Proceedings of the 2001 DOE Hydrogen Program Review
NREL/CP-570-30535

RENEWABLE HYDROGEN SYSTEMS INTEGRATION AND PERFORMANCE MODELING

Roger Jacobson, Richard Purcell, Daniel Wermers
Desert Research Institute
Reno, NV 89512
Byard Wood, Denis Donovan, Denise Lane, Michael Matheus
University of Nevada, Reno
Reno, NV 89557

Abstract

This project has developed and tested a renewable energy fuel cell (REF) system for off-grid or supplemental power application. The system is composed of solar panels (2 kW), wind turbines (3 kW), inverter (4 kW), electrolyzer (5 kW), batteries, hydrogen tank, fuel cell (2 kW), load cell (5 kW), computer system, and miscellaneous sensors and electronic components (Snyder 2000). The operation of the REF system is controlled by the computer and is designed to provide the power required by the load bank utilizing power from the solar panels, wind turbines and/or the fuel cell. A major emphasis of this project was to develop a computer system to evaluate inputs from approximately 25 sensors and utilize this information to control the entire system, including the fuel cell. The basic logic is that the electrolyzer generates hydrogen during times when excess solar and wind energy is available and then the fuel cell utilizes this hydrogen to produce electricity when there is insufficient solar and wind energy. The REF system functions very well in the Reno, Nevada, environment, which has a good balance of solar and wind energy throughout the year.

Introduction

Fuel cell systems utilizing renewable energy are attracting increasing interest. This attention is perhaps related to energy costs, reliability of energy and a need to feel in control of one's energy future. If individuals are planning to purchase a system based on logic and not because they just want one, at least three major conditions should be met for a system such as described above: competitive energy costs, reliable system and ease of use. The major focus of this project was the last component, ease of use, because without a system that was self-managed and controlled, most users will avoid use because of the complexity and time required to operate this system. The system needs to appear seamless to the user so that the exact source of energy at any particular time is not known and no system adjustments are required if power consumption increases or decreases.

The basic operating philosophy of the REF system is to carefully monitor all of the component sensors to determine system conditions and then to have the computer control the operation to match the power demand and optimize the system function. All electrical components are connected to a 24 VDC busbar (Figure 1), which allows power to be managed between power input, energy storage and power consumption devices. The busbar voltage is also a major parameter that is monitored to determine the REF system function and health. There are several REF system logic controls, such as not permitting the electrolyzer and the fuel cell to operate at the same time because the electrolyzer is only to operate when excess power is available. Another reason to not operate the fuel cell when sufficient wind and solar energy are available is to maximize system efficiency. When power is used to operate the electrolyzer and the hydrogen is then used to produce electricity from a fuel cell, the efficiencies of both the fuel cell and electrolyzer (both much less than 100%) need to be combined to get the overall system efficiency (20-30% depending on conditions).

The logic control for the REF system was a challenge because the sensor data needed to be collected every few seconds for real time system control and the same computer needed to be sending out device control signals on a real time basis. This control is particularly critical when operating the fuel cell under changing power conditions. The situation is only possible because there is a small battery pack in the REF system that helps "buffer" the system and allow the fuel cell a few seconds to change power output and match power demands.

Discussion

System Configuration

As discussed previously, the REF system is complex but is comprised, primarily, of commercially available components that are configured to produce power from renewable non-polluting sources and provide reliable power that will require a minimum attention by the user. The basic components are shown in Figure 1. The details of the fuel cell system are shown in Figure 2 with both the computer inputs and commands shown as well as the control of the hydrogen and airflow. The computer first determines if power from the fuel cell is required. If so, then it starts the fuel cell and monitors its performance until power is no longer needed from the fuel cell. At that time the computer performs a shutdown procedure. There are also two ARGA hydrogen detectors, one by the electrolyzer and the second near the fuel cell, that are constantly monitored and if any hydrogen is detected the system closes the valve from the hydrogen tank and stops the electrolyzer.

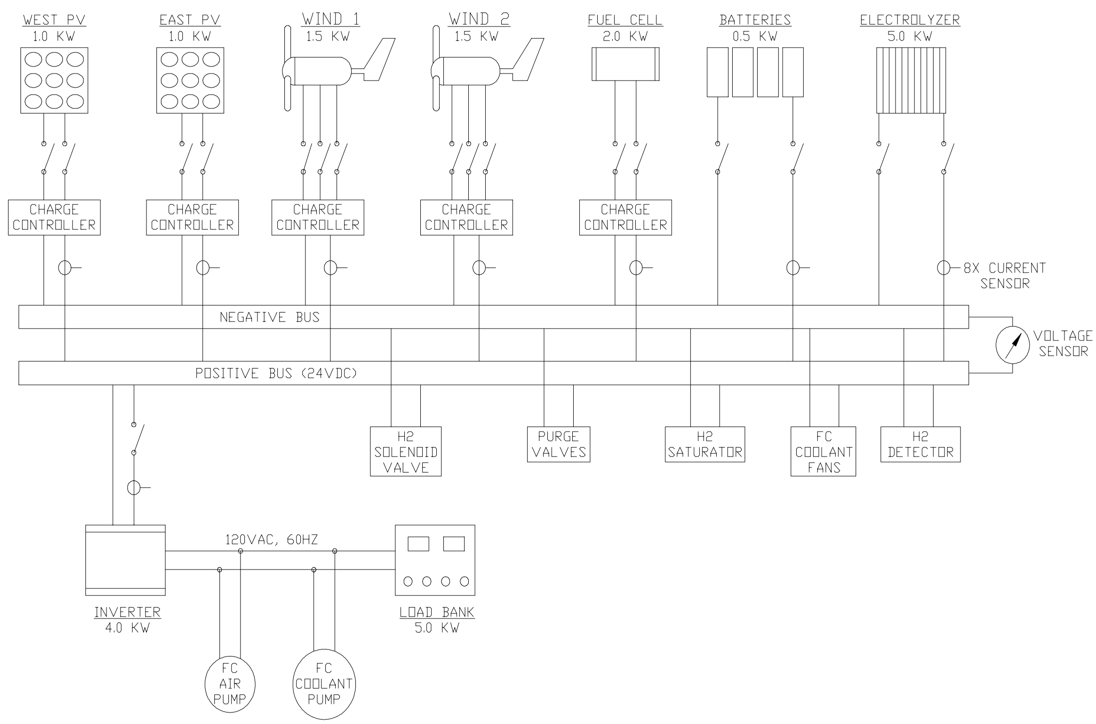


Figure 1. Connections to a Common Electrical Bus

Energy for the system is provided by two Siemen solar panels, each producing 1 kW, mounted on Zomeworks trackers. Two Bergey 1.5 kW wind turbines mounted on individual sixty-foot towers also provide additional power. This power is converted to 24 VDC by Trace and Bergey charge controllers and fed onto a common 24 VDC electrical bus. Current from the busbar keeps a small battery pack charged, feeds power to the load bank via a Trace inverter and also supplies power to the electrolyzer. The load bank is a series of resistors that can be programmed to simulate any type of electrical load profile.

The electrolyzer is a major piece of equipment, representing nearly half of the total cost of the REF system. It was purchased from Stuart Energy and delivered as a completed system in its own cargo box. The hydrogen is compressed to approximately 100 psi and stored in an 80 cubic foot tank. The hydrogen pressure is dropped to approximately 5 psi before being introduced into the fuel cell. Air is introduced into the fuel cell by the use of a Gast linear air pump (blower) and is also controlled by the computer so that air flow can match hydrogen flow and produce variable power outputs. The fuel cell has a maximum output of approximately 2 kW and was manufactured by Dais-Analytic. Most of the remaining components (e.g. the cooling system, charge controller and multiplexer) shown on Figure 2 were fabricated by DRI after purchasing required parts. The load cell is manufactured by Simplex and consists of a series of resistors that can be programmed in 125 Watt increments either manually of by computer.

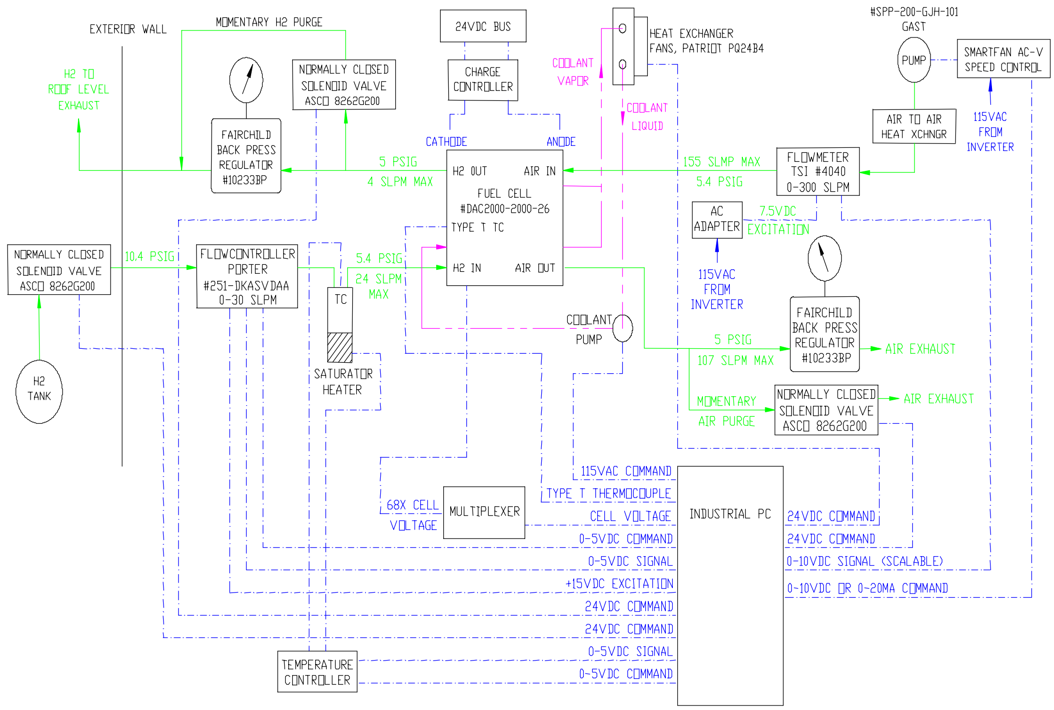


Figure 2 – Fuel Cell System

One of the unique features of this system is having so many different, major components hooked to the 24 VDC bus. The components have substantially different voltage-current characteristics. Commercial charge controllers are used with the solar panels and wind turbines to deal with this problem. The fuel cell has a large voltage mismatch, having an output voltage that varies from 38 - 65 VDC. A commercial charge controller was modified for this task. The electrolyzer is the single largest electrical component (5 kW) and it is hooked directly to the bus. This means there is no way of throttling or controlling its current draw; it is either on or off. It is limited only by what voltage is available on the bus. On a typical day, the electrolyzer will draw 1 – 2 kW. This means that when a moderate amount of excess energy, say 800 W, is available to produce hydrogen (after meeting the load profile), the electrolyzer cannot be started as it will consume the 800 W of excess energy plus a portion of what was going to meet the load profile. The electrolyzer size is a good match for the renewable peak power, but is oversized for a typical day. The most cost effective way to control the electrolyzer current would be to use a smaller unit (say 2-3 kW) from the outset; this also will more closely match the voltage-current traits of the buffer batteries. Another choice would be to add and subtract cells as required via relays; this requires the cells be configured differently during manufacture. The approach that offers the most control, and makes the most sense for our existing installation, would be to add an adjustable dc/dc converter that allows the electrolyzer current draw to be matched to the excessive power available.

Sensor Array

Sensors are critical for the proper functioning of the entire REF system because they measure total system performance and feed these data to the computer for decision making. A summary of the sensors is shown in Figure 3, with several of the sensors listed actually having several measured parameters associated with them. One example is wind energy, which is generated by two wind turbines and is comprised of five sensors: 2 anemometers, wind direction and 2 that measure amperes. At the present time, the REF system has 27 sensors but the number changes as the system evolves. Also several of the sensors are redundant. There are also several sensors that provide secondary information and need not be sampled every 0.1 - 5 seconds but rather every few minutes.

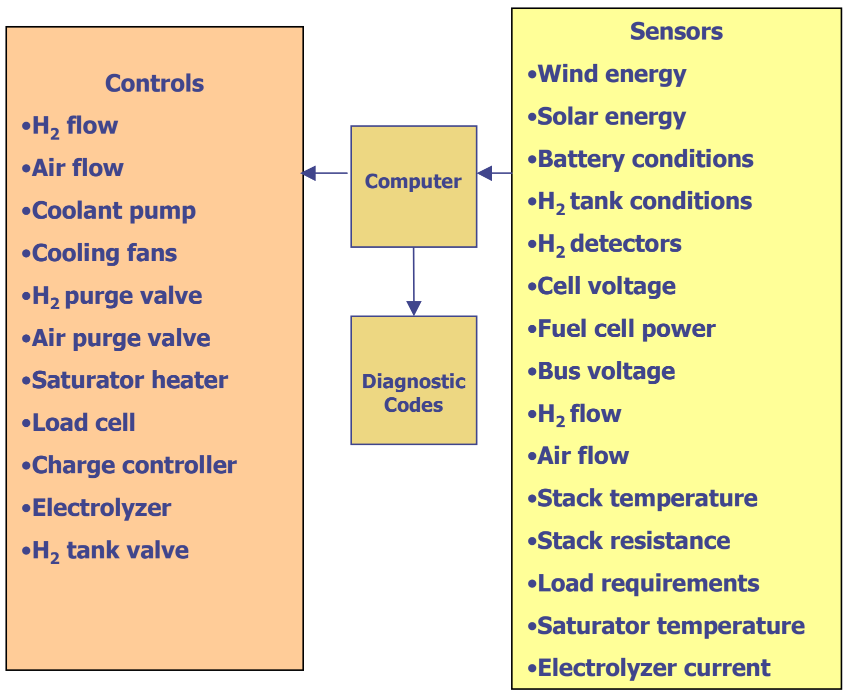


Figure 3 – Logic Control Diagram

Both the solar and wind energy are intermittent sources of energy as is demonstrated in Figures 4 and 5. Even during daylight hours the solar resource is variable because of changes in cloud cover. This is demonstrated by the solar energy variability as seen in Figure 4. The wind energy is an even less reliable resource. It is also one that is more difficult to predict when sufficient wind will be available to generate power. The data demonstrate that the wind needs to blow approximately 10 mph before any power is generated. Until the wind approaches 20 mph, minimal power is generated. Wind energy utilization is one of the more difficult problems for which to develop logic control because the duration and strength of the wind resource, which is unknown, is critical. The wind energy is used in one of three ways: 1) to keep the batteries charged, which is easy to program and requires little power because the battery pack is small; 2) to provide power to the load bank; and 3) to generate hydrogen by powering the electrolyzer. The last is most difficult because there is some startup time required before hydrogen production begins and substantial power is consumed before hydrogen can be produced, compressed and stored. The electrolyzer is also the largest energy sink in the REF system. It cannot be throttled, so it acts as a nominal 1-2 kW load that is either on or off. If the wind runs for short time intervals and then stops, it is not prudent to start the electrolyzer and therefore the program must consider many factors when determining if the electrolyzer should be started. This problem is more acute at night when no solar energy is available. The use of wind energy to power the load cell is relatively straightforward but there is a problem of power switching under certain circumstances. One example is at night when operating on the fuel cell at a relatively low load and then the wind starts blowing and producing enough power to power the load cell and also the electrolyzer. The question is at what point is the fuel cell shut off and the electrolyzer started, because it has been determined that the wind will continue to blow for some minimum time.

Busbar voltage is monitored as an indicator of the overall system condition. All power goes through this component and therefore it is the best single measurement of whether or not power is being supplied at rates that are sustainable. Figure 6 illustrates the changes in voltage on the busbar when the REF system has the electrolyzer operating (2/27 and 2/28) versus days when the electrolyzer is not functioning (2/24 and 2/25).

The voltage and flow of current to and from the batteries (Figure 7) are also carefully monitored to insure that the batteries are functioning normally and that they are not placed in a condition where they can be damaged. The battery pack is essential to the function of the REF system because it provides a buffering of current in the system, especially during changes in power consumption of devices, such as the electrolyzer and load cell. Current flow from batteries is also carefully monitored when increasing the power of the fuel cell to meet the load cell demand. The power from the fuel cell is increased until the current flow from the batteries is zero.

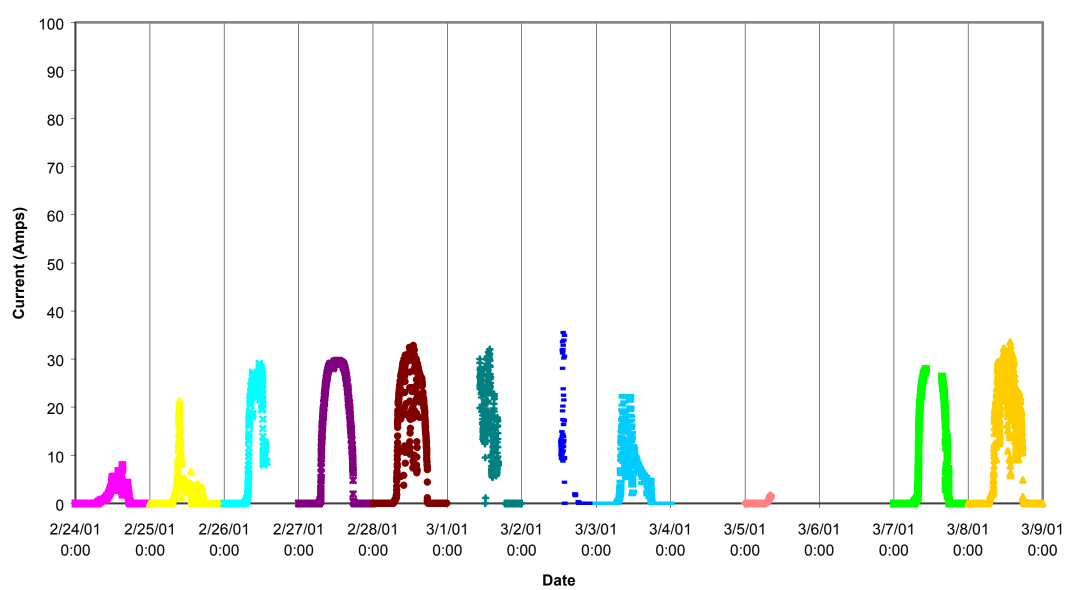
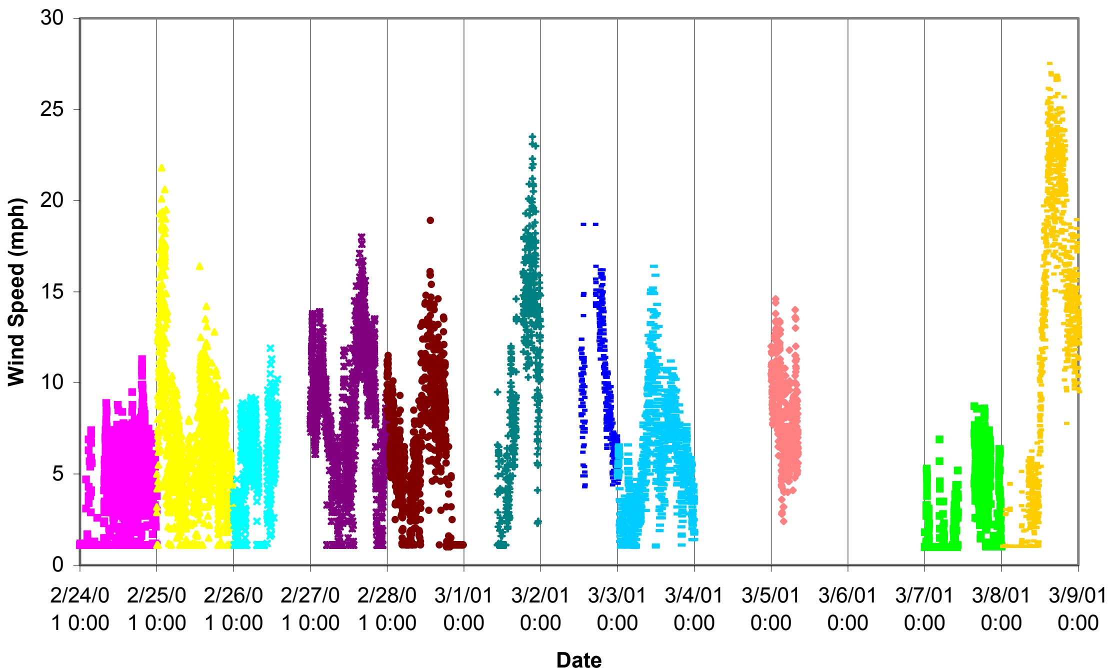


Figure 4 – Solar Energy Production



.

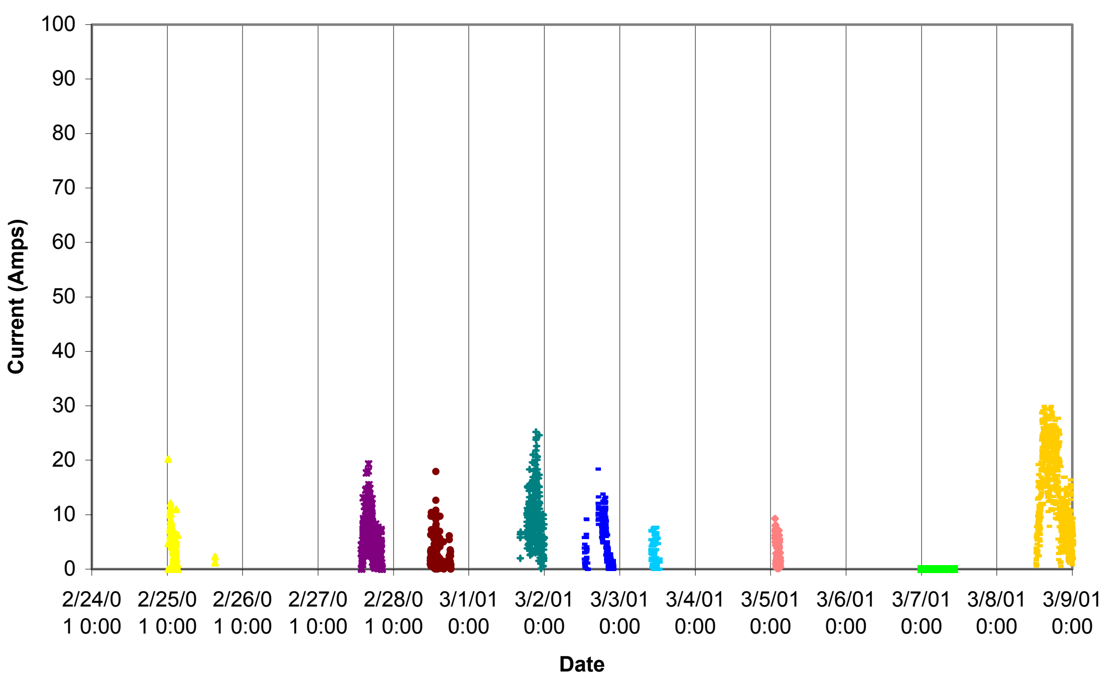


Figure 5 – Wind Velocity and Energy Production

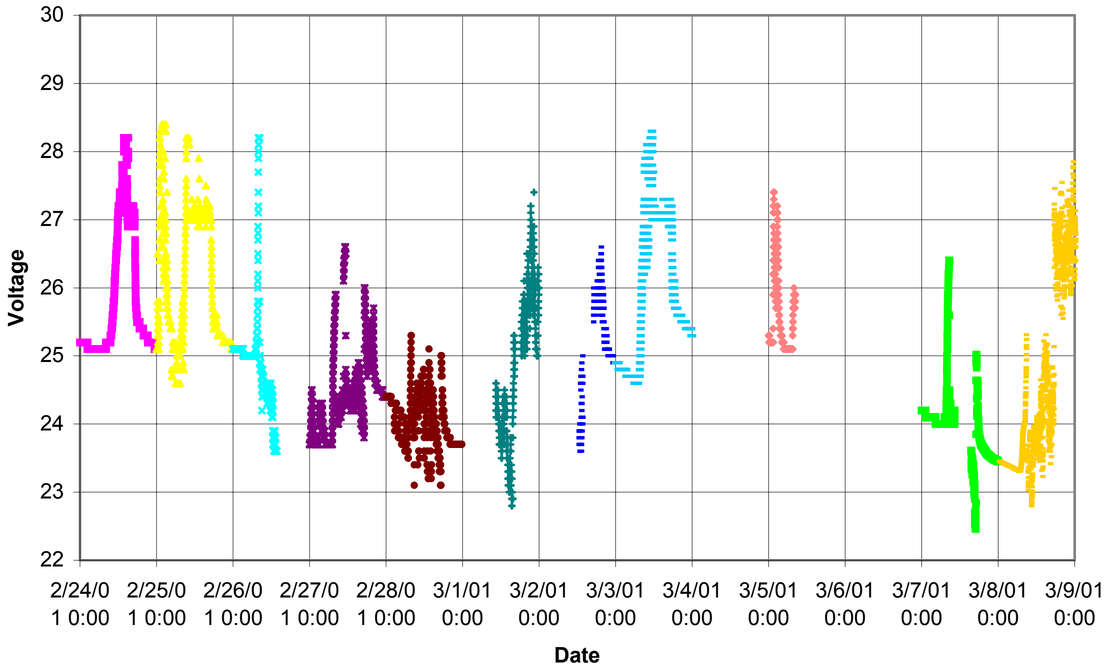


Figure 6 – Busbar Voltage

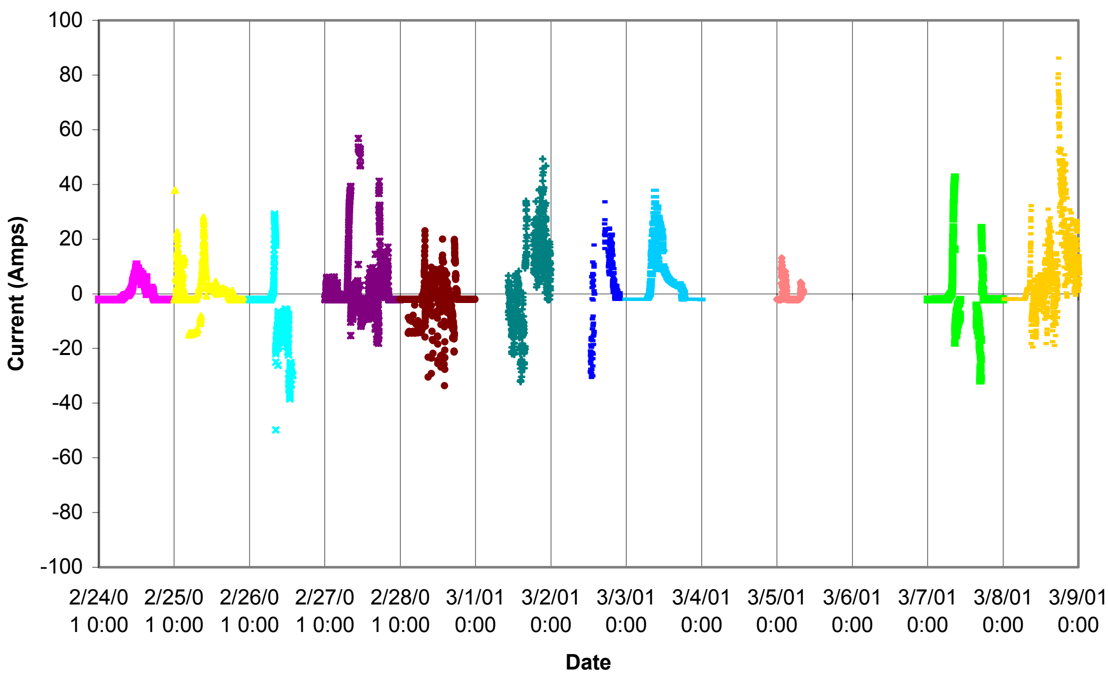


Figure 7 – Battery Current Flow

The REF system control was undertaken as a two-step process in order to clearly separate the component control from the logic control programming. The first step was to establish a computer control for all of the individual components shown in Figure 3 and to carefully test to ensure that the control worked under a wide variety of conditions. Some of the controls were a simple on/off application, such as the coolant pump, cooling fans, and the purge valves. Other controls (hydrogen and air flow, etc.) were more complex and required the ability to operate under different settings. There also needed to be a calibration curve established between the computer settings and the amount of hydrogen or air delivered per unit time. The system was designed using LabView software and is flexible so that additional components may be added in the future.

System Control Design

The most complicated system control application was to develop a fully automated system that can take sensor information and establish a set of system controls that will operate the entire system in a "hands off" mode. Version 1 was designed to handle most of the anticipated conditions that the REF system was expected to confront in normal operation. The general power consumption on a 24-hour basis needed to be establish (Figure 8) so that the load cell could be programmed. This information was obtained by estimating the total energy available, on a daily basis, in both the winter and summer and then assuming as a first approximation that one half of the power produced by solar and wind energy would be used to produce hydrogen for utilization in the fuel cell (Figure 9). These values need to be refined as more data become available and the calculations should be done on a monthly basis. The daily load profile shown in Figure 8 was constructed to represent a low nighttime load followed in the winter by an increased load from 6 to 8 AM and then an intermediate load during the day. There is also an evening peak until 10 PM and then a low nighttime load. Summer power differs in that there is a mid-day high caused by air conditioning but otherwise the two profiles are similar. This profile is approximately what a residential load will represent in Western states but there will not be a constant load during any time interval. Also the changes in power consumption will not be represented as a step function. These were established as initial operating conditions in an attempt to bracket the fuel cell power output and generally determine how much solar and wind power will be required for hydrogen production.

The programming logic has three basic decision criteria: 1) is power from the fuel cell required to match load bank demand; 2) is there enough excess power to run the electrolyzer and 3) does an unsafe condition exist? There are dozens of other decisions that also need to be made during daily operation. System operation and control can perhaps be best described by analyzing the general operation during a typical day (Figure 8). Starting at midnight, the power consumption is low and totally supplied by the fuel cell using hydrogen stored from previous days. If there is a small amount of wind energy then it supplies the demand and the fuel cell is off. If there is substantial wind then it will supply the low base load and also operate the electrolyzer and produce hydrogen. This will occur only until the hydrogen tank is full. This entire operation with the required decisions and control is made by the computer obtaining information from an array of sensors. At 6:00 AM the power demand increases and on a typical day the fuel cell output will increase to meet this new demand. There generally is not sufficient solar energy to supply power but if wind energy is available it will be utilized to offset the load and possibly to produce hydrogen. In the winter the power demand decreases at 8:00 AM as people leave the house and the load for the next nine hours is supplied by a combination of wind, solar and fuel cell power. Again if sufficient solar and wind energy are available hydrogen will be generated for future use in the fuel cell. This is the period of time when most of the hydrogen is produced and stored. At 5:00 PM the power demand increases and generally the power will be supplied by the fuel cell unless there is wind power available. In an attempt to maximize REF system efficiency, solar and wind power are utilized directly rather then producing hydrogen and operating the fuel cell. The power is reduced at 10:00 PM and the load is generally carried by the fuel cell unless there is sufficient wind energy. During this entire time several sensors are checking for unsafe conditions, such as a hydrogen leak, and if any are detected the REF system is shut down in a safe manner and an error code displayed.

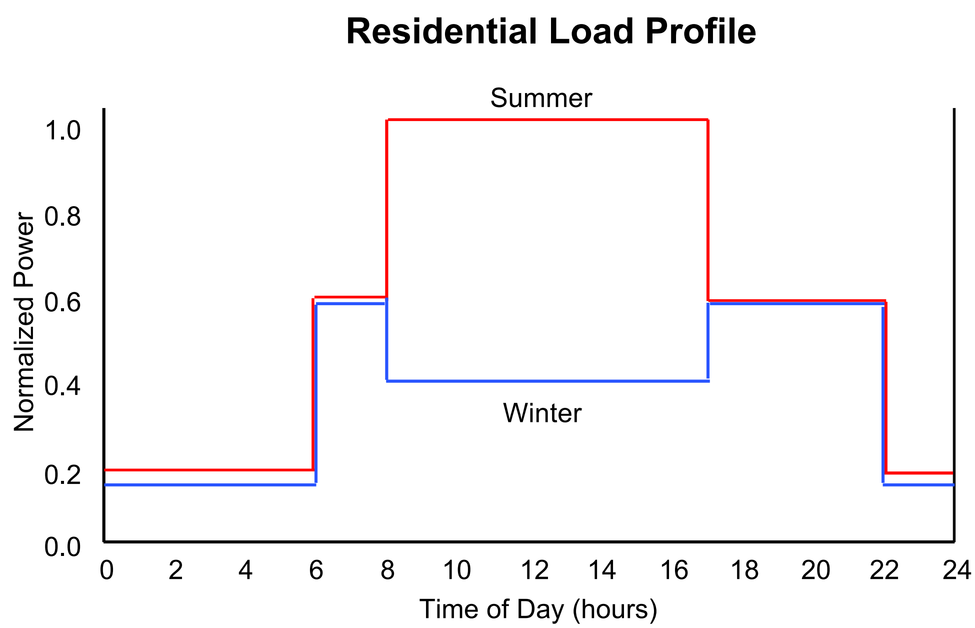


Figure 8 – Residential Load Profile

The above description is generally how the system behaves but there are a series of decisions made based on sensor input. Some of the more common operations can be described as a series of if-then statements:

- Busbar voltage < 26 VDC, then assess power requirements
  - are batteries charging or discharging?
  - if charging then fuel cell off; if discharging, is electrolyzer on?
  - if electrolyzer on, turn off and re-assess power requirements
  - if still discharging, initiate sequence to bring fuel cell online
- Busbar voltage > 26 VDC, then fuel cell off
  - is the hydrogen tank full?
  - if yes, don't activate electrolyzer
  - if no, then are wind or solar power available?
  - if no, don't activate electroyzer; if yes, then activate

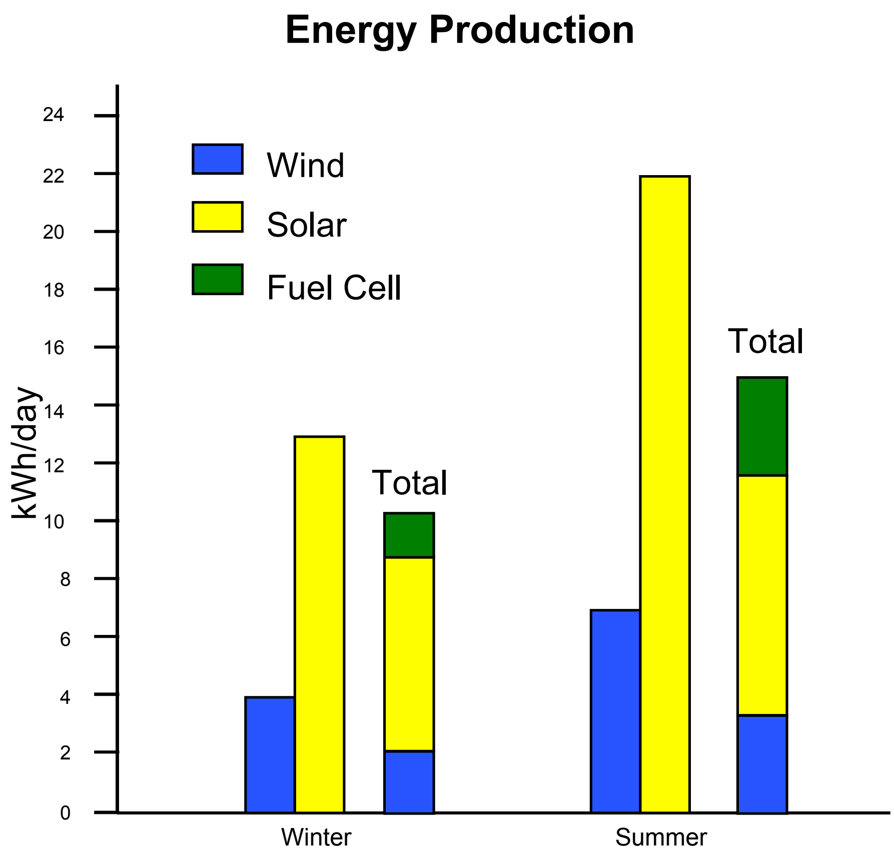


Figure 9 – Energy Production from the REF System

These are some examples of the type of decisions that are made continuously during any day of operation. The goal is to keep the batteries at a near full charge and only allow them to be discharged for a short period of time and then recharged. This allows the batteries to act as a buffer for the REF system when components such as the electrolyzer or load bank are suddenly turned on or up.

Conclusion

The REF system is viable for numerous applications, provided component costs can be reduced. It can be made reliable and the entire system can operate seamlessly and with a minimum of user time. The basic REF system configuration is sound, with the common 24 VDC busbar being essential to the overall system. Several of the components could have been sized differently but they were available at the beginning of the project. Integrating sensor data into the system worked well using LabView software and Fieldpoint hardware and also provides great flexibility for changes and additions. Establishing computer control of individual components before attempting to have the entire REF system run by the computer was very prudent. Several issues were solved quickly because it was possible to readily separate component functions and isolate problems. Version 1.0 of the software REF system control has been completed, which provides the ability to collect real time data and utilize this information to control numerous components to provide seamless power to a load bank. The software will be tested with increasingly complex conditions and modified as required to continue to provide the power required at the load bank and also operate in a safe manner.

Future Work

The next research phase will focus on: 1) developing advanced software; 2) evaluating how to make the existing system more functional and cost-effective; 3) collecting performance data under various load profiles (farm/ranch, business, etc.); and 4) exploring ways to optimize the system and increase efficiency. Advanced software development will focus on handling more complex real world conditions that occur during sustained operation. This will include the failure of various components, as well as, major changes in power consumption coupled with a dramatic decrease in solar or wind energy. Version 1.0 of the software makes decisions strictly based on current conditions with no capability to forecast future energy supply over the next few days. The next version will explore various options to incorporate forecast information into conditioning the control logic to manage power in the REF system. Optimal performance by having the computer fine-tune the system is important to obtain maximum efficiency. One way this will be accomplished is by making small changes in the flow of hydrogen and air and carefully monitor fuel cell power output to achieve the best power to input ratio.

Adding capacity to various components will be evaluated in order to obtain a system that is sized properly for the expected conditions. At the present time several components appear to be undersized but with more operating information it will be possible to make a definitive evaluation and reconfigure the system. Collecting data utilizing other load profiles will greatly increase the utility of the REF system and allow for the refinement of the software system. Other simulations should include the farm/ranch and small business applications. Another key component of future work needs to focus on increasing system efficiency by reducing parasitic losses and other operating inefficiencies. A major focus of this activity is to refine the operating conditions of the 5 kW electrolyzer, which is either off or on. In the on condition, the power consumption is high and not able to be controlled. A better system would have a charge controller on the electrolyzer so that small amounts of excess solar or wind energy could be used to generate hydrogen.

Acknowledgments

The REF system development is funded by the U.S. Department of Energy, Office of Power Technologies through the Hydrogen Program. Assistance on electrolyzer operation was provided by Stuart Energy and DIAS-Analytic helped with the fuel cell setup. Los Alamos National Laboratory provided valuable assistance on defining fuel cell operating conditions. The Desert Research Institute provided financial assistance and help from facilities was invaluable in getting the sensors to work properly.

References

Snyder, J.D. 2000. An Integrated Renewable Hydrogen Energy System. Unpublished Master's Thesis, University of Nevada, Reno, 198 p.