	100	100
Total storage volume (gal)	10,000,000	10,000,000	10,000,000
Single storage tank cost	62,100	45,000	20,000
Fittings	2,350	1,600	2,350
Saddles	2,150	1,500	2,150
Total storage tank cost	6,660,000	4,810,000	2,450,000
Controller and DAQ	25,000	18,000	10,000
Power electronics cost/kWp to load	700	500	300
Power electronics total cost	4,200,000	3,000,000	1,800,000
Compressor	25,000	20,000	15,000
Shipping elecytrolyzer	15,000	10,000	8,000
Shipping storage tanks	150,000	150,000	100,000
Shipping fuel cell	75,000	75,000	75,000
Shipping compressor	600	600	600
Site preparation	75,000	75,000	75,000
Fuel cell, electrolyzer housing	15,000	15,000	15,000
Water processing equipment	85,000	70,000	60,000
Switch out system at load	120,000	120,000	
Storage batteries	50,000	50,000	25,000
System final design w/Arctic engr	125,000	110,000	100,000
System safety and permitting	15,000	15,000	15,000
Renewable power required (kWp)	22,205	19,182	12,571
Renewable installed cost per kWp	2,000	1,300	750
Renewable installed cost total	44,409,938	24,936,284	9,428,571
System component subtotal	$150,558,660	$52,061,702	$18,520,329
Capital cost ($/Wp)	25.09	8.68	3.09
System performance			
Fuel cell system efficiency	0.276	0.320	0.488
Average load power consumption (kW)	3,300.00	3,300.00	3,300.00
Longest possible storage time (days)	5.93	6.87	10.48