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Fuelling future cars

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Abstract

The pressing need to improve the global urban air quality has provided the impetus for electric cars. Over the years, a great deal of research and development work has been carried out, and is still underway, on various types of electric cars. This article presents an assessment on the power and energy requirements of the electric cars, and provides a prognosis on their commercial viability. To be commercially viable, the electric cars have to perform beyond the conventional Otto and Diesel engine cars. An electric car, which fails in meeting this requirement, is unlikely to achieve anything but a niche market share.

Keywords: Electric cars, power, energy.

1. Introduction

In the late 1890s, at the dawn of the automobile era, steam, gasoline and electric vehicles all competed to become the dominant automobile technology. By the early 1900s, the battle was over and the internal combustion engine vehicles (ICEVs) were poised to become the prime movers of the twentieth century. At present, about 60 million ICEVs are manufactured every year worldwide and it is projected that there would be more than a billion ICEVs on the earth's roads by 2004. This upsurge in the use of ICEVs is causing considerable pollution problems in our urban conurbations, which has brought in emission legislation all over the world requiring the induction of zero-emission vehicles (ZEVs).

ZEVs were initially thought to mean battery-powered vehicles. However, pure battery-powered vehicles are no longer regarded as an acceptable alternative to ICEVs except possibly as neighbourhood electric vehicles that are designed to provide low-speed (ca. 45 km/h) transportation in restricted areas such as university campuses, hospitals, airports, theme parks, industrial parks, holiday resorts, residential complexes and city centers [1, 2].

The above situation does not imply that there are no legitimate uses of pure battery-powered electric cars today as fleet vehicles, as community cars and as second cars for families, which already own a gasoline automobile for long-distance travel. One solution to this enigma might be to take the pure-battery-powered electric cars out of the developmental laboratories and put them in the hands of the real drivers. Some will find these vehicles inadequate, but many others may not. With this proposition in mind, Saturn, in partnership

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with General Motors Advanced Technology Vehicles, now offers GEN II EVI to consumers through a lease-only program. Select Saturn retail facilities in California and Arizona distribute and service EVI. Saturn believes that this is the best way to ensure total customer enthusiasm for the early customers in their vehicle. Leasing will provide the customers with a known and consistent cost of ownership. Saturn covers all routine maintenance and service under the terms of 3-year/36000-miles new-vehicle limited warranty. This includes everything from batteries to tyres. Saturn also provides a 24-hour roadside assistance program to make every aspect of EVI lease trouble-free.

While the fate of the pure battery-powered electric cars hangs in limbo, hybrid electric vehicles (HEVs) are becoming a commercial reality. Sales of HEVs are predicted to increase tenfold around the world in the next five years, and, in a few years time, will account about 5% of the global new vehicle market. Last five years has also seen a dramatic development in fuel cells, which have advanced to the point where manufacturers believe that the technology is commercially viable and capable of delivering sufficient energy for running the cars [3]. Automotive industry leaders project that within two decades, between 7 and 20% of new cars sold in the world will be powered by fuel cells. Accordingly, we can envision a global fleet of as many as about 80 million fuel cell vehicles (FCVs) on the earth's roads by 2020.

This article presents an assessment on the power and energy requirements of electric cars and provides a prognosis on their commercial viability.

2. Power and energy requirements of electric automobiles

To assess the energy and power requirements of an electric automobile, it is appropriate to quantitatively estimate the power and energy required for driving a modem ICEV [4]. Neglecting relatively minor losses due to road camber and curvature, the power required at the drive wheel (P_{traction}) may be expressed as,

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

where P_{grade} is the power required for the gradient, P_{accel}, the power required for acceleration, P_{tyres}, the rolling resistance power consumed by the tyres, and P_{aero}, the power consumed by the aerodynamic drag.

The first two terms in eqn (1) describe the rates of change of potential (PE) and kinetic (KE) energies associated during climbing and acceleration, respectively. The power required for these actions may be estimated from the Newtonian mechanics as follows,

$$P_{\text{grade}} = \mathrm{d(PE)/d}t = Mgv \sin q, \tag{2}$$

and,

$$P_{\text{accel}} = \mathrm{d(KE)/d}t = d(\mathrm{I}/2\ Mv^2)/\mathrm{d}t = Mav \tag{3}$$

where M is the mass (kg) of the car, v, its velocity (m/s), 'a', its acceleration (m/s^2), and tan$q$, the gradient. The potential and kinetic energies acquired by the car as a result of climbing and acceleration represent reversibly stored energies and, in principle, may be recovered by appropriate regenerative methods wherein the mechanical energy is converted and stored as electrical energy.

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

$$P_{\text{tyres}} = C_t M g v, \tag{4}$$

and,

$$P_{\text{aero}} = 0.5\, \mathrm{d} C_a A\, (v + w)^2 v, \tag{5}$$

where C_t and C_a are dimensionless tyre friction and aerodynamic drag coefficients, respectively, d, the air density (kg/m^3), w, the head-wind velocity (m/s), g (= 9.8 m/s^2), the gravitational acceleration, and A, the frontal cross-sectional area (m^2) 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, its power requirements may be estimated from eqns (2)–(5). For the irreversible losses, eqns (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 velocities, 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 the total power requirement to about 12 kW. It is noteworthy that for both these estimates, the wind speed (w) has been taken to be zero for the sake of simplicity, but, in practice, its effect on the performance of the car could be quite substantial. For example, P_{aero} at a favourable tail wind speed of 30 km/h will be as low as 0.8 kW but would amount to 4 kW at a similar opposing tail wind velocity. Accordingly, the energy performance of the car will drop from 40 km/kWh to 15 km/kWh [5]. Taking the example of a hill with a substantial 10% gradient, climbing at 100 km/h requires about 50 kW, including tyre friction and aerodynamic drag. Acceleration is more demanding, particularly at high velocities. For example, acceleration at 5 km/h/s requires 30 kW at 50 km/h but increases to 66 kW at 100 km/h.

The above estimates are for the power supplied to the wheel of the car and do not include the 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 but anecdotal information suggests that the efficiency of the power conditioning electronics together with the electrical and mechanical drive train is likely to be about 0.85. Additional power may also be required to power the accessories like radio, lights, steering, and airconditioning, etc. which is likely to add about 5 kW to the total power demand of the car.

An analysis of this kind indicates that the power plant of a modern car must be capable of delivering about 65 kW of sustained power for accessories and hill climbing, with burst-power requirement for a few tens of seconds to about 105 kW during acceleration. For a car with these performance characteristics, this sets the upper power limit required, but in common usage rarely exceeds 20 kW while cruising.

The heating value of gasoline fuel is 32.5 MJ/L but a heating value of only 6.5 MJ/l will be available with an ICEV of near 20% well-to-wheel efficiency. This is about 1.82 kWh/l

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

Battery type	Nominal cell voltage (V)	Specific energy (Wh/kg)	Energy density (Wh/l)	Specific power (W/kg)	Specific density (W/l)	Self-discharge (%/month)	Cycle life
Lead–acid	2.0	35	70	~200	~400	4–8	250–500
Lithium–ion	3.6	115	260	20–250	400–500	5–10	500–1000
Lithium–polymer	3.0	100–200	150–350	>200	>350	~1	200–1000
Nickel–cadmium	1.2	40–60	60–100	140–220	220–350	10–20	300–700
Nickel–metal hydride	1.2	60	220	130	475	30	300–500
Zinc–air	1.2	146	204	150	190	~5	~200
Zebra	2.6	100	160	150	250	~1	~1000

of the gasoline fuel and considering the average drive range of the car with the parameters listed above as ~10 km/l, it would amount to 182 Wh/km. The heating value of the diesel fuel is 35.95 MJ/l and accordingly the estimated energy will be 201 Wh/km for the diesel-driven cars, which have well-to-wheel efficiency of about 30% and a drive range of about 15 km/l. It is mandatory that electric vehicles (EVs) meet these power and energy requirements. Various types of EVs are described in the following sections.

3. Pure battery-powered electric vehicles

The power and energy density parameters of various promising storage batteries for electric vehicles are given in Table I. From the cost perspective, lead–acid batteries appear to be most attractive, but with an energy density of only about 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. When the high-temperature zebra batteries are rejected for their inability to offer acceptable intermittent operational performance, it is seen from Table I that the most viable battery systems are either the nickel–metal hydride or lithium secondary types. Even neglecting the high cost of these battery systems, their energy densities still require 2–3 kg of battery to travel 1 km. At 1 kg/km, the zinc–air battery is approaching an acceptable performance, but technical difficulties in achieving a truly rechargeable system continue to frustrate their commercial implementation. It is noteworthy that the vanadium redox and zinc–bromine flow batteries have also been projected as possible contenders for vehicular traction. These batteries, however, have problems of excessive self-discharge. Besides, vanadium and bromine are highly toxic.

4. Hybrid electric vehicles (HEVs)

Hybrid electric vehicles have been extensively discussed by Rand *et al.* [6]. HEVs have two separate power sources, one to provide range and the other to supply peak power. Most conventional ICE passenger cars are grossly overpowered for urban or highway driving, to ensure that sufficient power is available to meet the demands of acceleration and hill-climbing. As discussed in Section 2, the steady power requirement is only 30% of the peak power demand. It follows that the main propulsion unit could be sized for steady urban and highway driving if the peak power could be provided by an auxiliary source. This would permit considerable savings in the volume, mass and cost of the main propulsion unit, as well as in fuel consumption. HEVs can use a variety of power-source configurations, namely, all electric, electric-mechanical, or heat-engine–battery.

All-electric HEVs could be driven by mains–battery, or battery–battery, or fuel cell–battery and/or supercapacitor. The advantage of an all-electric hybrid is that it is emission-free, but the disadvantage is the mass and cost associated with the storage of electrochemical energy. Many fuel cells and batteries are limited in power output and, in the case of batteries, rate of charge acceptance. By hybridizing either of these power sources with a battery of high specific power, or a supercapacitor, it is possible to improve both vehicle performance and the acceptance of regenerative-braking energy. To date, few vehicles of this type have been built.

Electric-mechanical HEVs comprise a main traction battery with an auxiliary flywheel to provide peak power and to store the energy obtained from regenerative braking. Much work was done on this concept in the US during the 1970s. The flywheel was bulky as well as heavy, and had limited energy-storage capacity. Since then, development work has been undertaken on high-speed flywheels, which use lightweight composite materials for the rotor. Consequently, both the energy storage per unit mass and volume have improved markedly. Lawrence Livermore National Laboratory in US has proposed coupling its zinc/air battery to a super-flywheel to produce a concept HEV with a range of 380 km. This vehicle would use a 70 kWh and 40 kW zinc/air battery in combination with a 0.5 kWh and 102 kW flywheel for acceleration and hill climbing. Super-flywheels resemble supercapacitors in having modest energy-storage capability, very high power output, long cycle lives, and high overall energy efficiencies.

The common objectives of heat-engine-battery HEVs are to reduce the urban pollution and the petroleum consumption that is associated with conventional ICEVs without restricting the driving range to that provided by battery-powered EVs. Within this HEV concept, there is scope for numerous designs and operating procedures to maximize range, provide a high-performance vehicle, maximize overall energy efficiency, and minimize capital and running costs. There are two basic heat-engine-battery HEV types, namely, series hybrids and parallel hybrids. In the series configuration, all the traction power is delivered by an electric motor and a heat engine is used intermittently to generate electrical energy that is fed to the battery-controller system. Such a HEV is a simpler concept and has more scope for both lower fuel consumption and reduced emissions, but it requires more powerful and highly efficient electric motors, a smaller ICE designed for running at constant speed, and a battery with a higher power rating. The parallel HEV, in which the wheels can be driven mechanically by a heat engine, or electrically by a battery-electric motor, or by both, offers the easier option to manufacture. On the other hand, complex control systems are required, especially if a flywheel is also incorporated.

In one typical version, the series HEV would have a battery, which is sufficiently large to meet the daily range and peak power requirements for city driving, and a small ICE (or gas turbine) to generate electricity purely as a ‘range extender’ for out-of-town driving. This is essentially an EV with an EV-sized battery and a small auxiliary engine. For urban driving, most of the energy consumed would be electricity from overnight charging. An alternative series concept is to have a larger engine and a smaller battery such that the engine, which is switched off during urban operation, provides the power almost entirely. Volvo is following the latter route with its ‘Environmental Concept Car, Urban Bus and City Truck’. In each of these designs, a gas turbine drives an alternator to power the EV as also to charge a nickel/metal hydride battery, which supplies the traction power in environmentally sensitive areas.

The parallel HEV has two distinct drive trains independent of each other. The engine is likely to be quite small and would be sized for steady highway driving. The battery provides auxiliary power for both acceleration and hill climbing, and also accepts regenerative-braking energy. Limited urban driving in the battery electric mode would also be possible. Most, if not all, of the energy consumed in this version would be from petroleum. Renault has adopted such a configuration in its new, small hybrid car (‘NEXT’). This vehicle has a 750-cc engine, which provides 35 kW of power to the front axle, and two auxiliary 7-kW electric motors, which drive the rear wheels. In July 1997, Toyota unveiled plans to mass-produce a parallel HEV (the ‘Prius’) powered by a 1500-cc engine and a nickel/metal hydride battery.

The designs of heat-engine-battery HEVs become even more complex when flywheels or supercapacitors are introduced as well. The flywheel requires the development of a continuously variable transmission together with a series of clutches. In addition, the power-control electronics are more complicated. The ultracapacitor resembles the flywheel in that it is a high power, low specific-energy device, which is ideal for meeting short-duration, peak-power demands and for recovering regenerative-braking energy. Being an electrical device, it is readily integrated into the EV’s control circuitry.

Opinions concerning the future prospects for heat-engine-battery HEVs are divided. Enthusiasts for the parallel hybrid point to the fact that it is essentially a conventional car, as accepted by the public, but with higher fuel efficiency and a larger battery. Moreover, such a vehicle could be built today with a standard lead/acid battery pack, which has suitably high power density. This is a very attractive proposition for automotive companies. Indeed, Fiat in Italy is offering its well-known Panda car in both an electric version (the ‘Panda Elettra’) and as a parallel hybrid. Since parallel HEVs possess essentially two independent power trains, the failure of one or the other should not leave the motorist stranded, which is a positive sales feature. Detractors point to the fact that such hybrids suffer from the complexity and cost of two propulsion systems, together with the difficulty of fitting them in the space available. On the other hand, it is contended that the series hybrid has all the advantages of electric traction, usually with a smaller battery than a pure-battery EV, as well as with greater range. Furthermore, the system has the merit of being practical with the state-of-the-art lead/acid batteries. At the end of the day, the prospects for heat-engine-battery HEVs, with their more complex engineering, may well hinge upon whether or not advanced batteries will become available with suitable performance at a price, which will make the pure-battery EV commercially viable.

The conventional ICEVs with an Otto engine have difficulty in achieving high efficiency and low emissions over a wide operating range of speed and torque. A major advantage of REVs lies in their improved energy efficiency when they employ a small engine, which is running at constant speed. Also, with mains charging, there is scope to adjust the ratio of petroleum fuel to electricity consumed, according to the design and the mode of operation.

Since the forces required to overcome rolling resistance to accelerate and to move uphill are each proportional to the vehicles mass (Section 2), it follows that a major saving in mass will lead to a corresponding significant improvement in energy efficiency. At present, the limitation on mass reduction of the ICEVs is set by the extensive use of steel in the bodywork, but there is scope to lighten vehicles through the greater employment of aluminium, magnesium, and/or composites. Such design changes are equally applicable to HEVs. Pure-battery EVs, on the other hand, are inevitably heavy because of the weight of the traction battery. This is true even with advanced batteries since extending the driving range is generally considered more important than reducing the mass.

The concept of a ‘hypercar’ has recently been advanced as a means to capitalize on the advantages of electric traction itself without incurring the disadvantages of pure-battery traction. This vehicle involves a synergy between an ultra-light weight body, streamlined to have a low aerodynamic drag coefficient, and a series-hybrid drive train. The projected curb weight is 480 kg for a 4–5-seater car. In the hypercar concept, the wheels are driven by one electric motor with a differential gear, or by a pair of motors for the front wheels, or by four small integral wheel motors each with an associated electronic controller. All the electricity is generated, as needed, by an onboard power plant, which converts fuel into electricity, by a number of different means that range from an ICE electric generator to a fuel cell. Thus, it is intended for the hypercar to operate without mains charging. A ‘buffer’ device, e.g. a battery, is used to store electrical energy produced in excess from the power plant or recovered from braking. The energy stored in the buffer augments the power plant for acceleration and hill climbing. This arrangement permits the use of a smaller engine than in an ICEV as well as a relatively small battery, which, in turn, compounds reduction in the structural mass of the vehicle. If the hypercar is fuelled by petroleum, then the engine needs to produce typically only ~10 kW of electrical power for steady driving on the flat. With respect to battery development, the hypercar requires a system with the capability for high-power output-input rather than for high energy storage.

It is difficult to predict the ultimate outcome in the light of the above said options. However, the massive advantage of HEVs is quite clear from the standpoint of both energy conservation and pollution minimization, and of sizing an engine for steady cruising and providing boost power from a separate unit. In view of these advantages, as well as the addiction of vehicle manufacturers to ICE technology and the in-place petroleum-refuelling infrastructure, it is very likely that a hybrid electric vehicle, most probably a hypercar, will be favoured for long-distance travel.

5. Fuel cell electric vehicles

Global activities on fuel cell vehicles (FCVs) have been reviewed recently [7–10]. There are six generic fuel cell systems, namely, (i) phosphoric acid fuel cells (PAFCs), (ii) alkaline fuel cells (AFCs), (iii) polymer-electrolyte fuel cells (PEFCs), (iv) molten carbonate fuel cells (MCFCs), (v) solid-oxide fuel cells (SOFCs), and (vi) direct methanol fuel cells (DMFCs) at various stages of development. But for automobiles, the low-operating temperature and rapid start-up characteristics, together with robust solid-state construction give PEFCs (Fig. 1) a clear advantage for application in cars. Since the specific energy density

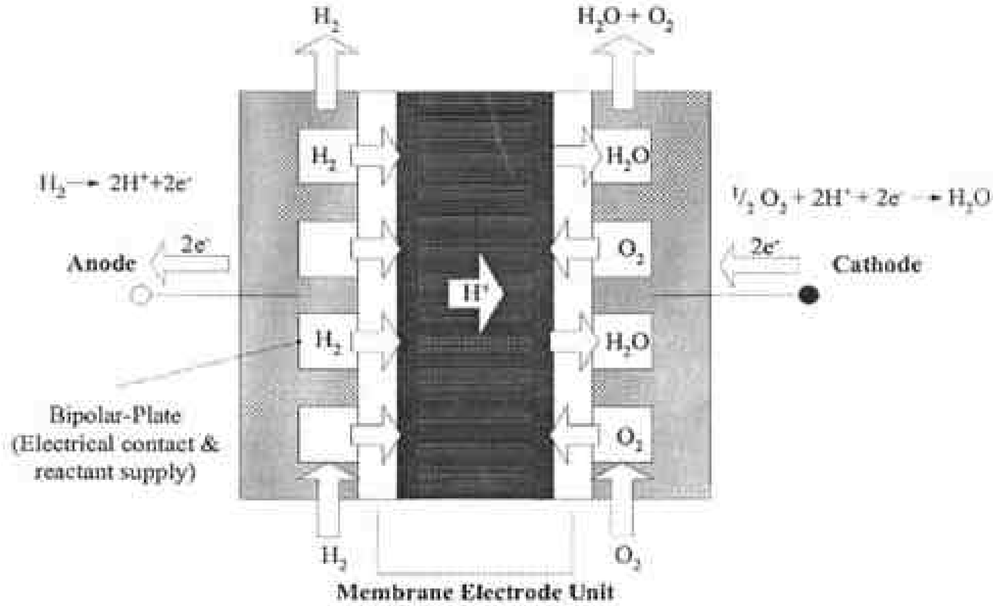

FIG. 1. Schematic representation of a PEFC.

of PEFC power plants (~ 1 kW/kg) is akin to that of the present-day ICEVs, comparable driving ranges may be expected. But the power density (~300 W/kg) of the present-day PEFCs tends to be substantially lesser than the ICEVs (~ 600 W/kg). A Ragone plot comparing the power and energy densities of PEFCs and IC engines is given in Fig. 2. The fuel

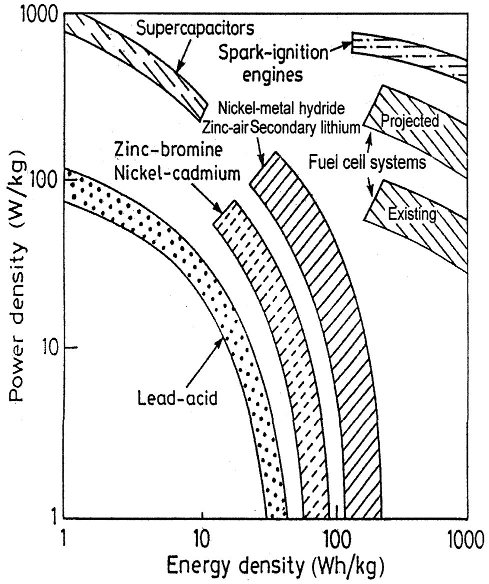

FIG. 2. A Ragone plot comparison of power and energy densities for existing supercapacitors, storage batteries, fuel cells, and spark-ignition engines.

cell system energy efficiency at present is about 60%, which is much higher than both the Otto (*ca.* 20%) as well as Diesel (*ca.* 30%) versions of ICEVs. Although the 105 kW of the power needed to provide the acceleration to the fuel cell-based automobile could be supplied by an appropriately sized PEFC alone, this will probably make the first generation systems excessively large and heavy. Additionally, the high cost of the newly developed fuel cells will persuade the car makers to use the smallest cells that will provide the required base power needs of about 65 kW.

Hydrogen, methanol and gasoline can be used as fuels in FCVs. Possible FCV configurations are depicted in Fig. 3. In brief, these configurations comprise a fuel cell system, a driving mechanism, which consists of a fuel supply system, an air supply system, a humidification system, and a thermal manager to control the operating temperature of the fuel cell stack.

Gasoline and in principle methanol can be supplied through the existing fuel distribution network for vehicles. But, a fuel reformer would be required to produce hydrogen from gasoline or methanol. This will increase both the complexity and the cost of the FCVs. Furthermore, with the reformers, the start-up time to normal operation reportedly varies from a few minutes upwards. Experts believe that for fuel cell-based automobiles, with an onboard fuel processor, it may be difficult to exceed the performance of the future ICEVs in terms of emission, efficiency, drivability, maintenance and first cost. Besides, at the operating temperatures of the PEFCs, carbon monoxide even at only 0.1% is sufficient to poison the platinum catalyst at the anode. Therefore, either a separate process or new carbon monoxide-tolerant catalysts needs to be developed for deployment at the anode. However, when hydrogen is used, a fuel processor is not necessary, and start-up time and response to load change are fast. But, hydrogen infrastructure costs are currently unacceptably high. Costs of tens to hundreds of billions of dollars are often quoted. Hydrogen onboard a vehicle can be stored as liquid hydrogen, as compressed hydrogen, as metal hydrides and as hydrogen absorbed in carbon nanotubes. The energy density of liquid hydrogen is appreciably high. But, to store hydrogen in liquid state, it is mandatory to maintain a temperature as low as –253°C at ambient pressure. This requires a highly insulated hydrogen tank making it cost intensive. Metal hydrides are heavy and time consuming for storing hydrogen. Carbon nanotubes are still in developmental stage but the US Department of Energy Development goal for these is slightly above the performance of the actual liquid hydrogen tank. The stored energy is low in the compressed hydrogen.

Prominent car manufacturers undertaking the development of fuel cell-based automobiles are Daimler–Chrysler who have a joint venture with Ballard, Excellsis, Ecostar and Ford, General Motors jointly with Opel, De Nora S.p.a., Fiat, Peugot in association with Citroën, Volkswagen in association with Volvo, Daewoo Motor, Diahatsu, Mitsubishi, Suzuki, Ronda, Hyundai, Mazda, Nissan, Renault, Toyota, and ZeVco. While some of these manufacturers are attempting to develop pure fuel cell-powered automobiles (Fig. 3), some are endeavouring to develop vehicles either with a fuel cell–battery hybrid system or with a fuel cell–supercapacitor hybrid system (Fig. 4).

In a clear demonstration of its commitment to have fuel-cell cars in series production by 2004, Daimler–Chrysler unveiled its NECAR-4 (New Electric Car) version in US on March

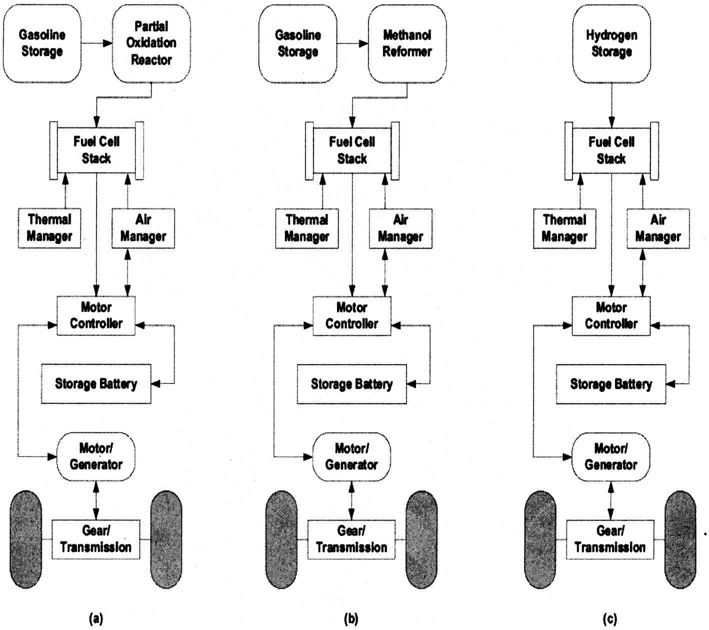

FIG. 3. Possible FCV configurations.

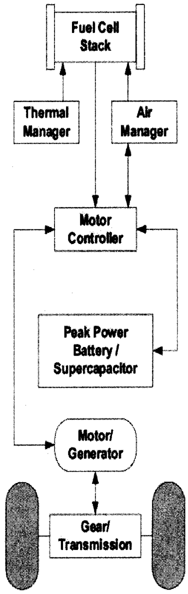

FIG. 4. A possible fuel cell-battery/supercapacitor hybrid configuration.

17, 1999. Its fuel cell power output has been increased by 40%, giving it a top speed of 145 km/h, acceleration to 48 km/h in 6 s and a range of up to 450 km, which is comparable to conventional ICEVs. Like its predecessor NECAR-3, the new car is based on a Mercedes-Benz A-Class subcompact car, which has a sandwich floor construction within which the system can be installed. For the first time, the complete PEFC system is mounted on the vehicle floor, allowing room for up to five passengers and cargo space. It is powered by liquid hydrogen stored in a cryogenic cylinder that takes up a part of the car boot. The engine was developed by Daimler Benz-Ballard (dbb) Fuel Cell Engines GmbH, while the vehicle uses an electric drive train from Ecostar Electric Drive Systems, a joint venture between Daimler–Chrysler, Ford and Ballard. Fuel cell stacks were supplied by Ballard. Daimler–Chrysler believes that the most challenging problems have been solved. The company will invest more than $ 1.4 billion on fuel cell technology development by the time the first FCVs come to market. This is about the same amount of money spent to introduce an entire line of profit-making vehicles, namely the Chrysler 300M, Chrysler Concorde, Chrysler LHS and Dodge Intrepid. The new race is to make them affordable. This is because to achieve widespread acceptance in coming years, the electric cars must have a clear economic advantage over ICEVs.

Ford plans to bring a new line of fuel cell cars based on its current Ford P2000 prototype. Ford FCVs will use tanks of liquid or gaseous hydrogen and will also be powered with Ballard's PEFC stack. The electricity generated from the fuel cell stack will be used by the car's electric induction motor/transaxle and electric power inverter to produce up to 90 kW of power. Ford also introduced P2000 SUV concept, a sport utility vehicle that will feature a fuel cell engine with a methanol reformer.

BMW in association with IFC, Messer AG, Linde and Solar Millennium AG is also developing a fuel cell vehicle. Renault SA of France and Nissan Motor Co. have decided to develop cars with fuel cells that run on gasoline. Renault is working with PSA Citroën to speed up the development of a commercially viable fuel cell car by 2010. Volkswagen introduced its first fuel cell-powered car at the California Fuel Cell Partnership headquarters' opening. The ZEV is called Bora HyMotion and its fuel cell engine runs on hydrogen and has a power output of 75 kW. Volkswagen is involved with CAPRI on a project to develop a prototype methanol FCV. Ballard will supply the fuel cell and Johnson Matthey a HotSpot reformer. In a joint project, Volvo and Volkswagen have announced plans for a methanol-fuelled PEFC hybrid golf-type car. London's Westminster City council has bought a fuel cell van from ZeVco for $47,000 for the upkeep of London's parks. It has a top speed of 100 km/h and is 50% cheaper to run than a conventional ICEV.

Other major players in the FCVs are General Motors in association with Opel. Following the successful demonstration of their Opel Fuel Cell Zafira with methanol reformer at the Paris Motor Show in October 1998, Opel and General Motors tested their liquid hydrogen-fuelled Opel HydroGen 1 at the Living Tomorrow Workshop at Brussels during June 2000 with a drive range of 400 km. Interestingly, the liquid hydrogen tank used with HydroGen 1 had an energy density of about 5 MJ/l and 6 MJ/kg, which is significantly higher than that for the ICEVs. GM's Delphi subsidiary is working with ARCO and Exxon to jointly develop onboard fuel-processing technology and hardware to convert gasoline to hydrogen for use in the PEFC systems.

In Asia, Daewoo Motor, Diahatsu, Honda, Hyundai, Mazda, Mitsubishi, Nissan, Suzuki, and Toyota have been involved in developing FCVs. Daewoo Motor reports that it will embark on a fuel cell research and development program with a state-run laboratory. Diahatsu presented its MOVE FCV-K-II, a four-seater FCV, which uses a high-pressure hydrogen tank system. The MOVE FCV-K-II uses a 30 kW Toyota fuel cell stack installed beneath the floor at the rear of the vehicle. Honda has developed a four-seater FCV, called the FCX-V3, which will be road-tested under the California Fuel Cell Partnership program. Ronda plans to build 300 FCVs during 2003 for sale in Japan. United Technologies and Ryundai have worked together to produce Santa Fe FCV. Suzuki unveiled a fuel cell-powered Covie two-seater at the 2001 Tokyo Motor Show. The vehicle features a GM fuel cell stack and uses natural gas as the fuel. The Ryundai Santa Fe FCV powered by a 75 kW PEFC stack scored best in two key performance tests at the Michelin Challenge Bibendum, an annual event where new automotive technologies are evaluated by independent judges. Toyota has demonstrated its new fuel cell hybrid vehicle, called the FCRV-4, based on the new Highlander SUV. Toyoto says that their FCV with a cruising range of about 250 km has three times the vehicle efficiency of an ICEV. Toyoto has also unveiled its FCRV-5, which runs on clean hydrocarbon. Toyota had plans to launch a commercial FCV in 2003. Exxon and Toyota are working together on technology to extract hydrogen from gasoline. Toyota keeps methanol as the preferred option in the near term.

The present estimated cost of PEFCs is about \$1,000–2,000/kW, which is a constraint for their commercialization and use in automotive applications. The fuel cell cost could be decreased through reduction of platinum loading, improvement in stack performance, and mass production. It is hoped that the PEFC cost will be decreased to 200/kW in 1–2 years. In the US, the target cost of fuel cell systems to be achieved by 2005 is \$50/kW. This could be achievable for a PEFC with a peak power density of 0.5 W/cm^2 using platinum catalyst loadings of 0.2 mg/cm^2 giving a catalyst cost of \$12–14/kW provided membrane costs are less than \$100/m^2 (or \$20/kW). GM claims to have achieved the fuel cell stacks with \$50/kW and is working to further reduce the cost to \$20/kW. In a recent technical cost analysis for PEFCs, it is surmised that this target cost can only be achieved with design changes that would substantially reduce the quantity of materials used. This obviously calls for more research and development on advanced and cost-effective fuel cell materials.

It has been demonstrated that if the fuel cell cost is high (\$1,000–2,000/kW) then hybridization can reduce the life-cycle cost (initial vehicle cost plus maintenance cost) of the FCVs. But if the fuel cell cost is \$ 50/kW then hybridization increases the life-cycle cost of the FCVs as it increases the initial vehicle cost.

The problems that remain to be tackled in the commercialization of the FCVs are: (i) reduction in cost, weight and volume of fuel cell systems, (ii) further improvements in driving dynamics, durability and reliability, development of cost-effective production technologies, and (iii) installation of refueling infrastructure for hydrogen.

An elegant solution to the problems associated with the installation of refueling infrastructure for 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. Methanol being liquid can be easily transported and dispensed within the current fuel network. Methanol has long-term environmental benefits because it could be produced renewably. Methanol is cheap and plentiful, and the only products of combustion in the fuel cell are carbon dioxide and water (Fig. 5). The advantages of direct methanol fuel cells (DMFCs) are that the changes in power demand can be simply accommodated by altering the supply of the methanol feed. The potential efficiency of a DMFC for an operational cell potential of 0.5 V is about 40% and its specific energy is *ca.* 6 kWh/kg. Since DMFCs operate at temperature below 150°C, there is no production of NO_x. Methanol is also stable in contact with mineral acids or acidic membranes, and it is easy to manufacture. Above all, the use of methanol directly as an electrochemically active fuel highly simplifies the engineering problems at the front end of the cell, driving down complexity and hence cost. A DMFC stack operating with a power density of *ca.* 0.25 W/cm^2 would be about the same size as a methanol reformer/PEFC system operating with a power density of about 1 W/cm^2.

During the last decade, significant advances have been made in the DMFC development. Power densities of 450 and 300 mW/cm^2 under oxygen and air-feed operation, respectively, and 200 mW/cm^2 at a cell potential of 0.5 V have been reported for cell operating at temperatures close to or above 100°C under pressurized condition with platinum loadings of 1–2 mg/cm^2. Besides, the development of DMFC stacks for both transportation and portable applications has gained momentum in the last 2–3 years, and stack power densities of 1 kW/l and an overall efficiency of 37% at a design point of 0.5 V per cell have been ac-

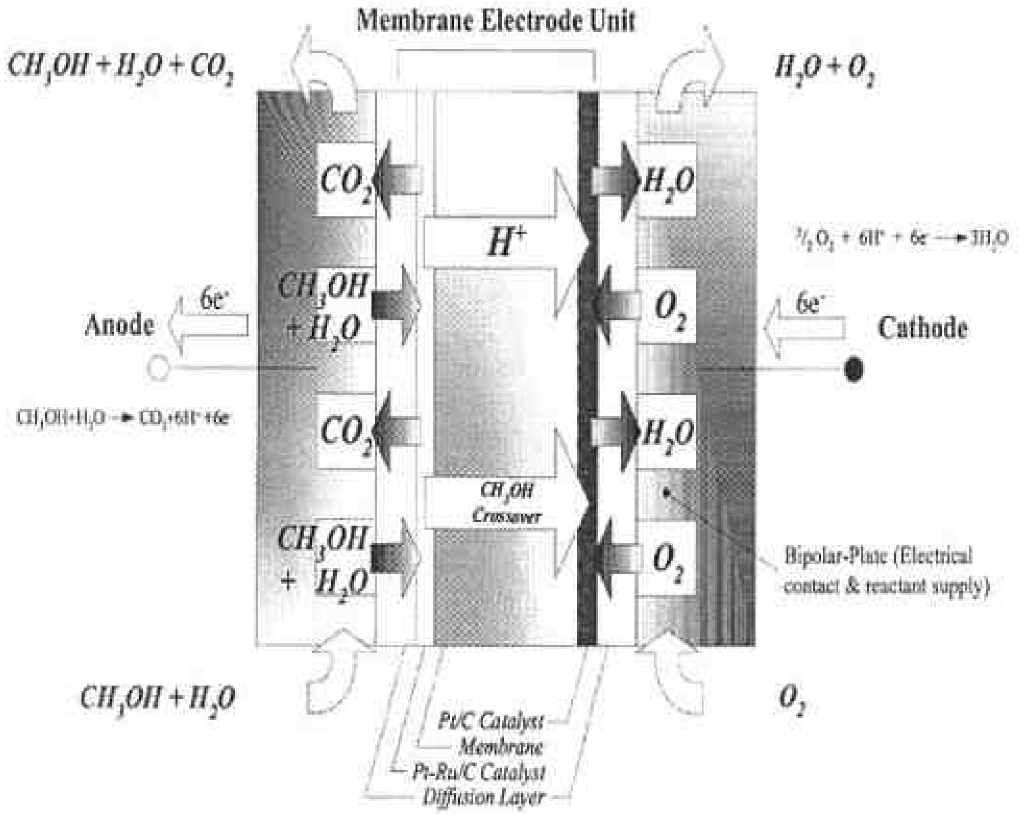

FIG. 5. Schematic representation of a DMFC.

complished. The performance of DMFCs is thus competitive with respect to the reformer-based hydrogen/air PEFCs, especially if one considers the complexity of the latter whole system. However, further improvements in the performance of DMFCs would be mandatory for their use in FCVs. A step in this direction appears to be the development of mixed-reactant DMFCs that rely upon the selectivity of anode and cathode electrocatalysts to separate the electrochemical oxidation and reduction of the oxidant without the need for physical separation of fuel and oxidant. In the mixed-reactant DMFCs, there would be no need for gas-tight structures within the stack providing relaxation for sealing and reactant delivery structures.

In the last few years, much progress has been made in bringing methanol fuel cell technology closer to the market place. On November 9, 2000, Ballard Power Systems and Daimler–Chrysler unveiled a DMFC prototype in Stuttgart, Germany, which used aqueous methanol to power a one-person demonstration vehicle. The main technological challenges here are to develop better anode catalysts, to overcome efficiency losses at the anode and to improve the membrane electrolytes as well as to find methanol-resistant cathode catalysts to prevent its methanol poisoning. Other alcohols, such as ethanol, ethylene glycol, propanol and diethyl ether have also been considered for use in fuel cells, but DMFCs undisputedly remain the most advanced systems in the category of direct alcohol fuel cells.

FIG. 6. Boeing's fuel cell-powered electric airplane (source: www.newton.res.it).

Today, methanol is being produced from otherwise flared or vented natural gas in many parts of the world. If only 10% of the natural gas flared each year was made available for the methanol fuel market, it would be enough to power 9.5 million FCVs annually. Besides, the technology to produce methanol from renewable feedstocks such as wood, municipal solid waste, agricultural feed stocks and sewage has been widely demonstrated. Accordingly, the availability and cost of methanol is probably not going to be the roadblock. The current US methanol production capacity stands at 35.7 million tons per year, and the wholesale spot market price for methanol is 33 cents per gallon. Methanol fuel cell vehicles (MFCVs) are indeed found to be so attractive that in order to develop readily accepted specifications for the safe and effective use of methanol in MFCVs, representatives from the oil, automotive and methanol industries have recently formed the Methanol Specification Council.

In recent years, direct borohydride fuel cells (DBFCs) are also emerging as strong contenders to PEFCs. DBFCs employ borohydrides as fuel, which have the virtues of both high capacities and high hydrogen content. DBFCs provide a cell voltage of 1.6 V as against 1.23 V from PEFCs. One of the potential borohydrides is $NaBH_4$, which contains 10.5 wt% of hydrogen, and its specific capacity is 5.67 Ah/g, a value much higher than the value of most hydrogen storage alloys (around 0.3–0.4 Ah/g).

6. The next wheeze

Fuel cells have always been and will probably continue to be years away for road vehicles. But an ongoing plan is to put them in air. Boeing plans the first test flight of a fuel cell-powered electric airplane in the late 2004 or early 2005. The project, which is being led by Boeing's Research and Technology Center in Madrid, Spain, could eventually lead to the application of fuel cell technology for commercial jet liners. For the Boeing aircraft

(Fig. 6), a 20 kW PEFC will meet the power demand for its straight and level flight, while the additional power for take-off and climb will come from lithium-ion batteries.

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