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The role of fuel cells in energy storage

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Abstract

A fuel cell-based energy storage system allows separation of power conversion and energy storage functions enabling each function to be individually optimized for performance, cost or other installation factors. This ability to separately optimize each element of an energy storage system can provide significant benefits for many applications. Various fuel cell/electrolyzer-based energy storage concepts and applications that employ these concepts using hydrogen as the energy storage medium are examined here. Technology and product development status of relevant PEM fuel cells, electrolyzers and complete regenerative fuel cell systems will be reviewed together with the status of various hydrogen storage technology options. © 2000 Elsevier Science S.A. All rights reserved.

Keywords: Fuel cell; Energy storage; Power

1. Introduction

Fuel cells are becoming widely accepted as a preferred means of generating electricity for distributed electrical power generation because of their high fuel conversion efficiency, environmental compatibility and reliable, quiet operation. While fuel cells are becoming recognized as a preferred direct energy conversion device, important roles also exist for fuel cells in traditional and non-traditional energy storage applications.

When used as an energy storage device, the fuel cell is combined with a fuel generation device, commonly an electrolyzer, to create a Regenerative Fuel Cell (RFC) system, which can convert electrical energy to a storable fuel and then use this fuel in a fuel cell reaction to provide electricity when needed. Most common types of RFCs proposed use hydrogen as the energy storage medium which is generated via electrolysis of water. This hydrogen–oxygen RFC cycle and possible applications of this technology to traditional energy storage uses are examined here.

The key to the effectiveness of an RFC system is the ability to separate the energy storage function from the power conversion function allowing each to be optimized. For example, if a moderate 5 kW power level is required as back-up power for a computer installation, a small fuel cell of this power rating can be located inside the computer center near the load. External to the building, hundreds of kilowatt-hours of energy could be stored as hydrogen safely outside. When power is needed, this hydrogen supplied to the fuel cell would allow full power operation of the load for many days; and a positive indication of remaining charge would always be available as measured by the amount of hydrogen remaining shown by the pressure in the storage tank. The result is a system that provides full back-up power for extended time periods with the energy storage medium, hydrogen, safely stored external to the building. By contrast, storage of equivalent amounts of energy via traditional lead–acid batteries requires an environmentally controlled room, which results in significant quantities of lead and acid being present in the facility.

The stored hydrogen would not be affected by temperature, duration of storage, or number of cycles of storage and could be fully discharged without any life degradation. When recharge of the tank was needed, this tank could be recharged by water electrolysis with power from the primary power source.

While this potential of RFCs has been studied for many years, RFCs have not found practical application, in part, due to the high cost of fuel cells, but also because no cost-effective means of generating and storing the hydrogen existed. However, recent developments in the status of Polymer Electrolyte Membrane (PEM) water electrolyzers are creating new options and fuel cells, especially PEM

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fuel cells, have become increasingly cost-effective driven by the needs of the automotive industry. Similar advancements have been made in the cost reduction of PEM electrolyzers through commercialization to serve the industrial gas commodity market.

2. RFC concept description and development status

Using the H_2O cycle as the energy storage medium, the RFC is elegantly simple in concept. Various other hydrogen couples have also been proposed that have advantages in specific applications, but the H_2O cycle has highly acceptable performance characteristics suitable for broad use as a back-up, standby or premium power system and has minimal environmental impact. This H_2O RFC is shown schematically in Fig. 1. As shown here, water is decomposed electrolytically into hydrogen and oxygen. The hydrogen is stored while the oxygen can either be stored, suitable for remote or extraterrestrial applications, or vented to the ambient air. When power is needed, the hydrogen is simply supplied to the fuel cell and electrical power is produced. This approach ensures that the fuel cell always has a supply of pure, fuel cell compatible hydrogen, pressurized and ready for use.

The only inputs required are electrical power, makeup water and air for reactant and cooling. When the oxygen is stored and used as a reactant, the need for ambient air and makeup water can be eliminated while simultaneously increasing the efficiency.

The key elements of the RFC are:

- The electrolysis subsystem
- The fuel cell subsystem
- The hydrogen storage system

Each of these is discussed below.

2.1. Electrolysis subsystem description

The electrolysis subsystem is the key to the functionality of an RFC as this system must both generate and pressurize the hydrogen to allow it to be easily stored. While water electrolyzers that use a liquid caustic electrolyte have been available for many decades, these conventional liquid electrolyte water electrolyzers have been limited by absolute and differential pressure capability. PEM water electrolyzers similar to the now widespread PEM fuel cell, are available that generate and store hydrogen at pressures that are suitable for storage either in conventional tanks or in metal hydrides.

The function of this PEM electrolysis cell is shown in Fig. 2. As shown here, water is introduced in the anode where it is electrolytically decomposed to oxygen, protons, and electrons. The oxygen evolves as gaseous O_2 at the surface of the electrode while the protons are driven through the membrane; the electrons move through the external circuit. At the cathode, the protons combine with the electrons to evolve gaseous hydrogen. As a solid electrolyte is used, no acidic or caustic material can contaminate either the gas or the system and the solid electrolyte also supports generation of gases directly at pressure. Typical cells can generate hydrogen at pressures up to 200 psi without a compressor, while maintaining the oxygen at ambient pressure, and pressures of up to 6000 psi have been reported [1]. The additional energy, the Nernst voltage, above that required for electrolysis is relative small, approximately 30 mV per decade of pressure increase. This results in an electrolysis overvoltage due to pressurization of only 0.030 V per cell to elevate the pressure from 1 to 10 bar and only 0.60 V per cell to pressurize from 1 to 100 bar.

2.1.1. PEM electrolysis development status

PEM electrolyzers were first developed in the 1970s and have been available for many years [2], primarily for military and aerospace uses to generate oxygen for life support aboard nuclear submarines, recharge of high pressure oxygen aboard commercial aircraft, and to generate life support oxygen aboard the International Space Station. Recently, PEM electrolyzers have been developed for commercial use to supply hydrogen to the industrial gas industry for use as a process gas in various manufacturing applications. While not specifically tailored to the needs of energy storage, this commercial manufacture of PEM electrolyzers is serving as a basis for cost reduction through serial production of the essential elements of the electrolysis system. Systems such as the HOGEN® series electrolyzers manufactured by Proton Energy Systems are now

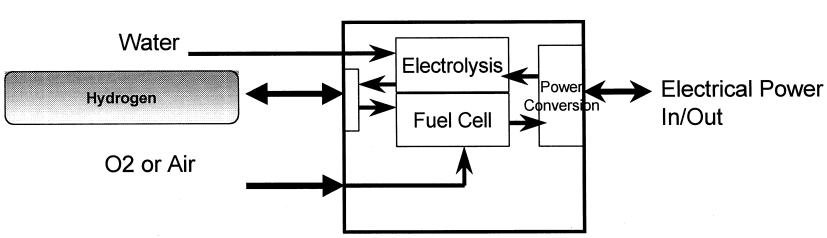

Fig. 1. The H_2O RFC system.

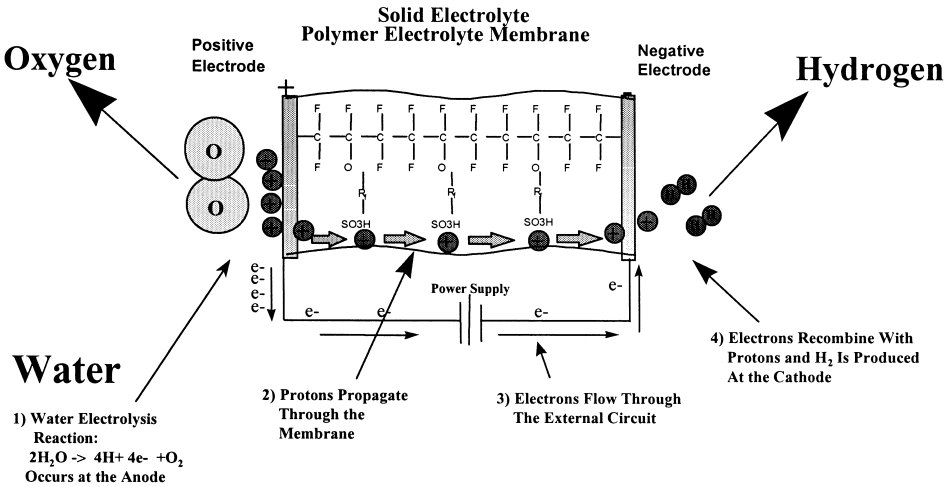

Fig. 2. PEM electrolysis cell cross-section.

commercially available sized to produce 0.5, 1.0, and 10 Nm^3 of hydrogen per hour.

2.2. Fuel cell subsystem

The PEM fuel cell is now widely espoused as the preferred low temperature energy conversion device and a PEM fuel cell is shown in cross-section in Fig. 3.

In the fuel cell reaction, the hydrogen and oxygen are supplied to the electrodes and electricity is generated producing water as the reaction by-product. While performance issues relating to PEM fuel cells for conventional applications such as automotive, residential, etc., are well-documented, additional issues arise when used in an RFC Although the figures above demonstrate the high degree of similarity of the electrolysis and fuel cell reactions, in a practical cell issues arise regarding reversibility of electrodes and water management. Catalysts must be unaffected by the direction of the reaction and water must be supplied to the cell in the electrolysis mode while water must be removed in the fuel cell mode to avoid flooding the cell. Additional system issues exist in regard to reversibility of system elements and choice of reactants. In a practical system, the RFC should be able to use either H_2–O_2 or H_2–air and be able to operate at higher pressure than normally associated with conventional fuel cells.

2.2.1. PEM fuel cell development status

2.2.1.1. Conventional PEM fuel cells. Much has been published on the development of conventional PEM fuel cells; suffice it to recognize that this high degree of development is creating a supportive environment with advances in membrane, catalyst, cell structure, etc. These PEM fuel cells operating on hydrogen–air or reformate–air are now in full scale development with various organizations targeting commercial sale at prices down to US$50/kW for automotive applications or less than

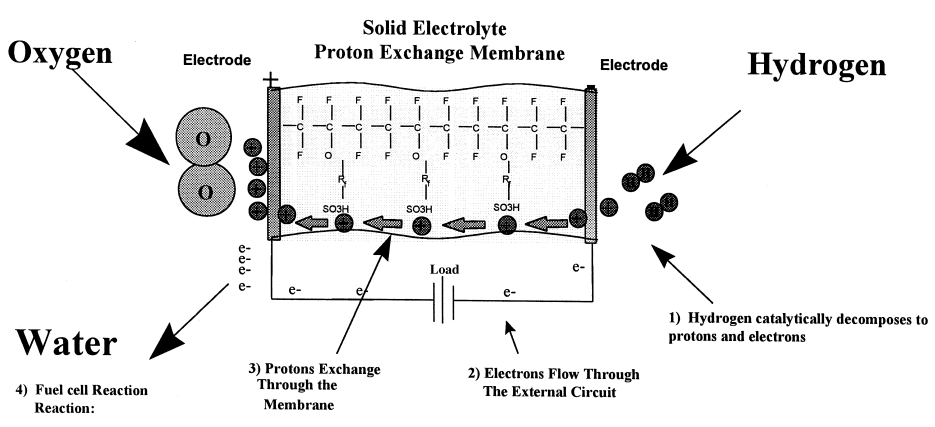

Fig. 3. PEM fuel cell cross-section.

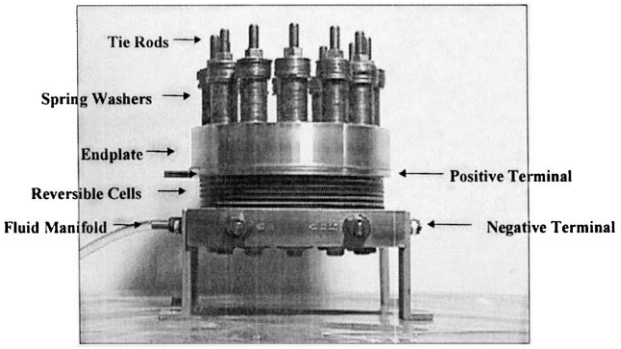

Fig. 4. The UNIGEN cell stack.

US$500/kW for stationary applications. These systems all are designed to operate as fuel-to-power conversion devices but can be operated from a stored source of hydrogen and in a very top level integration could be employed as the fuel cell element of a RFC. Various claims are now made in regard to the timing of such commercialization with recent announcements by Plug Power targeting the year 2001 for full scale commercial launch of residential size systems and Daimler Chrysler and others in the auto industry targeting the year 2003.

2.2.1.2. Reversible PEM fuel cells. With the support of both NASA and EPRI, Proton Energy Systems has been developing Unitized Regenerative Fuel Cell (URFC) technology since 1998. As part of this program effort, a commercial water electrolysis cell stack, having an active area of 0.1 ft^2, was modified to operate as a URFC. In this regard, cell manifolding was modified to accommodate new coolant passages and cell flow field structures and Membrane Electrode Assemblies (MEAs), designed to operate reversibly, were incorporated into the cell stack assembly. The specific cell stack used for testing can be seen below in Fig. 4.

This cell stack design is capable of being operated to pressures of over 150 psi. Cells can be added to the stack based on system output voltage requirements or necessary recharge rates. This test cell design was assembled, checked, and mounted in the test system prior to operational testing.

Performance testing of the UNIGEN was initiated using a single cell operating at various conditions to establish a performance baseline. These data resulted in polarization curves collected at varying pressure and temperature. Polarization curves, which detail the relationship between cell current density and voltage for dedicated fuel cell and electrolysis systems using Nafion 117, a commercially available polymer electrolyte membrane, are provided in Fig. 5. Importantly, the data shown in these polarization curves indicate that Proton's URFC performs identically to dedicated electrolyzers and fuel cells at 120°F under similar pressure conditions.

In Fig. 5, the UNIGEN fuel cell and electrolysis data were collected at 119°F and respective operating pressure of 50 psi O_2 and 40 psi H_2. This polarization set was compared to that of a dedicated electrolyzer (119°F 200/150 PSIG H_2/O_2), a primary fuel cell (120°F 80/85 PSIG H_2/O_2) and another URFC operating at 120°F 40/50 PSIG H_2/O_2. This comparison shows that the Proton UNIGEN performs almost identically to the dedi-

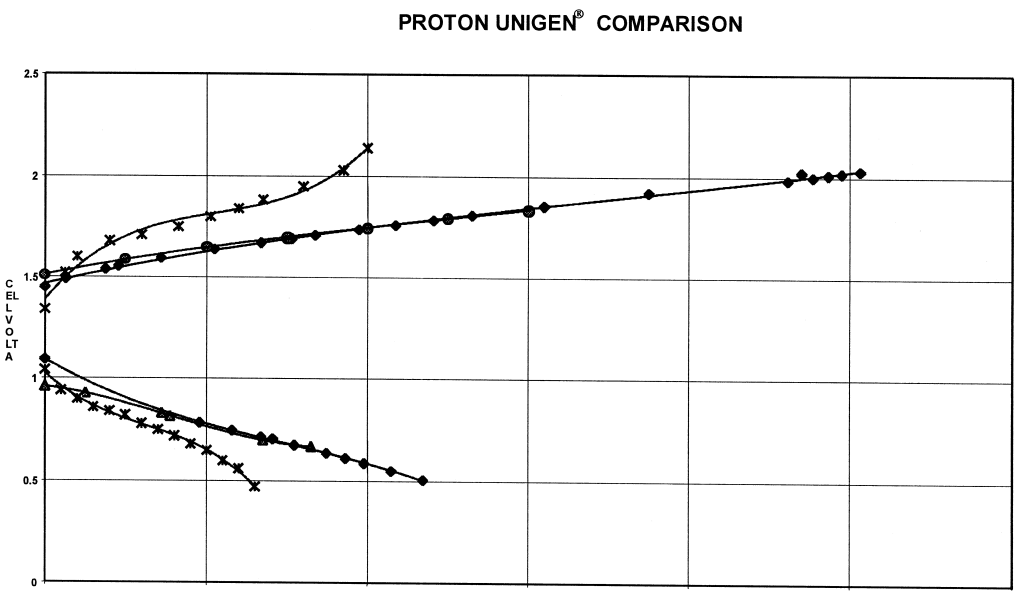

Fig. 5. Proton UNIGEN comparison. ♦ UNIGEN fuel cell mode at 119°F 40/50 PSIG H_2/O_2. ♦ UNIGEN electrolyzer mode at 119°F 40/50 PSIG H_2/O_2. ▲ Primary fuel cell literature reference at 120°F 80/85 PSIG H_2/O_2 (see footnote). ● Proton NASA HOGEN® 10 ELECTROLYZER at 119°F normalized 200/150 PSIG H_2/O_2. X LLNL URFC electrolyzer mode at 120°F 40/50 PSIG H_2/O_2 (see footnote). X LLNL URFC fuel cell mode at 120°F 40/50 PSIG H_2/O_2 (see footnote).

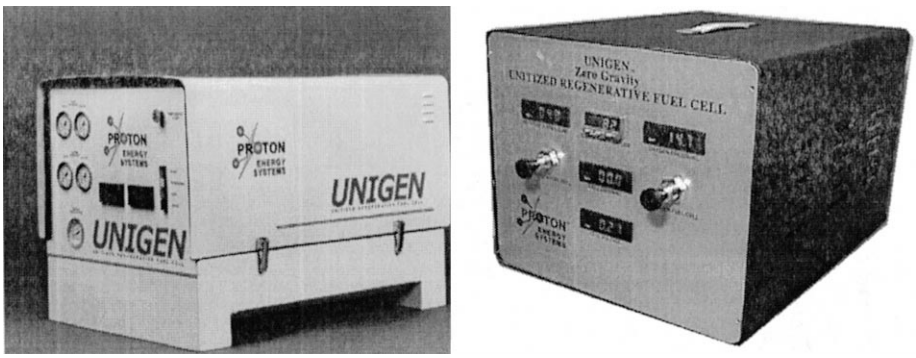

Fig. 6. The EPRI and NASA URFC system packages.

cated electrolyzer and fuel cell. It should be noted that the dedicated fuel cell actually operated at a higher pressure, 80/85 PSIG H_2/O_2, while the Proton UNIGEN was tested at 40/50 PSIG H_2/O_2. It is expected that with higher reactant feed pressures, fuel cell performance will increase. In the same chart, the Proton UNIGEN is compared to another URFC operated at Lawrence Livermore National Laboratory. It is evident in this comparison that the Proton UNIGEN outperforms the LLNL URFC at identical reactant pressures 40/50 PSIG H_2/O_2 and similar temperatures (119°F UNIGEN and 120°F LLNL URFC).

2.2.1.3. System integration. One of the key challenges in the deployment of RFCs for energy storage is the evolution of a compact reliable system package that can implement the reversible cycle. In this regard, the EPRI and NASA programs have both included development of integrated test articles. Each of these systems includes all of the mechanical and electrical control required for fully automatic reversible operation as well including on-board hydrogen storage.

The EPRI system is a liquid water feed electrolysis cycle–passive fuel cell water removal system with active cooling. The NASA test unit, by contrast, was designed as a zero-gravity compatible, static water feed electrolyzer with passive cooling which has reduced system complexity and parts count. These early test units, Fig. 6, illustrate the ability of the RFC cycle to be implemented in compact systems despite the need to manage complex reversible system dynamics.

2.2.1.4. URFC efficiency. Electric to electric round trip efficiency calculations were completed to compare the Proton UNIGEN to another URFC and a dedicated fuel cell/dedicated electrolyzer. This comparison can be seen in Fig. 7.

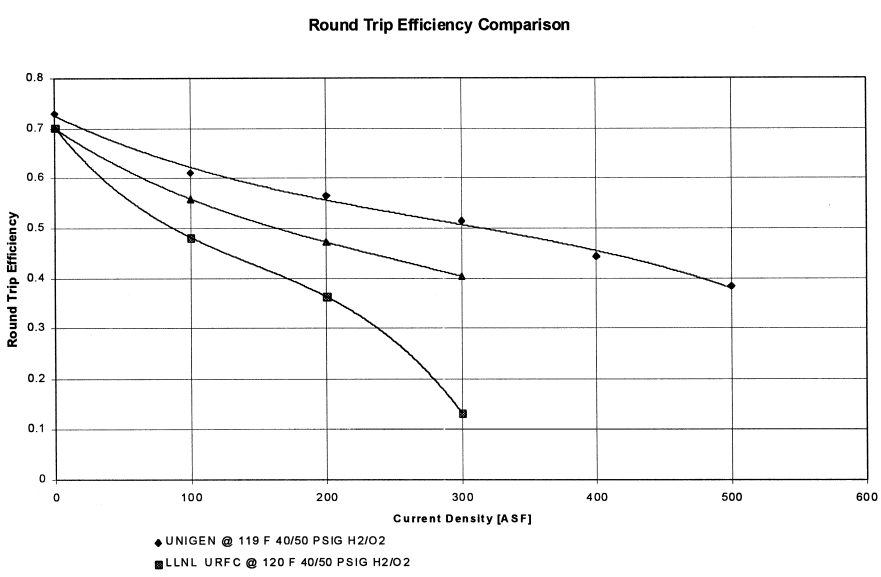

Fig. 7. URFC round trip efficiency. ◆ UNIGEN at 119°F 40/50 PSIG H_2/O_2. ■ LLNL URFC at 120°F 40/50 PSIG H_2/O_2. ▲ Literature reference fuel cell/NASA HOGEN® 10 electrolyzer at 120°F 140/118 PSIG H_2/O_2 normalized.

Table 1
Hydrogen storage technology comparison

Characteristic	Low press tankage	High pressure	Carbon nanofibers-tubes	Metal hydrides
Volume	High	Medium	Low	Low
Weight/unit stored	Medium	Medium-steel tanks Low-advanced tanks	Low	Medium
Cost per unit of storage	Low tank cost is low and operate at stack pressure	Low–moderate (additional equipment needed to pressurize above stack pressure)	NA–	NA–High for present technology projected to be very low in production
Life	20+ years	20+ years	TBD	TBD
Cycle life	20,000+	20,000+	TBD	TBD
Temperature effects	None — tank standards include temperature effects	None — tank standards include temperature effects	TBD	Must remove heat when charging
Charge measurement	Pressure — direct	Pressure — direct	TBD	Pressure — calibrated for hydride
Technical risk	Low	Low	High	Medium for 5% loading
Charging issues	None — operates at electrolysis stack pressure (10 bar)	Requires compressor above stack pressure	TBD	Requires 10 bar pressure and dry gas
Technical maturity	High	High	Low	Medium

The round trip efficiency of the process is simply the overall efficiency for the electrolysis process multiplied by the overall efficiency for the fuel cell process. The calculation assumes an equivalent division of operating time between fuel cell and electrolysis cell operation. Round trip efficiency calculations were performed by using data at the following conditions: UNIGEN (119°F 40/50 PSIG H_2/O_2), LLNL URFC (120°F 40/50 PSIG H_2/O_2), and a reference Fuel Cell/HOGEN® 10 Electrolyzer combination (120°F 140/118 PSIG H_2/O_2 normalized).

Efficiency calculation. The following calculations determine the round trip efficiency of the electrolysis and fuel cell processes.

Electrolysis process. The voltage efficiency of the electrolysis process is defined as follows:

$$V_{\text{eff}} = \text{Thermal Neutral Voltage}/\text{Cell Voltage} = 1.53/V$$

The current efficiency of the process is defined as follows:

$$I_{\text{eff}} = (\text{Cell Current Density} - \text{Diffusion Losses}) / \text{Cell Current Density} = \text{ASF} - (\text{ASF}\,O_2 + \text{ASF}\,H_2)/\text{ASF}$$

Gas diffusion losses are defined from the parametric relationship that follows for Nafion 117:

$$\text{ASF}\,O_2 = (1467/(348 - T) - 3.7) * P/132.26$$

$$\text{ASF}\,H_2 = (2561/(421 - T) * P/132.26$$

In these equations ASF H_2 and ASF O_2 are permeation losses in amperes per square foot. T is temperature in degrees Fahrenheit and P is gas pressure in psia. The overall efficiency of the electrolysis process is equal to the voltage efficiency multiplied by the current efficiency.

Fuel cell process. The voltage efficiency of the fuel cell process is defined as follows:

$$V_{\text{eff}} = \text{Cell Voltage}/\text{Thermal Neutral Voltage} = V/1.53$$

The current efficiency of the process is defined as follows:

$$I_{\text{eff}} = (\text{Cell Current Density} - \text{Diffusion Losses}) / \text{Cell Current Density} = \text{ASF} - (\text{ASF}\,O_2 + \text{ASF}\,H_2)/\text{ASF}$$

The overall efficiency of the electrolysis process is equal to the voltage efficiency multiplied by the current efficiency.

In Fig. 7, the Proton UNIGEN showed highly promising results based on these efficiency calculations. This is very encouraging due to the fact that the UNIGEN was compared to established references.

2.3. Hydrogen storage subsystem

2.3.1. Function and characteristics

While electrolysis is key to the functionality of the H_2O RFC, effective hydrogen storage is the key to practical implementation. To achieve both technical and commercial success, a manner of storing hydrogen is required that combines cost, life, installation, and other factors to a degree that is acceptable for a given application. Table 1 summarizes an initial evaluation of four classes of hydrogen storage from low pressure tankage to advanced carbon and metal hydride materials. As shown here, the low pressure tanks are the most voluminous of the options but are presently the most cost-effective and are a highly mature technology. Given the large size of these tanks, this form of storage can be most practically utilized in remote or commercial setting where the tank can be suitably sited. The impact of tank siting, however, can be minimal as the fuel cell can be located near the load while the tank can be located external to the building in a suitable utility area. Of course carbon and metal hydride technologies are very promising and when matured are likely to become the preferred method of storage.

The use of modified liquid propane tanks for hydrogen is highly viable and a cost-effective option that has now been proven through many years of application by industrial gas companies. For example, one company, Brown Industries of Salina, KS has installed over 50 large low pressure liquid propane tanks that are now used for hydrogen storage with over 15 years of reliable operation. Given both the highly mature state of the liquid propane tank industry and the long-term success in using these tank for hydrogen, this form of storage appears to be a low cost practical means of storing hydrogen in an RFC system.

3. Benefits compared to conventional batteries

3.1. General

Implementation of an RFC using hydrogen as an energy storage medium provides a manner of storing energy that has many advantages. Stored as hydrogen, the energy can be retained for long periods of time and is insensitive to cycle life, temperature, or self-discharge. Table 2 below, highlights the comparative performance of the URFC as compared with conventional batteries. Costs data are based on a 200 kW h RFC system supplying a 2-kW load and an equivalent set of GNB Absolyte lead–acid batteries typically used for renewable energy storage systems.

These advantages can provide both an improvement of energy storage utility for existing applications and can create new opportunities. As discussed in the initial example, RFCs used as back-up or standby power systems can provide a higher degree of utility than conventional battery sets by providing longer periods of back-up power with less installation impact at lower overall cost. In grid-connected applications, the ability to store large amounts of energy without life or cycle life limitations enables the

Table 2
RFCs show significant advantages over batteries for many applications

	Batteries	URFC
Life cost 200 kW h system	US$120,000	US$20,000
Incremental additional storage life cycle cost	US$150–300/kW h	US$20/kW h
Calendar life	5–8 years	System: 20 years with maintenance
Cycle life	6400 at 10% DoD 800 at 100% DoD	20,000 + cycles at 100% DoD
Maintenance required	Complete battery replacement after cycle life or calendar life limit reached	Cell stack only refurb after 60,000 h
Environmental operating hazard	Batteries need indoor storage, acid present	H_2 stored outside system can be either indoor or outdoor
Disposal hazard	Lead, acid issues	None: discharged system has no hazardous materials

RFC to be used to assist utilities via distributed load management. In such an application, the RFC generates and stores hydrogen during off-peak hours and generates electricity at periods of peak demand.

In off-grid applications such as PV or wind-based energy systems, power for dark or low-wind conditions is conventionally provided by batteries coupled to a diesel generating set. In such an application, the batteries supply power until their stored energy is depleted then the generating set provides additional power by recharging the batteries. For these off-grid applications, the RFC could replace most of the batteries and greatly reduce or eliminate the need for a back-up generating set. If the RFC were coupled to a reformer that could utilize a hydrocarbon fuel, the generating set hardware could be eliminated altogether while the use of stored hydrogen as the primary energy storage medium would minimize the logistic resupply of the back-up hydrocarbon fuel.

3.2. Overall cost-effectiveness

As shown in Fig. 8, the URFC can achieve considerable cost advantage where the amount of energy stored is high relative to the instantaneous power output from the fuel cell. This relationship holds for a significant range of conditions. Fig. 8 illustrates the relationship of Life Cycle Cost to energy stored for a 2 kW power source as compared with conventional Absolyte lead–acid batteries. As shown here, the difference in cost can become quite dramatic as the amount of energy stored increases, but batteries do show favorable characteristics as the energy to power ratio (kW h/kW) decreases. In the development of these projections, the end user price paid for the 2 kW fuel cell is estimated at US$1000/kW and the cost of energy storage is estimated at US$20–US$30/kW h. Energy storage data is derived actual quotations for low pressure tankage in low (1–10) quantity purchases. Fuel cell estimates are for mature production based on internal Proton Energy Systems, projections for this size unit and represent the price paid by an end-user including markups for distribution.

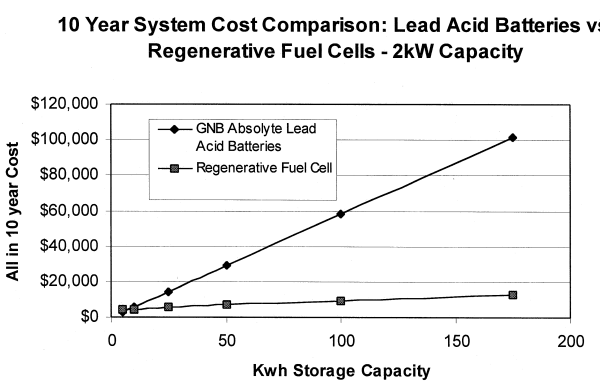

Fig. 8. 10-year life cycle cost comparison of URFC and batteries.

3.3. Comparison to new energy storage technologies

While lead–acid batteries are now the mature and dominant technology for energy storage the H_2–O_2 RFC is only one of many emerging energy storage technologies that are under active development [3] including:

- Zinc–air batteries
- Lithium polymer batteries
- Zinc–bromine batteries
- Nickel zinc batteries
- Sodium sulfur batteries
- Zinc–air fuel cells
- Ultracapacitors
- Flywheels
- Superconducting Magnetic Energy System (SMES)

These technologies span a wide range of power and energy applications from the conventional standby role to provision of very high levels of power supplied for a short time, such as provided by superconducting storage. Table 3 summarizes these technologies together with the H_2–O_2 RFC with respect to several key parameters.

As shown here, a number of technologies also offer promise of improved energy storage capability but only the RFC technologies, in the Zn–Air and Hydrogen–Air configurations, offer the promise of true low-cost, high-capac-

Table 3
The H_2–O_2 RFC and other emerging energy storage technologies

Technology	Life	$/kW h	W h/kg	W h/l	Comments
Zinc–air batteries		> US$400	200+	275+	Cycle life limited to < 70 cycles Prototype far from commercialization
Lithium polymer batteries	1200 h (200 cycles at 80%$ DoD)	US$600	155	220	Prototypes in field test Production 2001
Zinc–bromine batteries		400	70–90		Prototype field test 2000 ZBB, SEA Austria developing (license from Exxon) Target size 0.5 MW
Nickel zinc batteries	100 to 300 cycles	100–300	> 100		Delco Remy, ERC, LBL Temp range −20°C to +60°C
Sodium sulfur batteries	1500+ cycles	180 to 350 at > 400 kW h	80	90	ABB, Hitachi, Yuasa, Silent Power, Nastech 30 years development cost, safety, thermal
Regenerative zinc–air fuel cells		US$60 to US$125 at 4 kW, 32 kW h level	150–200	200–250	Metallic power planning commercial introduction
Flywheels	Long cycle life, wide temperature range	2000–4000	20		High power, short discharge 1st applications
Superconducting magnetic energy system (SMES)					500 kW–2 MW initial systems < 1 kW h, very fast response; Suitable for MW size applications
H_2–O_2 or H_2–air RFC	> 20,000 cycles > 40000 hours operating	90–150 at 4 kW, 32 kW h	400–1000 at 200–300 bar, 100–150 at 10–20 bar		Additional kW h < US$20/kW h, Small power unit can locate External storage unit −60°C to +60°C, Self-regenerating with no operator intervention

ity systems due to the separate optimization of power and energy functions.

4. Summary

The RFC is rapidly evolving to be able to provide high levels of energy storage capability at a fraction of the cost of conventional lead–acid batteries and could achieve commercial viability sooner than many PEM fuel cell architectures that require reformed hydrocarbons. This is due to the low cost and high availability of medium pressure hydrogen storage, the recent advancement in self-pressuring PEM electrolyzers and the rapid development of both primary and reversible PEM fuel cell stacks and systems. Two of the three key elements of the RFC, the PEM electrolyzer and the hydrogen storage are now commercially available and the final element, the fuel cell or reversible cell is rapidly progressing. Storage of hydrogen in medium pressure tanks is cost-effective but limited by tank size; it is suitable for remote or industrial applications. Development of both high pressure generation capability and of low pressure solid state storage in hydrides or in carbon will enhance widespread acceptability and use.

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