Future cars: The electric option

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Global economic, environmental and political issues are pushing car manufacturers to consider electric power systems as an alternative to the current spark ignition engine. In this article, we analyse the power and energy requirements of a modern car and conclude that a viable electric car could be operated with a 50 kW polymer electrolyte fuel cell (PEFC) stack to provide power for cruising and climbing, coupled in parallel with a 30 kW supercapacitor or battery bank to supply additional short term burst power during acceleration.

ENERGY is the pervasive element of a modern industrial economy. A substantial proportion of our present day energy need is met through fossil fuels derived from ultimately finite reserves and thus cannot be sustained indefinitely in the longer term. Besides, the deleterious effects of excessive consumption of carbonaceous fuels on the economy and ecology of a large part of the world is already apparent. While much debate surrounds the utilization of fully renewable energy sources like solar, hydro, biomass, etc. these will be unable to provide adequate energy into the foreseeable future. Instead, it is being increasingly realized that there is an urgent need to extract more useable energy from present non-renewable fuels.

Of all the sources of carbonaceous fuels, petroleum is by far the most convenient and therefore valuable. However, it is the least abundant and not widely distributed, rendering countries with the largest reserves disproportionate economic and political sway. Most recent estimates have suggested that, at present and projected discovery, production and consumption rates, world oil-supply will fail to meet demand by about the year 2010 (refs 1–4). Concerns of this kind have brought into sharp focus the need to develop new, more energy efficient and environmentally benign energy systems. Indeed, the development of systems of this kind is expected to become one of the significant drivers of national economies into the next millennium.

The vast majority of existing energy generating systems are of the thermo-mechanical type involving reciprocating engines or rotary turbines. They use the fuel in a controlled internal combustion or by raising high pressure steam. While well known reversible thermodynamic considerations impose a predictable efficiency limitation on heat engines of these kinds, additional irreversible losses associated with the expanding combustion products in the confinements of combustion chamber also occur. For example, with large multi-megawatt thermo-mechanical systems like diesel engines and gas turbines, thermal efficiencies in excess of 40% may be achieved and, with a combined cycle to raise steam from their hot exhaust, gas turbines can achieve values approaching 60%. By contrast, the smaller 100 kW class Otto cycle, spark-ignition engines as used in modern cars, can achieve little more than 20% efficiency under a typical range of driving conditions.

It has long been considered that electric traction for cars is a viable way of improving both the emission and energy efficiency of these vehicles. In the urban environment, battery-powered cars have the considerable advantages of essentially zero-emissions and high energy conversion efficiency. However, when overall emission and energy efficiency is extended to include battery charging and discharging, power generation and distribution, the actual global gains may not be so attractive[5]. Any actual gains will depend on the battery type and its operational characteristics as well as the energy source used in the power station. For example, it has been estimated that with the mixture of energy used to generate electrical power in Australia, battery-powered vehicles could lead to a 20% reduction in CO_2 emission[6].

In response to increasing concerns over urban air quality, the State of California enacted in 1994, legislation requiring that by 1998, 2% of cars offered for sale be zero-emission, increasing to 5% by 2000 and ultimately to 10% by 2003. These deadlines have subsequently been amended, largely because of the failure of battery-powered vehicles, which were originally seen as the solution, to perform at a level approaching that of the existing spark ignition-powered cars. Indeed, pure battery- powered cars are no longer regarded as an acceptable or viable alternative, except possibly for local commuter use. More recently, the advantage of on-board electricity generation in a fuel cell has been recognized and a considerable effort has been mounted internationally to develop systems with acceptable performance and cost to address the needs of the modern motorist.

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Traction kinematics

To properly assess options for systems to power electric vehicles, it is necessary to estimate quantitatively the power and energy required to propel a modern car of the type shown in Figure 1. Neglecting relatively minor losses due to road camber and curvature, the power required at the drive wheel ($P_{traction}$) may be written as:

$$P_{traction} = P_{grade} + P_{accel} + P_{tyres} + P_{aero}\,. \tag{1}$$

The first two terms in eq. (1) describe the rates of change in potential (PE) and kinetic (KE) energies associated with climbing and acceleration, respectively. The power required for these actions may be estimated from Newtonian kinematics, thus:

$$P_{grade} = \mathrm{d(PE)/dt} = Mgv \sin \theta, \text{ and} \tag{2}$$

$$P_{accel} = \mathrm{d(KE)/dt} = Mv\, \mathrm{d}v/\mathrm{d}t = Mav, \tag{3}$$

where M is the mass of the car, v its velocity, a its acceleration and tan θ the gradient.

The potential and kinetic energies acquired by the car as a result of climbing and acceleration represent reversibly stored energy and, in principle, may be recovered by appropriate regenerative methods.

The last two terms in eq. (1) describe the power which is required to overcome tyre friction and aerodynamic drag which are irreversibly lost, mainly as heat and noise and cannot be recovered. The power required here may be estimated from the following empirical relations:

$$P_{tyres} = C_t\, Mgv, \tag{4}$$

and

$$P_{aero} = 0.5\, dC_a A(v + w)^2\, v, \tag{5}$$

where C_t and C_a are dimensionless tyre friction and aerodynamic drag coefficients, respectively, d is the air density, w is the head wind velocity, g is gravitational acceleration, and A is the frontal cross-sectional area of the car.

From the parameters associated with a typical modern medium size car, viz. $M = 1400$ kg; $A = 2.2$ m^2; $C_t = 0.01$; $C_a = 0.3$; $d = 1.17$ kg/m^3; $g = 9.8$ m/s^2, its power requirements may be estimated from eqs (2)–(5). For the irreversible losses, eqs. (4) and (5) show that while P_{tyres} is linearly dependent on velocity, P_{aero} varies as the third power of velocity and although negligible at low velocity, the latter becomes the dominant irreversible loss at high speed. As an example, for these parameters, for a car traveling at about 50 km/h, tyre friction is twice the aerodynamic drag and together amount to about 3 kW. At 100 km/h highway cruising, aerodynamic drag increases considerably to over twice the tyre friction, increasing total power requirement to about 12 kW.

Taking the example of a hill with a substantial 10% gradient, climbing at 80 km/h requires about 38 kW, including tyre friction and aerodynamic drag. Acceleration is more demanding, particularly at high velocity. For example, acceleration at 5 km/h/s requires 29 kW at 50 km/h and increases to 66 kW at 100 km/h.

The above estimates are for the power supplied to the wheels of the car and do not include losses incurred in delivering that power to the wheels. At this time in the development of electric traction systems, a precise estimate of this is difficult to obtain. Anecdotal information suggests that the efficiency of the power conditioning electronics, together with the electrical and mechanical drive train (ε_{drive}), is likely to be about 0.85. Additional power (P_{access}) may also be required to power accessories like radios, lights, steering, air-conditioning, etc. which is likely to add about 4 kW to the total power demand of the car.

In this way, the instantaneous total power required from the electric power system (P_{total}) will be given by:

$$P_{total} = P_{traction}/\varepsilon_{drive} + P_{access}\,. \tag{6}$$

An analysis of this kind indicates that the power plant of a modern car must be capable of delivering about 50 kW of sustained power for accessories and hill climbing, with burst power for a few tens of seconds to about 80 kW during acceleration. For a car with these performance characteristics, this sets the upper power limit required, with more common usage rarely exceeding 15 kW while cruising.

Equations (2)–(5) show that with the exception of aerodynamic losses, the power requirements scale with the mass of the car. While new light-weight materials and construction methods, together with design innovations to reduce aerodynamic drag may be able to reduce the power and energy requirements of the car, gains in excess of about 25% will be difficult to achieve within an acceptable cost regime.

The energy consumed by a car is simply the time integral of the traction and accessory power plus that consumed by the power plant at idle (E_{idle}) thus:

$$E_{total} = \int P_{total}\, \mathrm{d}t + E_{idle}\,. \tag{7}$$

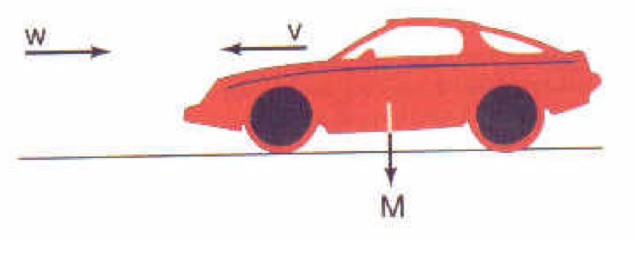

Figure 1. A modern spark-ignition engine car; M is its mass, v its velocity and w is the head-wind velocity.

E_{total} depends on the nature of the drive cycle the car is required to perform. Many estimates have been made for selection of acceleration – climb – cruise – idle sequences designed to simulate common driving practices. As with the power requirements of the car, E_{total} is very dependent on car mass. For the car parameters listed above, this may be expected to be near 200 Wh/km. For a modern spark ignition engine operating at about 20% efficiency under normal driving conditions, this corresponds to a rate of petrol consumption of about 10 litres/100 km.

From this quantitative analysis of the power and energy requirements of a car, the suitability of the various electric power options may be objectively evaluated.

Electric power options

In the preceding section, both the power and energy demands of a modern car were discussed. In brief, it was concluded that a base sustainable power of 50 kW, supplemented with short acceleration bursts to 80 kW will suffice in most driving requirements. Energy demand depends greatly on driving characteristics, but under normal usage can be expected to be about 200 Wh/km. The question remains as to which electric power option best satisfies these requirements. In addition, the system should be of robust and of compact construction and with near-ambient temperature operation to facilitate rapid start-up and intermittent usage. We will now consider the relative merits of supercapacitors, storage batteries and fuel cells to achieve these objectives.

Supercapacitors

The charge separation, which occurs at the interface between the electrode surface and the electrolyte acts as a pseudo-capacitor and as such is capable of storing significant amounts of energy. Such an electrolytic capacitor can store far greater amounts of energy than a simple capacitor consisting of two plates separated by gas or vacuum as dielectric. New supercapacitors based on this principle require conducting electrodes with surface areas in excess of 2000 m^2/g and are typically fabricated from activated carbons. Additional pseudo-capacitance at, for example, a highly-dispersed ruthenium oxide surface, can further enhance their energy capacity. Since the stored energy is essentially non-redox, supercapacitors may be rapidly charged and discharged, and are capable of delivering power densities in excess of 1 kW/kg, albiet at relatively low energy densities, typically less than 5 kWh/kg. Nevertheless, supercapacitors appear ideally suited for delivering the burst acceleration power requirements of an electric car at a relatively low weight penalty.

Storage batteries

Batteries store a fixed amount of chemical energy and may be recharged when the electrochemically active materials in them have been exhausted. As a result of a largely technically mature range of design, electrode type, electrolyte and operating temperature, modern rechargeable storage batteries offer a significant diversity of operational characteristics, including power and energy density, and life-time, balanced always by the cost of the system. Storage batteries which may be considered for electric car applications are given in Table 1 along with their energy and power densities.

From the cost perspective, lead-acid batteries appear the most attractive, but with an energy density of only 35 Wh/kg, almost 6 kg of battery is required to drive a car for 1 km. Coupled with its relatively slow recharge characteristics, it is immediately apparent that the lead-acid battery, in spite of its technical maturity and low cost, is an unacceptable option. Indeed, the failure of General Motors EV1 to find consumer acceptance may, at least in part, be linked to its dependence on lead-acid batteries[5]. When the high-temperature batteries are rejected for their inability to offer acceptable intermittent operational performance, it is seen from Table 1 that the most viable battery systems are either the nickel-metal hydride or lithium-ion types. Even neglecting the relatively high cost of these battery systems, their energy densities still require 2–2.5 kg of battery to travel 1 km. At 1 kg/km, the zinc–air battery is approaching an acceptable performance but technical difficulties in producing a truly rechargeable system continue to

Table 1. A comparison of the most promising storage batteries for electric cars

Cell type	Nominal (V)	Specific energy (Wh/kg)	Energy density (Wh/l)	Specific power (W/kg)	Power density (W/l)	Self discharge life (%/month)	Cycle	Comments
Lead–acid	2.0	35	70	~200	~400	4–8	250–500	Least-cost technology
Lithium–ion	3.6	115	260	200–250	400–500	5–10	500–1000	Intrinsically safe; contains no metallic lithium
Lithium–polymer	3.0	100–200	150–350	> 200	> 350	~1	200–1000	Not yet available commercially; contains metallic lithium
Nickel–cadmium	1.2	40–60	60–100	140–220	220–350	10–20	300–700	Exhibits memory effect and contains toxic cadmium
Nickel–metal hydride	1.2	60	220	130	475	30	300–500	No memory effect; cadmium free
Zinc–air	1.2	146	204	150	190	~5	~200	Requires air-management
Na–$NiCl_2$	2.6	100	160	150	250	~1	~1000	High-temperature

frustrate their implementation.

Fuel cells

For their high power and energy densities, fuel cells are emerging as the most viable candidate for powering electric cars. Like storage batteries, fuel cells deliver energy by consuming electroactive chemicals, but differ significantly in that these chemicals are delivered on-demand to the cell. As a result, a fuel cell can generate energy continuously and for as long as the electroactive chemicals are supplied to the cell. Typically, these chemicals consist of a fuel to the anode and air to the cathode. Although the first hydrogen–oxygen fuel cell was demonstrated as early as 1839 by Sir William Grove, most fuel cell developments have taken place in the last 50 years; initially with developments for the space industry of the sixties, followed by the energy crisis of the seventies and more recently, with the push to electric cars. With the profound advances in fuel cell technology that have been achieved in the last decade, there is emerging of a truly new electrochemical energy technology with the potential to challenge the *status quo* of combustion engines. Most recent developments in PEFC are delivering systems with power densities approaching 30 W/kg with overall energy efficiencies substantially greater than the 20% of a modern car spark ignition engine. While the future of the fuel cell to meet emerging energy needs is promising, the challenge today remains to reduce the cost of these systems to a level where they can properly assert their intrinsic efficiency and environmental advantages.

There are many types of fuel cells differentiated by the nature of the electrolyte as shown in Table 2. The suitability of a fuel cell for a given application depends mainly on its operational temperature.

Perspective for electric cars

The relative power and energy densities of current generation supercapacitors, storage batteries and fuel cells may be summarized in a Ragone diagram of the type shown in Figure 2. As discussed earlier, the overall energy demand of a modern electric car is about 200 Wh/km, in which case the power plant should be capable of delivering in excess of 500 Wh/kg to keep the power plant within acceptable weight limits. It is immediately apparent that this cannot be achieved by any of the direct electric storage systems, viz. supercapacitors or batteries, and that it is unlikely to be an achievable target for these systems within the foreseeable future. At best, storage battery and supercapacitor-powered vehicles may be able to establish a limited niche in short-range commuter vehicles, especially where the relatively long recharge times can be accommodated by the pattern of vehicle usage.

For transportation, the low operating temperature and rapid start start-up characteristics, together with its robust solid-state construction gives the polymer electrolyte fuel cell (PEFC) a clear advantage for application in cars. A typical construction of a PEFC is shown schematically in Figure 3 (ref. 7). Its energy conversion efficiency at the operating cell voltage of 0.6 V is about 50%, much higher than any spark ignition engine.

The preferred fuel for the PEFC is hydrogen. While many

Table 2. Contending fuel cell technologies and their operational temperatures

Type	Electrolyte	Fuel	Operating temperature (°C)	Cell reactions
Solid polymer electrolyte fuel cell (PEFC)	Solid–polymer electrolyte membrane (Nafion)	Hydrogen	60–90	Cathode : $O_2 + 4H^+ + 4e^- \quad 4H_2O$ Anode : $2H_2 \quad 4H^+ + 4e^-$ Cell reaction : $O_2 + 2H_2 \quad 2\,H_2O$ (1.23 V)
Solid polymer electrolyte direct methanol fuel cell (SPE–DMFC)	Solid–polymer electrolyte membrane (Nafion)	Methanol	60–90	Cathode : $3/2\,O_2 + 6H^+ + 6e^- \quad 3H_2O$ Anode : $CH_3OH + H_2O \quad CO_2 + 6H^+ + 6e^-$ Cell reaction : $3/2\,O_2 + CH_3OH \quad CO_2 + 2H_2O$ (~ 1.19 V)
Alkaline fuel cell (AFC)	Aqueous KOH	Hydrogen	60–120	Cathode : $O_2 + 2H_2O + 4e^- \quad 4OH^-$ Anode : $2H_2 + 4OH^- \quad 4H_2O + 4e^-$ Cell reaction : $O_2 + 2H_2 \quad 2H_2O$ (1.23 V)
Phosphoric acid fuel cell (PAFC)	Phosphoric acid	Hydrogen	180–210	Cathode : $O_2 + 4\,H^+ + 4\,e^- \quad 2H_2O$ Anode : $2H_2 \quad 4H^+ + 4e^-$ Cell reaction : $O_2 + 2H_2 \quad 2H_2O$ (1.23 V)
Molten carbonate fuel cell (MCFC)	Molten carbonate melts (Li_2CO_3/Na_2CO_3)	Hydrogen	600–700	Cathode : $1/2\,O_2 + CO_2 + 2e^- \quad CO_3^{2-}$ Anode : $H_2 + CO_3^{2-} \quad H_2O + CO_2 + 2e^-$ Cell reaction : $H_2 + 1/2\,O_2 \quad H_2O$ (~ 1.5 V)
Solid oxide fuel cell (SOFC)	Yttria-stabilized zirconia ($ZrO_2–Y_2O_3$)	Methane/ hydrogen	1000	Cathode : $O_2 + 4e^- \quad 2O^{2-}$ Anode : $2H_2 + 2O^{2-} \quad 2H_2O + 4e^-$ (hydrogen) or $1/2\,CH_4 + 2O^{2-} \quad H_2O + 1/2\,CO_2 + 4e^-$ (methane) Cell reaction : $O_2 + 2\,H_2 \quad 2\,H_2O$ (~ 1.1 V) (hydrogen) or $O_2 + 1/2\,CH_4 \quad H_2O + 1/2\,CO_2$ (~ 1.1 V) (methane)

Figure 3. Schematic representation of a polymer electrolyte fuel

strategies for providing hydrogen to the PEFC are presently being evaluated, the most acceptable proposal appears to be to generate it on-board and on-demand from liquid hydrocarbons or methanol. The technical challenge, however, is to modify large-scale industrial processes like steam reforming or partial-oxidation to lightweight reactors that can fit inside a car.

Prototype cars recently unveiled by Chrysler–Daimler, shown in Figure 4, are based on steam reforming of methanol. Methanol is relatively easy to process on-board and may be conveniently distributed through the existing service-station infrastructure. Meanwhile, partial oxidation reactors for processing gasoline, which is favoured by the Department of Energy in the US, are being developed by Epyx Corporation.

Partial oxidation offers compact reactors, fast start-up and rapid dynamic response while steam reforming produces more hydrogen with an increased fuel efficiency. Johnson Matthey in the UK have developed a methanol processor called the HotSpot which uses the heat produced by the partial oxidation process to drive the steam reforming reaction. This compact system ensures fast start-up and optimum fuel efficiency. The present generation HotSpot module can generate over 750 litres of hydrogen per hour, enough to power a 1 to 1.5 kW PEFC, depending on the operating voltage.

The hydrogen produced by steam reforming and partial oxidation of methanol (see Figure 5) contains carbon dioxide (20%) and a trace of carbon monoxide (2%). At the low operating temperature of the PEFC, carbon monoxide at levels in excess of about 0.001% poisons the platinum catalyst at the anode. Two strategies to circumvent this are under investigation. Either the carbon monoxide must be removed from the hydrogen stream in a separate process or new carbon monoxide-tolerant catalysts developed for deployment at the anode.

An elegant solution to the problems associated with the need for gaseous hydrogen fuel, lies in operating the PEFC directly with a liquid fuel. Much consideration is therefore being given to PEFCs that run on air plus a mixture of methanol and water. The main technological challenges here are to develop better anode catalysts to overcome efficiency losses at the anode and to improve the membrane electrolyte, and cathode catalysts to prevent methanol poisoning of the cathode.

It has been estimated that such a direct methanol fuel cell (DMFC) producing around 0.25 W/cm^2 of electrode, would be about the same size as a conventional methanol reformer/PEFC system operating at a power density of about 1 W/cm^2. Indeed, the development of a commercially feasible solid polymer electrolyte direct methanol fuel cell (SPE–DMFC) would be considerably simpler in both its construction and operation, and is widely regarded as the 'holy grail' of fuel cell technologies.

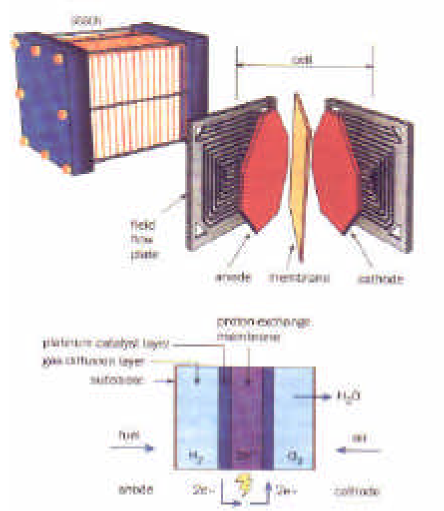

Figure 4. The Chrysler–Daimler prototype electric car.

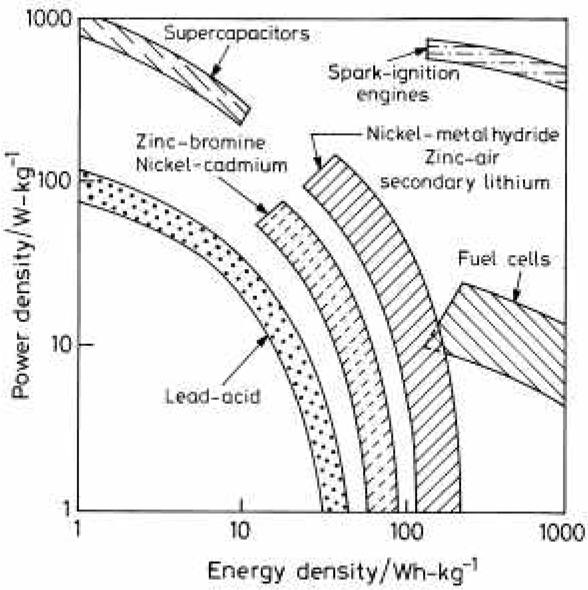

Figure 2. A Ragone plot comparison of power and energy densities of supercapacitors, storage batteries, fuel cells and spark ignition engines. In order to affect the appropriate comparisons, the energy densities of the spark ignition engines and fuel cells include typical

At present, the PEFC is emerging as the most viable electric power option for cars. Since the energy density of the PEFC power plant and fuel is similar to that of the present day spark ignition engines, comparable driving ranges may be expected. However, the power density of present PEFC systems tends to be less than that of spark ignition engines. Although the 80 kW of power needed to provide the acceleration could be supplied by a large PEFC alone, this will probably make the first generation system excessively large and heavy. Additionally, the high cost of newly developed fuel cells will persuade the car makers to use the smallest cells that will provide the required base power needs of about 50 kW. An acceptable compromise could be achieved with a supplementary parallel electric storage system using either high power density supercapacitors or less likely, storage batteries to provide the short duration acceleration. This electric storage system could also be used to regeneratively recover the energy which would be otherwise lost during braking. Since energy density is less important than power density for the acceleration of a car, supercapacitors would appear to be a superior alternative to any of the present storage battery options.

Figure 4. The Chrysler–Daimler prototype electric car.

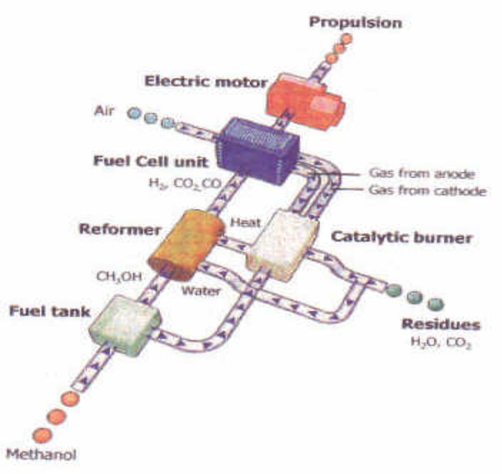

Figure 5. Schematic representation of the methanol reformer to be used for on-board reforming in the electric car.

Conclusion

From the foregoing, it is seen that a satisfactory system to meet the power and energy need of a modern car could be met with a 50 kW PEFC stack coupled in parallel with a 30 kW supercapacitor and/or battery bank to provide the short term power for acceleration. With the development of electric propulsion for cars in its infancy, the final mixing and matching of the various electric power options will depend as much on new and refined technological developments as it will on consumer demands. However, it is being increasingly recognized that the PEFC will become the system of choice for the primary power source. Finally, as the raft of economic, environmental and political issues associated with the burgeoning use of increasingly limited liquid petroleum reserves unfurl over the coming decades, the move to electric propulsion systems for cars will inevitably hasten the development of new and improved PEFC and associated electric power systems.

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Received 29 June 1999; accepted 27 August 1999