Realizing the Dream: Greenhouse Gas Free Transportation Through the Application of Canada's Fuel Cell Technology

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Abstract

Fuel cells (FCs) generate electrical power without combustion using electrochemical processes and therefore do not have to first convert the fuel to heat and shaft-power before electricity is produced. They are, therefore, high efficiency energy converters and unlike batteries are able to continuously provide electrical power as long as fuel and air are fed to the electrodes. Fuel cells are now of great interest to the automotive industry throughout the world (1). The most economic fuel for fuel cells is reformed natural gas that is favoured by the utility industry, but methanol (as well, ethanol is being proposed by a GM, Shell, Argonne study(2)) is one contender for fuel cells being developed for transportation. Several different fuel cell technologies exist. Recent developments in solid oxide fuel cell (SOFC) technology suggest that SOFCs could more easily adapt to conventional gasoline and diesel fuels and are less prone to catalyst poisoning than other fuel cells such as the solid polymer electrolyte (PEM) type, often also called the proton exchange membrane (PEM) fuel cell, being developed by Ballard in Canada. However, there remain significant development problems for SOFC technology related to the high operating temperatures (700 to 1000 deg C).

In this paper, the range of fuel cell technologies now being developed will be reviewed since there is a convergence in the use of fuel cells for the production of power in distributed fixed systems and power sources for transportation.

The factors that will determine the dominating technologies for automobile and truck propulsion in the future are the same as those currently in play. These factors are: performance, cost and convenience of the technologies. A common feature in these three factors is efficiency from which the environmental impact of the technology is largely determined. Electric propulsion in some form will ultimately be favoured over combustion systems because combustion systems are limited by fundamental thermodynamic factors that do not apply to the electric systems. Therefore, electric energy conversion of fuels by batteries, supercapacitors, and fuel cells is cheaper in fuel use and therefore more economical to the vehicle owners and produces less environmental impact.

Furthermore, with deregulation of electric utilities in many parts of the world (3), serious concerns are being raised about the reliability of the electric grid. This paper will explore why there will be increased commercial incentives for joint ventures between the utilities and the automotive industry to develop new generations of electric and hybrid/electric vehicles and the supporting infrastructure. In some cases, the infrastructure will include the concepts of distributed generation. The "multiple use hybrid electric vehicle" (MUHEV) suggested by ESTCO in 1995 is a concept in which the power plant on the electric vehicle will also be used to

feed electric power and heat into the home/electric power grid. The MUHEV concept could offer very significant benefits in flexibility and operational performance and make a significant contribution to reduction in greenhouse gas production in transportation.

Introduction

The multi-use hybrid electric vehicle (MUHEV) is a concept in which transportation utilizing clean hybrid electric vehicles is integrated with building heating and cooling as well as the electric power grid to form a new highly efficient transportation and distributed energy system (4). In a study conducted in the mid-1990s, gasoline and natural gas fueled ICE generators and a micro turbine were used in the analysis as sources of auxiliary power on a hybrid vehicle which was designed to generate heat and electricity while connected to building. Fuel cells were not yet sufficiently developed to be included in the analysis. Unfortunately, this analysis did not show a net value to the vehicle owner for the production of electricity in competition with a power from the utility grid except in remote areas where the grid would be unavailable or where power costs were high.

The total power capability of automobiles produced each year now exceeds the total capacity of all the power stations in the world. The integration of mobile power sources and fixed power systems has begun to attract considerable attention since the introduction of commercially viable hybrid electric drives which are, in effect, mobile electric generators. Other authors have suggested that the owner of such hybrid electric vehicles could actually make money by selling power back into the grid at a profit and that this fact will be a key factor in the commercialization path for hydrogen fuel cells for both mobile and distributed power applications (5).

In Canada, Ballard has been the world leader in the commercialization of fuel cells, having made brilliant strategic alliances with the automotive industry and technical progress beyond the wildest dreams of only a few years ago (1). Now the automobile industry is faced with enormous challenges to integrate a new propulsion technology and hydrogen-based fuel infrastructure which is poised to displace the less efficient and polluting 100 year old internal combustion engine (ICE).

Fuel Cell Developments-the technological options

The first fuel cells to enter the utility market in the late 1980s have been the phosphoric acid fuel cells (PAFCs). There are over 170 of the 200KW PAFC systems operating on natural gas now in service. Some of these units have been in operation for over tens of thousands of hours. The PEMFCs, SOFCs and Molten Carbonate fuel cells (MCFCs) are in field test and demonstration at this time. The efficiencies of these FCs range from 35 to 40% for PAFCs to 60% for the MCFC and SOFC. The quietness and clean running characteristics of FCs offer very flexible options for power plant siting. The greatest challenge for FCs is to reduce their costs so that they can compete with turbine and conventional energy conversion technologies. Similar to turbine technology, FCs, especially the high temperature MCFCs and SOFCs, offer extremely high efficiency when used in co-generation applications.

Types of Fuel Cells

Fuel cells can be classified by use of various categories, depending on the combination of type of fuel and oxidant, whether the fuel is processed outside (external reforming) or inside (internal reforming) of the fuel cell, the type of electrolyte, the temperature of operation, whether the reactants are fed to the cell by internal or external manifolds, etc. It is convenient (and has become standard practice) to primarily refer to fuel cells by the type of electrolyte used. This is logical because many other characteristics, particularly operating temperature, are limited by the electrolyte properties. A brief description of various electrolyte cells of current interest follows.

Proton Exchange Membrane (PEM) Fuel Cell:

The electrolyte in this fuel cell is an ion exchange membrane (fluorinated sulfonic acid polymer or other similar polymers) which is an excellent proton conductor. The only liquid in this fuel cell is water, thus corrosion problems are minimal. Water management in the membrane is critical for efficient performance; the fuel cell must operate under conditions where the by-product water does not evaporate faster than it is produced because the membrane must be hydrated. Because of the limitation on the operating temperature imposed by the polymer and problems with water balance, usually less than 120°C, a H_2-rich gas with little or no CO is used, and higher catalysts loadings (Pt in most cases) than those used in PEMFCs are required in both the anode and cathode.

Alkaline Fuel Cell (AFC):

The electrolyte in this fuel cell is concentrated (85 wt%) KOH in fuel cells operated at high temperature (~250°C), or less concentrated (35-50 wt%) KOH for lower temperature (< 120°C) operation. The electrolyte is retained in a matrix (usually asbestos), and a wide range of electrocatalysts can be used (e.g., Ni, Ag, metal oxides, spinels and noble metals).

Phosphoric Acid Fuel Cell (PAFC):

Concentrated phosphoric acid is used for the electrolyte in this fuel cell, which operates at 150-220°C. At lower temperatures, phosphoric acid is a poor ionic conductor and CO poisoning of the Pt electrocatalyst in the anode becomes more severe. The relative stability of concentrated phosphoric acid is high compared to other common acids, consequently the PAFC is capable of operating at the high end of the acid temperature range (100-220°C). In addition, the use of concentrated acid (~100%) minimizes the water vapor pressure so water management in the cell is not difficult. The matrix universally used to retain the acid is silicon carbide (3), and the electrocatalyst in both the anode and cathode is Pt. ***Molten Carbonate Fuel Cell (MCFC)***:

The electrolyte in this fuel cell is usually a combination of alkali (Na, K) carbonates, which is retained in a ceramic matrix of $LiAlO_2$. The fuel cell operates at 600-700°C where the alkali carbonates form a highly conductive molten salt, with carbonate ions providing ionic conduction. At the high operating temperatures in MCFCs, Ni (anode) and nickel oxide (cathode) are adequate to promote reaction and noble metals are not required.

Solid Oxide Fuel Cell (SOFC):

The electrolyte in this fuel cell is a solid, nonporous metal oxide, usually Y_2O_3-stabilized ZrO_2. The cell operates at 650-1000°C where ionic conduction by oxygen ions takes place. Typically, the anode is Co-ZrO_2 or Ni-ZrO_2 cermet, and the cathode is Sr-doped $LaMnO_3$.

Fuel Cell Characteristics

Fuel cells have many favourable characteristics for energy conversion devices; several of these general characteristics are:

- high energy conversion efficiency relatively independent of size or load
- modular design
- size flexibility
- very low environmental intrusion
- cogeneration capability
- siting ability
- fuel flexibility
- rapid load following capability

The general negative features of fuel cells for energy conversion include:

- sensitivity to certain fuel contaminants
- high market entry cost
- endurance/reliability has not been demonstrated

One of the main attractive features of fuel cell systems is their expected high fuel-to-electricity efficiency (40-60% based on lower heating value of the fuel), which is higher than that of many competing energy conversion systems. In addition, fuel cells operate at a constant temperature and the heat from the electrochemical reaction is available for cogeneration applications. Since fuel cells operate at near constant efficiency, independent of size, small fuel cells operate nearly as efficiently as large ones (the fuel processor efficiency is size dependent, therefore, small fuel cell power plants using externally reformed hydrocarbon fuels would have a lower overall system efficiency). Thus, fuel cell power plants can be configured in a wide range of electrical output, ranging from watts to megawatts. Fuel cells are quiet and operate with virtually no gaseous or solid emissions, but they are sensitive to certain fuel contaminants which must be minimized in the fuel gas. Table 1 summarizes the impact of the major constituents within fuel gases on the various fuel cells. The two major impediments to the widespread use of fuel cells are: 1) high initial cost and 2) endurance operation; it is these two aspects which are the major focus of technological effort.

Table 1 Summary of Major Fuel Constituents Impact on PAFC, MCFC, SOFC, and PEFC

Gas Species	PAFC	MCFC	SOFC	PEMFC
H_2	fuel	fuel	fuel	fuel
CO	poison (>0.5%)	fuel	fuel	poison (> 10 ppm)
CH_4	diluent	diluent	fuel	diluent
CO_2 & H_2O	diluent	diluent	diluent	diluent
S as (H_2S & COS)	poison (>50 ppm)	poison (> 0.5 ppm)	poison (> 1.0 ppm)	No studies to date (11)

Advantages/Disadvantages of Different Types of Fuel Cells

Different types of fuel cells have significantly different operating regimes. As a result, their materials of construction, fabrication techniques, and system requirements differ. These distinctions result in individual advantages and disadvantages which govern the potential of the various cells to be used for different applications.

The AFC was one of the first modern fuel cells to be developed, beginning in 1960. The application at that time was to provide on-board electric power for the Apollo space vehicle. Desirable attributes of the AFC include its excellent performance on hydrogen (H_2) and oxygen (O_2) compared to other candidate fuel cells due to its active O_2 electrode kinetics and its flexibility to use a wide range of electrocatalysts, an attribute which provides development flexibility. Once development was underway for space application, terrestrial applications began to be investigated. Developers recognized that pure hydrogen would be required in the fuel stream. This is because the carbon dioxide (CO_2) in any reformed fuel reacts with the potassium hydroxide (KOH) electrolyte to form a solid carbonate, destroying the electrolyte's ion mobility. Pure H_2 could be supplied to the anode by passing a reformed, H_2-rich fuel stream by a precious metal (palladium/silver) membrane. The H_2 molecule is able to pass through the membrane by absorption and mass transfer, and into the fuel cell anode. However, a significant pressure differential is required across the membrane and the membrane is prohibitive in cost. Even the small amount of CO_2 in ambient air, the source of O_2 for the reaction, would have to be scrubbed. Investigations soon showed that the scrubbing of the small amount of CO_2 within the air, coupled with the purification of the hydrogen, was not cost effective and that terrestrial application of the AFC could be limited to special applications at best.

The CO_2 in the reformed fuel gas stream and the air does not react with the electrolyte in an acid electrolyte cell, but is a diluent. This attribute and the relatively low temperature of the PAFC made it a prime, early candidate for terrestrial application. Although its cell performance is somewhat lower than the alkaline cell due to the cathode's slow oxygen reaction rate, and although the cell still requires hydrocarbon fuels to be reformed into an H_2-rich gas, the PAFC's system efficiency improved due to its higher temperature environment and less complex fuel conversion (no membrane and attendant pressure drop). The need for the process air scrubber is also eliminated. The rejected heat from the cell is high enough in temperature to heat water or air in a system operating at atmospheric pressure. Some steam is available in pressurized PAFCs, a key point in expanding cogeneration applications.

PAFC systems achieve about 37 to 42% electrical efficiency (based on the higher heating value (HHV) of natural gas). This is at the low end of the efficiency goal for fuel cell power plants. PAFCs use high cost precious metal catalysts such as platinum. The fuel has to be reformed externally to the cell, and carbon monoxide (CO) has to be shifted by a water gas reaction to below 3 to 5 vol% at the inlet to the fuel cell anode or it poisons the catalyst. These limitations have prompted development of the alternate, higher temperature cells, MCFC and SOFC.

Many of the disadvantages of the lower temperature cells can be alleviated with the higher operating temperature MCFC (approximately 650°C). This temperature results in several benefits: the cell can be made of commonly available sheet metals that can be stamped for less costly fabrication, the cell reactions occur with nickel catalysts rather than with expensive precious metal catalysts, reforming can take place within the cell provided a reforming catalyst is added (results in a large efficiency gain), CO is a directly usable fuel, and the rejected cell heat is of sufficiently high temperature to drive a gas turbine and/or produce a high pressure steam for use in a steam turbine or for cogeneration.

The MCFC has some disadvantages, however: a source of CO_2 is required at the cathode to form the carbonate ion, the cell has a very low sulfur tolerance compared to the PAFC, and the higher temperatures promote material problems, particularly mechanical stability which impacts life.

The SOFC is the fuel cell with the longest, continuous development period, starting in the late 1950s, several year before the AFC. Since the electrolyte is a solid, the cell can be cast into flexible shapes, such as tubular, planar, or monolithic. The solid construction of the cell also alleviates any corrosion problems characterized by the liquid electrolyte cells and has the advantage of being impervious to gas cross-over from one electrode to the other. The absence of liquid also eliminates the problem of electrolyte movement or flooding in the electrodes. The kinetics of the cell are fast and CO is a directly useable fuel as it is in the MCFC. There is no requirement for CO_2 at the anode as with the MCFC. At the temperature of presently operating SOFCs (1000°C), fuel can be reformed within the cell with no additional reforming catalysts. The temperature of an SOFC is significantly higher than that of the MCFC. However, some of the rejected heat from an SOFC is needed for preheating the incoming process air. The high temperature of the SOFC has its drawbacks. There are thermal expansion mismatches among materials and sealing between cells is difficult in the flat plate configurations. The high operating temperature places severe constraints on materials selection and results in difficult fabrication processes. The SOFC also exhibits a high electrical resistivity in the electrolyte which results in a lower cell performance than the MCFC by approximately 100 mV. Researchers would like to develop cells at a reduced temperature of 650°C, but the electrical resistivity of the solid electrolyte material presently used increases.

The PEMFC, like the SOFC, has a solid electrolyte. As a result, this cell exhibits excellent resistance to gas crossover. In contrast to the SOFC, the cell operates at a low 80°C. This results in a capability to bring the cell to its operating temperature quickly, but the rejected heat cannot be used for cogeneration or additional power purposes. Test results have shown that the cell can operate at very high current densities compared to the other cells.

Developers are using the advantages of the fuel cells to identify early applications of fuel cell power plants. It is the function of development to mitigate the disadvantages described to expand the application potential. Many research development issues are being addressed for each of the cell types.

Transportation

In Canada, Ballard Power Systems has made significant technical and commercial progress in field trials with their PEM fuel cell systems in transportation applications (1,6,7). Ballard fuel cells have been installed in buses and been incorporated into a large number of developmental vehicles by major automobile companies such as Ford. However, to date, Japan has been at the forefront of advanced electric power source commercialisation for automobile applications. In December 1997, Toyota began to sell the world's first mass-produced hybrid gas engine/electric vehicle called the Prius. Over 50,000 of these vehicles are presently in service and have been sold in Canada and the USA. In short, Prius achieves twice the fuel economy of normal gasoline fuelled vehicles in the same class, while producing only one-tenth of the emissions permitted by Japanese regulations, and at a selling price comparable to that of a loaded conventional vehicle (see Table 2 for specifications of two Japanese hybrids now available in North America. All major automobile manufacturers are investing significantly in power source research that includes electric, hybrid, cleaner conventional engines, and compressed natural gas vehicles. The ICE/battery hybrid vehicle is a prime target for the fuel cell and represents a stepping-stone to the truly zero emission vehicle. An excellent up to date summary of the status of the automobile industry fuel cell activities is provided by the recent Fuel Cell Summit (8).

Table 2 Specifications of two hybrid vehicles now sold commercially (from Kempton et al (9))

Vehicle Characteristics	Toyota Prius	Honda Insight
Battery type	NiMh. 6.5 Ah 38 modules. 6 cells. 1.2V	NiMh. 6.5 Ah. 20 modules. 6 cells. 1.2 V
Battery Energy stored (kWh)	1.8	0.9
Battery cycle life (cycles)	1000	1000
Battery calendar life (years)	5-6	5-6
Maximum electrical power output to motor (kW)	30	10
Battery cost[c] ($/kWh)	843-1123	843-1123
Replacement labor (h)	2	2
Gasoline tank (gallon)	12	10
Efficiency electrical (kWh/gal)	8.8	n.a.
Max range (miles)	600	650
Efficiency of vehicle (mi/gal)	50	65

The potential impact of the EV and HEV vehicle fleet in California on the electric utilities can be seen from the size of the projected fleet shown in Table 3 and that the cumulative power capability would be over 2000 MW electric (9).

Table 3 Projected EV and HEV vehicles for sale in California under CARB regulations (advanced technology partial zero emission vehicle (AT-PZEV)(from Kempton et al (9))

	Number of Vehicles Sold Annually					
	2003	2004	2005	2006	2007	2008
If 4% ZEV (no AT-PZEVs)						
ZEVs						
If 100% full function EV	9,300	9,300	9,300	9,300	9,300	9,300
If 100% City EV	23,500	23,500	23,500	29,400	29,400	29,400
AT-PZEV[b] (e.g. Hybrid)	0	0	0	0	0	0
If 2% ZEV and 2% AT-PZEV						
ZEVs						
If 100% full function EV	4,650	4,650	4,650	5,800	5,800	5,800
If 100% City EV	11,750	11,750	11,750	14,700	14,700	14,700
AT-PZEV[b] (e.g. Hybrid)	10,700	21,500	32,200	43,000	43,000	43,000

[a] Figures do not include the potential effect of efficiency credit or power train warranty credit.
[b] AT-PZEVs are assumed to be vehicles with a 0.45 allowance (before multiplier), such as the hybrid vehicles, Toyota Prius and Honda Insight.

Distributed power

Distributed generation (DG) consists of the use of small power sources, generally less than 30MW units, located close to the user and to the load. DG sources are usually connected to the existing power grid. For the past 30 years the large central coal-fired and nuclear power stations have become less economic and difficult to site due to environmental issues. However, the cost and performance of small and modular power source options have improved. There are now DG options from large 300MW gas-fired combined-cycle power plants to very small plants of a few kilowatts.

The utility industry is also restructuring as a result of government deregulation, especially where electrical power rates are highest, such as in the USA and in parts of Canada (e.g., Ontario). This allows customers to select the best and cheapest options for energy that best meets their needs. In many cases, DG will be the most likely option. It should also be noted that the gas industry is also being deregulated and considerable restructuring is occurring in it as well. In some cases the electrical and gas industries are combining to form energy companies in which there are new synergies possible with respect to the use of DG.

The gas industry identifies six DG technologies: from the large and fully commercial diesel engines through gas engines, gas turbines, microturbines, fuel cells, and photovoltaics. Microturbines and fuel cells are not yet fully commercial but are very close. By the year 2010 fuel cells can be expected in the DG market place

The applications of DG fit into a new concept of the energy service provider. Due to deregulation, competition is separating the services of the energy sector into the following categories: basic energy supply, distribution, capacity to meet peak load, reserve capacity to maintain additional capacity for emergencies, reliability from outages, power quality, and back-up and standby power services. It is therefore likely that the provision of energy will become much more complex and open many new options to the energy user. Indeed, power marketers are already operating in North America creating an active power trading market.

The use of DG is only one part of a reinvented power market. The magnitude of the changes and the uncertainty of the timing are creating a strong incentive for many power customers to consider DG as a form of security since there is likely to be less reliability of power in a more diversified and deregulated industry. In some cases, companies are being forced to downsize and are reluctant to invest in the needed infrastructure and maintenance due to financial pressures brought about by the restructuring. These factors can lead to major outages, some of which have already occurred, e.g. those in the US in 1996 and 1998 and in California over the past two years.

The cost electric power generated by two of the hybrid electric vehicles now being sold is shown in Table 4 with fuel based on gasoline and Table 5 based on CNG (9). Several market scenarios were analyzed and in several instances in California the owner of an HEV could potentially make a net profit by sale of power to the grid. Analysis indicates that for the system of integrated grid to HEVs and EVs there must be a large fleet of vehicles which are managed by a telemetric control so that the utility can draw upon a statistically known power supply and that the sale of power by an individual owner does not restrict the use of the vehicle for the owner.

Table 4 Cost to HEV owner $ per kWh for sale to grid based on gasoline fuel (from Kempton et al (9))

Costs	Toyota Prius (16.6 kW)	Honda Insight (10kW)
C_E ($/kWh)	0.21	0.23
C_D ($/kWh)	0.04	0.06
C_{fuel} ($/gallon)	1.50	1.50
C_{AC} ($/year)	578	578

Table 5 Cost to HEV owner $ per kWh for sale to grid based on CNG fuel (from Kempton et al (9))

Costs	Toyota Prius (16.6 kW)	Honda Insight (10 kW)
C_E ($/kWh)	0.19	0.21
C_{fuel}($/kg)	0.47	0.47
C_D($/kWh)	0.04	0.06
C_{AC} ($/year)	580	580

Convergent trends: electric drive, distributed power, and telecommunications

The rapid development of fuel cell technology for vehicle propulsion and for distributed power applications is giving rise to much discussion on fuel options (8). There is no agreement in the automotive industry with respect to the hydrogen source for on-board fuel cells. Direct hydrogen storage in high- pressure tanks or hydrides, reformed from methanol or gasoline are all options being promoted by major players. However, if reformed hydrogen were available from domestic sources where fuel cells were being applied in a distributed power mode, then vehicle refueling could be easily accomplished overnight. The two-way grid connection of fuel cell vehicles is now being considered as was suggested in the MUHEV study (4). The concept is shown diagrammatically in Figure 1 below.

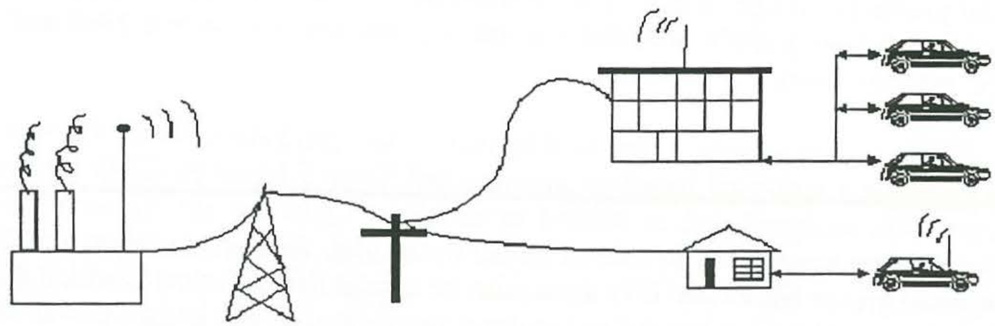

Figure 1 Two-way energy flow schematic with control system based on the MUHEV concept (diagram from Kempton et al (9))

In the case of battery EVs, the state of charge of the vehicle battery over a 24-hour cycle is shown in Figure 2. A "smart" controller is necessary that recognizes the energy required for the drive home and limits the energy delivered to the grid. The key to this overall system is the development of advanced telecommunication technology that keeps the vehicle in touch with the grid manager likely through an intermediate company that coordinates the power available from a fleet of vehicles that it manages. A similar system would apply to hybrid vehicles or to fuel cell vehicles, but these would have the fuel use controlled in the energy to grid mode so as not to inconvenience the vehicle owner.

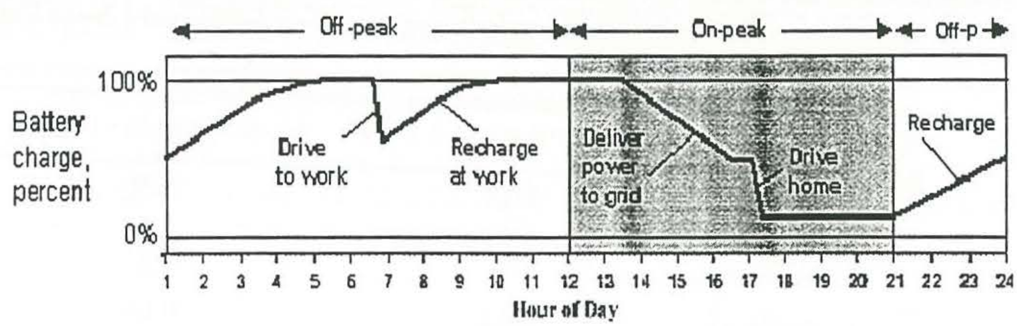

Figure 2 State of charge of an EV operated as a MUHEV (diagram from Kempton et al (9))

The market opportunities associated with a joint development of fuel cells in mobile and fixed applications have recently been discussed by Lovins and Williams (5). The move by the automotive industry, strongly influenced by government and environmental pressure groups, to develop super efficient vehicle designs has also opened many new options for the propulsion systems. However, the electric drive option is clearly favored no matter what the prime power source due to the need for efficiency and low emissions. When the renewable energy sources are considered in the context of a growing hydrogen production industry, they are seen to expand as well.

In a significant expansion of the MUHEV concept, the vehicle–to-grid two-way sharing of electrical power has been analyzed and some striking findings have been reported (9). Even without the inclusion of heat as in the MUHEV analysis, there appears to be the possibility of very substantive revenue to the owners of electric drive vehicles that are grid connected. Table 5 shows that for regulation applications, which are the most positive, owners could have net revenues of several thousand dollars per year. This type of approach could alleviate the need for special incentives for the purchase of EV or HEVs.

Table 5 Revenue and costs for EV and HEV owners to sell to the grid for regulation application (from Kempton et al (9))

Vehicle Type	Power (kW)	Annual Revenue *1998*	*1999*	*2000* [a]	Annual Costs
Battery					
Lead-acid prototype	16.6	\$4.479	\$4.688	\$9.813	\$1.317
Honda EV Plus	16.6	\$4.479	\$4.688	\$9.813	\$2.756
Th!nk	16.6	\$4.479	\$4.688	\$9.813	\$1.906
Fuel Cell [b]					
On-board compressed H_2	16.6	\$2.567	\$2.671	\$7.796	\$1.756–\$5.551 [c]
Stationary reformer	16.6	\$2.567	\$2.671	\$7.796	\$3.290
Hybrid					
Enlarged battery	4.6	\$2.391	\$1.299	\$2.719	\$2.391
Gasoline/motor-generator [d]	16.6	\$2.567	\$2.671	\$7.796	\$3.326
Natural gas/motor-generator [d]	16.6	\$2.567	\$2.671	\$7.796	\$3.067

[a] In August of 1999, the CAISO began to operate separate markets for regulation down and regulation up.
[b] Providing only regulation-up (from vehicle to grid). The revenue will be only for regulation-up.
[c] For a range of energy cost (0.09-0.38) depending on the range of H_2 costs.
[d] Based on the Toyota Prius motor-generator nominal power 30 kW; V2G power 16.6 kW.

Summary

The conclusion of this review is that there is a convergence of industrial opportunities, that if accepted and developed, can lead more rapidly to both cleaner transportation and a reliable and affordable electrical supply with a growth in the use of renewable forms of energy. Fuel cell and battery technologies along with hydrogen fuel, in some form, will play a leading role. Electrochemistry is the key to the new century.

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