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Fuelling the Car of the Future

Paul McGuiness
Jožef Stefan Institute, Slovenia

Whether you worry about man-made global warming due to the burning of fossil fuels, or not, you have to face up to the fact that the supply of crude oil that we convert to petrol and diesel is finite, and the time when it will no longer be possible to match supply with demand is not so far away. Projections vary, but even the most optimistic do not predict much more than 20 years. For this reason we need to start looking very seriously at ways we can fuel our vehicles in a post-crude-oil future. Hydrogen is a popular option, but is it a realistic one? Don't the Brazilians run their cars on alcohol? Is that a strategy we could apply world wide? And what about battery-powered vehicles? Is that just for golf carts? The answer, as it turns out, is not to go for a single option, rather we will have to employ a combination of some of these technologies to keep us on the road.

Keywords: automobiles, internal combustion engine, hybrid electric vehicle, fuels, renewable energy sources

0 INTRODUCTION

In the industrialised world, approximately 97% of the energy consumed by cars, vans, lorries and airplanes comes from refined crude oil [1]. With the end of plentiful supplies of cheap crude oil in sight we need to look closely at alternative ways of powering our transport systems. In simple terms we appear to have two choices, either we find an alternative to the refined petroleum product we use now, for example, biodiesel, ethanol or hydrogen, and so keep vehicles with internal combustion engines (albeit with a different fuel), or we look at a radical change to the way we store the energy in the vehicle, for example, hydrogen-storage materials or batteries, and go for vehicles that are driven by electric motors. In this article we will look at how realistic these choices are and attempt to predict how the engines of vehicles will change over the next 20 years or so, based on the best information available now.

1 STAYING WITH THE INTERNAL COMBUSTION ENGINE

The internal combustion engine (ICE) has been the main power unit of the motorcar for more than 100 years. Despite a mechanical efficiency of just 20% or so [1] it has seen off, among others, gas engines, the Hornsby-Ackroyd oil engine and the rotary Wankel engine. Although the classic four-stroke cycle has remained largely unaltered, engineers and scientists have continued to improve the design in terms of power output and fuel economy, and it is very likely that the ICE will continue to be the mainstay of the car's power-production unit for a long time yet. In the first half of this paper we look at alternatives to petrol that we can put in the tank.

1.1 Ethanol

Ethanol is an alternative fuel popular with farmers, who anticipate healthy profits, and car companies, who will not have to make any major changes to the engines they are already producing. The world's total production of ethanol in 2006 amounted to 51 billion litres, with 69% of this coming from Brazil and the United States [2] (Fig. 1). Ethanol can be used as both a motor fuel and as a fuel additive. In Brazil, for example, 50% of cars can run on 100% ethanol; this figure includes ethanol-only engines and what are called "flex-fuel" engines, which can run on any mixture of ethanol and gasoline. In the United States, however, only 6m of the country's 237m cars and lorries can be described as "semi-flex-fuel" vehicles, able to use a fuel called E85 (85% ethanol). In Brazil the ethanol is produced from sugar cane; this makes Brazilian ethanol easier and cheaper to make than American ethanol, which is normally produced from maize. The maize-based fuel has two main

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*Corr. Author's Address: Jozef Stefan Institute, Department for Nanostructured Materials, Jamova 39, SI-1000 Ljubljana, Slovenia, paul.mcguiness@ijs.si

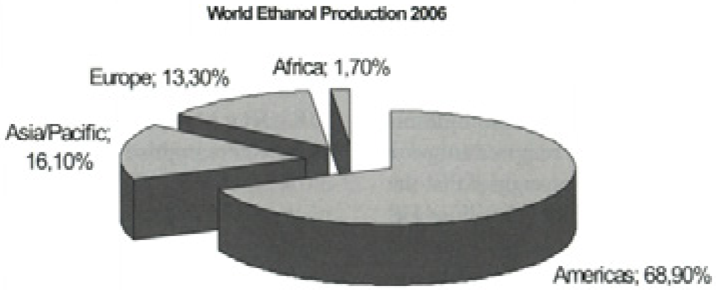

Fig. 1. *A breakdown of global ethanol production for 2006*

disadvantages. Firstly, it is expensive; its price at a gas station in the US is only competitive with petroleum because the country's taxpayers subsidise production to the tune of $6 billion a year. Secondly, corn ethanol has dubious green credentials. Researchers in California [3] have reported that maize-based ethanol is only some 10–15% better than gasoline in terms of greenhouse-gas emissions. There are, however, alternative ways of producing ethanol under investigation; one of the most promising involves making it from straw, woodchips or anything containing cellulose. This idea has proved popular with the American president, who has pledged $385m in government subsidies to bring cellulose-based ethanol to the market [4]. One additional problem with ethanol is that it is less energy intensive than petrol (about 30% less energy per unit volume [5]), which means accepting lower performance, a shorter range between fill ups or a larger fuel tank, taking up passenger space in the vehicle. However, a recent report in Nature [6] suggests that the problems associated with the lower energy density of ethanol can be overcome by producing it straight from fructose, which is present in fruits such as apples, pears, berries and melons as well as some vegetables. The resulting fuel is not only energy rich, it is also water repellent, so overcoming another problem associated with ethanol.

1.2 Biodiesel

Biodiesel is a diesel-equivalent fuel produced from biological sources, such as vegetable oils, and can be used in an unmodified diesel engine. This property distinguishes it from vegetable oils, which require the vehicle's engine to be modified. In contrast to the situation regarding ethanol, when it comes to biodiesel, Europe is the dominant player (Fig. 2). Biodiesel is both non-toxic and biodegradable, and produces only 40% as much CO_2 as conventional diesel because most of the CO_2 released during the combustion process was absorbed from the atmosphere by the crops that were later processed to produce the biodiesel. One of the most attractive features of biodiesel is that it can be produced from a very wide range of oils. These include rapeseed and soyabean oils,

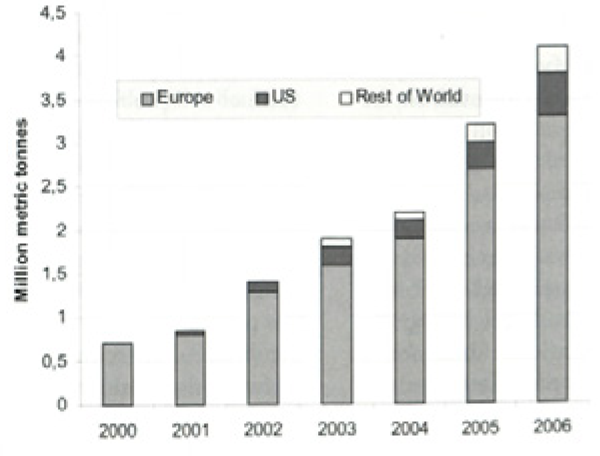

Fig. 2. *World biodiesel production from 2000 to 2006*

sunflower, canola and palm oils, waste vegetable oils, animal fats, and some forms of sewage [7]. The most obvious problem associated with a shift away from fossil-fuel-based petroleum to biofuels is the huge amounts of farmland required to grow the plant feedstock. Best estimates suggest that the US could produce only 25% of the 80 billion US gallons of diesel fuel it consumes every year if it was to use all its fallow, set-aside and export-crop lands [8]. Conservationists are also very worried about how the chopping down of tropical forests to clear space for growing biofuel feedstock could threaten the existence of the natural habitat of enormous numbers of animal species, including our close relatives, the great apes [9]. However, it would also be foolish to overlook the politically sensitive issue of rich Western countries growing food for fuel while poorer parts of the world struggle to grow enough food to feed their populations [10]. In the US, estimates of the total amount of fuel used for heating and transportation put the figure at about 230 billion US gallons [11]. This figure dwarfs the total amount of vegetable oils used for all purposes (3 billion US gallons) [12], which means that at best, biodiesel will fill a niche market as just one of the fuels that will begin to replace petroleum over the next 20 years.

1.3 Vegetable Oils

Many vegetable oils have similar properties to diesel, which means that with simple engine modifications they can be used to fuel a wide range of vehicles. Two grades are available: straight vegetable oils (SVOs) and waste vegetable oils (WVOs). It is ironic that Rudolf Diesel, who invented the diesel engine, originally designed it to run on peanut oil; however, it was soon discovered that the engine would also run on the cheaper petroleum oil, and as a result the diesel engine has been a heavy polluter throughout most of its history. Today, most diesel cars can run on SVO with a few simple modifications costing less than €500. Viscosity is SVO's main drawback, which means that it must be preheated in the fuel tank or blended with straight diesel during the winter months. The legal situation with regard to using vegetable oil to fuel your car is far from clear. In the US, for example, the conversion of an automobile to run on vegetable oil is illegal under United States Environmental Protection Agency guidelines. Taxation also remains a mostly unresolved issue, although Germany, Canada, and Ireland have decided to impose a 0% tax. In the UK, Her Majesty's Revenue & Customs have decided to impose the full diesel excise rate of £0.47 per litre [13].

WVOs are widely available as they are a waste product from the food-processing industry and the restaurant industry, in particular fast-food outlets; however, the collection and cleaning costs are likely to keep this form of oil from ever becoming a profitable product.

1.4 Hydrogen

Internal combustion engines (ICEs) designed to run on hydrogen are only slightly modified versions of the petroleum engines in most of today's cars. The introduction of the hydrogen ICE is often seen as a way of moving quickly towards a hydrogen-fuel economy without having to wait for fuel cells (necessary to generate electricity from the hydrogen) to become a practical and economic reality for fully electric-powered vehicles. Of the world's major car manufacturers, Ford and BMW have been most active in the pursuit of the hydrogen ICE, and in an attempt to publicise the success of their work on hydrogen vehicles, BMW built the BMW H2R. Designed and developed in only 10 months, this 6-litre V12 generates 232 HP and has a top speed of over 187 mph. BMW have also announced the Hydrogen 7, a derivative of the 7 Series 12-cylinder engine, which will be able to run on liquid hydrogen or gasoline. Plans were to begin sales to customers in Europe and the US in 2007 [14].

At first glance the hydrogen-powered ICE is a compelling solution, but although it gets around the fuel-cell problem (of which more later) it does not solve many intractable problems associated with hydrogen as a fuel. First off, how do we make the hydrogen? There is little or no hydrogen gas in the atmosphere, which means we need to create the hydrogen by breaking the chemical bonds in water, or methane or some other compound. All this takes energy, and this energy has to come from somewhere. With the prospects for solar panels covering the world's deserts still a long way off, the only realistic solutions involve using fossil fuels, but then that negates any benefit of using hydrogen in the first place, or renewables, but they would be better used displacing coal-fired power stations than replacing gasoline. Using hydrogen from renewable sources has a carbon-dioxide avoidance cost of $600/tonne, which is a factor of 10 higher than most other avoidance strategies under consideration [15]. Secondly, how would the hydrogen be distributed? There is a tendency in the pro-hydrogen lobby to talk in terms of millions of mass-produced low-cost fuel-cell cars being refuelled by hydrogen from a Europe- or US-wide system of super-insulated pipelines carrying liquid hydrogen. But who is going to fund the building of this pipeline, especially when the advantages of hydrogen as a viable fuel for vehicles are far from clear? And what about the energy costs of making liquid hydrogen? Turning hydrogen gas into liquid hydrogen costs you a third to a half of the energy in the resulting liquid hydrogen [16], and then because you have to keep it in an un-pressurised fuel tank in the car at -241°C a quarter of the hydrogen will boil away every week. Analyses looking at hydrogen-powered vehicles have suggested that hydrogen will not play any sort of role in transport until after 2035 [17], and a report by the National Research Council in the US suggested that the DOE should stop funding research on high-pressure tanks and liquid hydrogen because they have little promise of any long-term practicality [18].

1.5 Other Fuels

Although much of Europe now has a single currency, European drivers are likely to face a wide variety of filling-up options in the near future. As well as the ethanol, biodiesel and oils described above there will be the opportunity to buy compressed natural gas, known as CNG, liquefied petroleum gas (LPG) and there will also be plug-in points for electric cars. Car manufacturers are responding to this multi-fuel situation by making their cars more flexible in terms of the fuels they can use. Fiat, for example, has introduced its Tetrafuel [19] system, which means that some of its cars can run on four different fuels: petrol, a mixture of petrol and ethanol, pure ethanol, and CNG. Not wishing to be left out, GM Europe has an Opel Zafira that can run on natural gas and some Saabs, the 9-5 and 9-3, can use ethanol mixes. Which of these fuels will win out depends as much on the policies of governments when it comes to taxation as on anything else. However, if supplies of crude oil from the oil fields of the world were to start drying up more quickly than currently anticipated there must be serious doubts as to whether the gaps in supply that would appear could be filled by any or all of these alternative fuels without introducing price increases that would see the mass abandonment of private vehicles and the serious problems that that would pose to governments.

2 SWITCHING TO VEHICLES WITH ELECTRIC MOTORS

Everyone in the automotive industry agrees that one day all cars will be electric vehicles. What they do not agree on is when that will be and how will the energy to drive the electric motors be stored in the vehicle. Right now the industry is divided into two camps: those who think that hydrogen combined with fuel cells will produce the electricity, and those who see batteries as the future. In the second half of this paper we take a closer look at these technologies.

2.1 Hydrogen-Powered Fuel-Cell Vehicles

The fuel cell is a device for combining hydrogen or hydrogen-containing gases with the oxygen in the atmosphere to produce electricity. This electricity can then be used to do work, like powering the wheels of a car. Much of the attraction of such a car comes from the rather narrow perspective of a car with a store of hydrogen, converting hydrogen to electricity, and then using this electricity to power the car while pure water drips from the "exhaust pipe". The broader reality is quite different. Not only is hydrogen awkward to produce in a clean process and enormously expensive to transport, by whatever method we choose, storing it in the car as a gas or in a storage material also presents us with massive problems – and that is before we get to the cost of fuel cells. We have already looked at the problems associated with liquid hydrogen, but hydrogen could also be stored in the car as a gas under high pressure or in solid-state form, for example, as a metal hydride. Unfortunately, hydrogen's volumetric energy density is very low (Fig. 3), which means we would have to use very high pressures to store on board about 4–5 kg of hydrogen to give a range of about

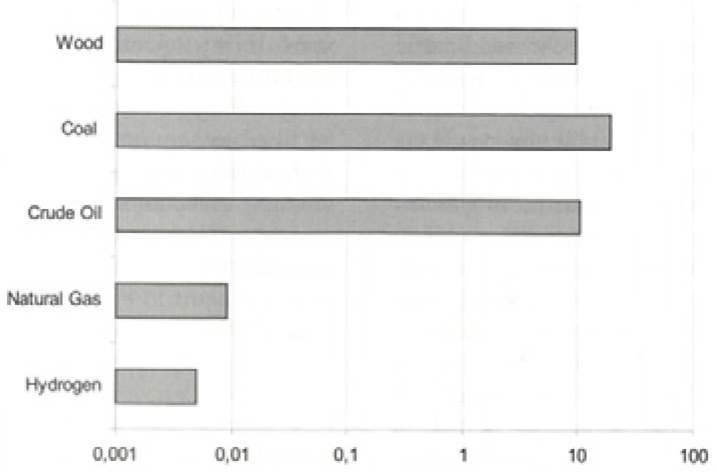

Fig. 3. *Volumetric energy density of some common fuels*

400–500 km. Maintaining gases safely at pressures up to 500 bar is a realistic possibility, albeit a very expensive one. A 500-bar hydrogen fuel tank would probably cost $2100 per kilogram of capacity [20]. Another problem with high-pressure tanks is their shape. The strength of the shell demands a cylinder; the last thing a car designer wants is to find a way of absorbing such a shape into the layout of the car.

So what about storing the hydrogen in solid-state form, in a hydrogen-storage material? The best known and most intensively researched hydrogen-storage materials are the metal hydrides. Put simply, the metal or alloy acts like a sponge, absorbing the hydrogen in atomic form into the matrix of the metal or alloy. The hydrogen atoms then occupy the interstitial sites between the metal atoms in a thermodynamically metastable system. The best of such systems can store up to a maximum of about 2 weight percent hydrogen [21] and [22], but that is not enough. Remembering that we need 4 to 5kg of hydrogen, that means our "fuel tank" would weigh at least 250kg – about the same weight as a large Harley Davidson motorcycle. This extra weight would hurt the fuel efficiency, one of the main reasons for having a hydrogen-powered vehicle in the first place. In spite of the fact that there have been no real breakthroughs in this area for 20 or 30 years, a lot of scientists, particularly in Europe, continue to plug away in this field. As part of its 5th Framework Programme the EU funded three projects – HYSTORY, FUCHSIA and HYMOSSES – with at least one more – STORHY – as part of the 6th Framework, with little sign of a major breakthrough in hydrogen-storage materials. Indeed, the surprising enthusiasm for funding hydrogen-storage research shown by oil companies like BP [23], Shell [24] and Chevron [25] would almost suggest they are attempting to improve their green credentials while knowing they are running little risk of being put out of business by hydrogen any time soon.

Researchers are also struggling with other issues relating to the onboard storage of hydrogen in a metal-hydride-type system. One problem that seems particularly tricky to solve is that of refuelling. Reversible metal-hydride systems are refuelled with a supply of pure hydrogen, but this refuelling period could take hours rather than a few minutes, making refuelling stops on a long journey something more than a quick stop at the petrol station.

Now let us turn to fuel cells. The first fuel cell was developed by the Welsh scientist Sir William Robert Grove in 1843, making this technology quite some years older than the ICE. A fuel cell differs from a battery in that it consumes reactant, which has to be replenished, while batteries store electrical energy chemically in a closed system. As far as automotive applications are concerned the most promising type of fuel cell is known as the proton-exchange-membrane (PEM) fuel cell, which uses hydrogen as the fuel and oxygen from the atmosphere as the oxidant. One of the most positive aspects of a hydrogen fuel-cell car is the so-called tank-to-wheel efficiency.

Under small loads this can be as high as 45%, with average values of about 36% on a driving cycle like the New European Driving Cycle [26]. The comparable value for a diesel-engined vehicle is about 22%. A more realistic figure, however, is the power-plant-to-wheel efficiency. In this case the values are reduced to 22 and 17%, respectively, when the hydrogen is stored as a high-pressure gas or as a liquid. A detailed investigation of the efficiencies of various fuel paths can be found in a 2004 review in Scientific American [27].

Fuel cells also suffer from being extremely expensive. Prices vary, but for a PEM fuel cell you would expect to pay anywhere from $1000 to $5000 per kW for a 10-kW to 100-kW motor. For a fuel cell to become competitive with an ICE these costs will have to tumble to less than $50 per kW. Mass production alone will not suffice; a technological breakthrough is required.

2.2 Battery-Powered Electric Vehicles

Whenever battery-powered vehicles are mentioned, most people instinctively think of a milk float or a golf cart. However, the reality of a modern battery electric vehicle (BEV) is very different. Many such vehicles are capable of accelerating faster than conventional gasoline-powered cars, they are also quiet, and they do not produce noxious fumes from an exhaust pipe. Over most of their history BEVs have had problems with the high costs of batteries, a limited range between "refuelling" stops, charging times and battery lifetimes. However, while hydrogen vehicles have been grabbing all the publicity, ongoing battery-technology developments have gone a long way to solving these problems. As of 2004, there were more than 55,000 BEVs in the US, with an annual growth rate of almost 40% [28] (Fig. 4).

There are, of course, still problems associated with BEVs. The purchase price of a BEV is typically 80% more than a comparable petrol or diesel car or van. Battery-replacement costs are also high, which means that leasing, at a cost of about €100 per month, is a popular option among owners. Running costs for a BEV are in the region of €0.01–0.02 per km, which means a saving of €1200 per year in fuel costs for a typical 15,000 km per year. However, if battery leasing costs are included, these cancel out the fuel savings. Whether BEVs are more environmentally friendly and reduce the consumption of fossil fuels depends on the source of the electricity used to charge them up. Like with the energy needed to produce hydrogen: if it is a clean source, we should be using that clean electricity to displace the electricity that comes from the dirtiest sources like coal, and if it is a dirty source, then we are really fooling ourselves if we say that a BEV is an emissions-free or environmentally friendly vehicle.

The Achilles' heal of a purely electric vehicle is the battery; the current technologies for electric motors are more than good enough. BEVs use many different types, e.g., lead-acid, NiCd,

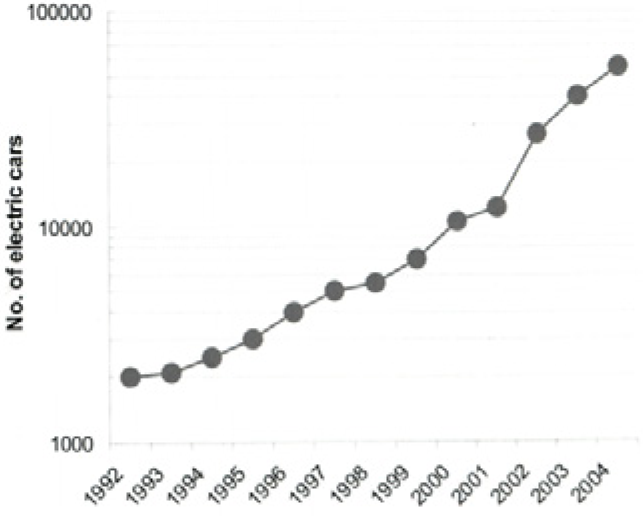

Fig. 4. *Growth in the number of electric cars in the US (1992 to 2004)*

nickel metal hydride, lithium ion, and Li-ion polymer. Of these, lead-acid batteries are the cheapest, most familiar and easily available. A typical lead-acid-battery-based car has a range of 30–80km, depending on a number of factors, like the use of headlights and the temperature. General Motors' EV1, the most famous all-electric car, never performed well in cold weather. However, new research [29] suggests that the use of foam grids in lead-acid batteries could significantly improve the range of such cars. Nickel metal hydride batteries can deliver up to 200 km of range, and vehicles fitted with lithium-ion batteries can drive as far as 400 to 500 km on a single charge, and although these figures represent ideal rather than real driving conditions it is clear that batteries are closer to being good enough than any hydrogen-storage material.

3 WHICH WAY DO WE GO FROM HERE?

So, having looked at a lot of alternatives, can we now predict what will be powering our cars 20 years from now? The truth is that none of the alternatives above – on their own – provide the answer. However, the beginnings of a solution are already with us, in the form of hybrid vehicles, the most popular example of which is the Toyota Prius. Hybrid vehicles combine a small, but fairly conventional, diesel or petrol engine with an electric motor. This electric motor runs from a battery, which is charged by regenerative braking, and used primarily at low speeds, when the petrol or diesel engine is at its most inefficient. It is this combination of saving energy during braking and optimising performance that makes hydrids very efficient vehicles, particularly on low-speed, stop-start urban cycles. The latest-model Prius, for example, has a City Fuel Economy figure of 4 litres/100km; about half what you would expect from a similar-sized petrol-driven car. However, these are early days; the next five years should see car showrooms displaying what are known as plug-in hybrids. A plug-in hybrid has the rechargeable batteries, the electric motor and the petrol or diesel engine, but it also has the option to charge these batteries from the electricity grid while the car is parked, so giving the car a significant all-electric range. As of 2007 there are no plug-in hybrid passenger vehicles in production [30], but both Toyota and General Motors, with its new Volt concept car, have signalled their intension to introduce them soon. GM claim that after being charged from a domestic power outlet for six hours the Volt will be able to drive about 65 km on the batteries alone, without consuming a drop of petrol from the tank. They are also boasting that the Volt could save an average motorist 500 (US) gallons (1850 litres) of petrol per year [31]. In other words, the plug-in hybrid is a stepping stone to the all-electric vehicle. But what makes it particularly attractive is that it can be done in many small steps without running the risk of introducing a disruptive technology – like hydrogen-powered vehicles – that would be both enormously expensive and far from certain to succeed. Then, as battery technology improves, each new generation of plug-in hybrids will have a smaller and less frequently required petrol engine until eventually the vehicle will have sufficient range in its batteries to dispense with the petrol engine altogether. But does that mean the hydrogen-powered car will never be a mainstream reality? We would have to conclude that the answer is almost certainly no. When it comes to storing energy in a mobile device, however we look at it – safety, cost, weight, recharging – batteries are likely to be as good or better than any hydrogen-storage techniques, and when it comes to transporting this energy, hydrogen can never match the ease with which we can distribute electricity through ordinary copper wires.

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