Nazi Sharks (or why Top Gear haven't done their arithmetic)

George Wallis, January 2009.

A Nazi shark. Please note that this paper in no way suggests that sharks are national socialists.

Introduction

This paper attempts to show why cars powered by hydrogen fuel cells are not the immediate future of private motoring, and why batteries have an important and immediate part to play. Just in case you don't get the 'Nazi sharks etc.' reference, it was made by James May while he was explaining how the fuel cell powered Honda FCX Clarity works [1]. Briefly, during the Top Gear show Jeremy Clarkson drove the battery powered Tesla Roadster, which broke, while May drove the Honda, which didn't. If you did get the reference, Tom Jones is certainly still going strong – good show – and I presume you're either glad or mildly disappointed that the 'etc.' wasn't chosen for illustrative purposes.

The paper will briefly examine the existing and possible future energy sources for vehicles, will try to disentangle some of the commonly used definitions for proposed vehicles, and will then examine the sustainable alternatives – and compatibilities – for road transport. Examples and direct comparisons will be provided where they can be useful.

Clarkson suggested that while 'the volthead has overtaken the petrolhead, (and yes, I've just heard, it is snowing in hell)' electric vehicles would be 'completely irrelevant' while May suggested that hydrogen would be the future since it 'fits the life we already have' [2].

Sorry chaps, but the future is happening, and this is how it works out.

Existing energy – the one transport fuel we have

Oil

Someone (can't remember just who at the moment – no, wait [3]) suggested that the recent global credit crunch and economic devastation 'is all because a Mexican man chose to fill his pickup with fuel, rather than pay his bloody mortgage bills'.

West Texas Intermediate reaching $147/bbl over last summer would suggest that we need to get as far away from oil as possible, in as short a time as possible, and in the UK that means road transport, more particularly private cars. Why? The petrochemical industry is necessarily tied to its feedstock. Aircraft cannot easily or cheaply use other forms of fuel, and the haulage industry – both light and heavy – can't easily do without the range that fossil fuels allow. Assuming that while most of us like our posties we wouldn't like them served on toast, we need to do something.

Why should we consider any of this when oil has recently dropped below $40/bbl? Because non-OPEC countries are past peak oil, because there is ever increasing demand from the developing world, because seven of the last eight global recessions have been preceded by a spike in oil prices, because the Kingdom of Saud appears to have been very close to peak production and is unwilling to add more (if it can), because every indication is that when the recession ends oil (and other fossil fuel) prices will get even more unstable, because UK balance of payments is... Fair enough?

Almost all existing road vehicles use either petrol or diesel. Without getting too bogged down in trivial detail, in the UK [4] consumption for vehicles in 2005 was as follows:

Diesel Buses	Diesel Cars	Petrol Cars	Motor-cycles	Diesel HGV	Diesel LGV	Petrol LGV
1,487.4	4,271.7	18,052.4	144.3	8,130.0	5,007.7	478.4

'Trivial detail' since many of these figures are best estimates, and it is impossible to separate private vehicle use from taxi journeys, for instance. 2005 was chosen since it was the height of the boom, oil prices had not yet set any inflation-adjusted records, and the figures were available. These figures are in thousands of tonnes of fuel per year. If we take the energy content [5] of petrol to be 13087kWh/tonne, and the energy content of diesel (DERV) to be 12668kWh/tonne, we arrive at the following figures expressed in TWh/yr:

Diesel Buses	Diesel Cars	Petrol Cars	Motor-cycles	Diesel HGV	Diesel LGV	Petrol LGV
19	54	240	1.9	100	64	5.9

TWh/yr (terra-watt hours per year) are a useful unit to use since they can more readily be compared with other means of power generation and energy use. The units have been rounded to 2 significant figures to make things a bit simpler. The total above is approximately equal to 485TWh/yr. In comparison aviation in the UK uses about 135TWh/yr, and the total UK energy requirement is about 2000TWh/yr. Let's simplify things further.

Exclude motorbikes – it's a comparatively trivial amount and their owners are already about as concerned with energy efficiency as they are going to be, one way or another. Exclude heavy goods vehicles, most of diesel and some petrol white vans, since they'll need range.

Some vans operate as delivery vehicles over short ranges though, so keep a low percentage of them. Use round figures. That then gives us:

Diesel Buses	Diesel Cars	Petrol Cars	Diesel LGV	Petrol LGV
20	55	240	5	5

For a total of 325TWh/yr, then knock a bit off for taxis and coaches and to allow for being conservative, so say 300TWh/yr that we can (perhaps) look to do something about immediately. To briefly convert back, that's about (25.7 x 1.09 to allow for refining) 28 million tonnes of crude oil per year. Anything saved from that can go to export for the time being.

Some vehicle definitions and examples

A jargon section has been provided at the end of the paper, so please feel free to browse that if there are any unfamiliar concepts. This section should be a lot more interesting after the decision to use actual cars as examples, with some explanation.

Clarkson's Ford GT	A modern re-interpretation of Ford's famous Le Mans winner, also famous for being the previous record holder at Dunsfold for the car to run out of fuel fastest – after 115km.	Power source	V8 petrol	
		Cost	£120 000	
		Lap time	1.21.9	
		Refuel time	c5mins	
		Refuel cost	£80.00	
Porsche 911 GT3	The driver's 911. Included for comparison with the Tesla Roadster.	Power source	Flat 6 petrol	
		Cost	£80 000	
		Lap time	1.27.2	
		Refuel time	c5mins	
		Refuel cost	£90.00	
Tesla Roadster	Battery Electric Vehicle (BEV) technology demonstrator (the batteries are water cooled and stored where an Elise's engine would be). New record holder for car to run out of juice fastest at Dunsfold – supposedly after 80km. <4sec to 100km/h, top speed 200km/h. Lapped as fast as a GT3. Maximum range c350km.	Power source	Battery	
		Cost	£92 000	
		Lap time	1.27.2	
		Refuel time	3½hrs 3phase; 16hrs single phase	
		Refuel cost	£3.50	
Toyota Prius	First generation hybrid. Good in traffic, less so on the open road (or track). Uses Ni-MH batteries to operate an electric motor over very short ranges, then a petrol unit to drive the wheels directly whilst simultaneously charging the batteries (hence parallel).	Power source	Parallel ICE hybrid	
		Cost	£18 000	
		Lap time	not timed	
		Refuel time	c5mins	
		Refuel cost	£45.00	
Honda FCX (Fuel Cell eXperimental) Clarity	Honda family sized vehicle. The first fuel cell powered car to go into limited production. A few minutes fill-up for 435km range. Capacitors or batteries are constantly charged by the fuel cell; they then power an electric motor (hence series).	Power source	Series FC hybrid	
		Cost	$1 000 000	
		Lap time	not tested	
		Refuel time	c5mins	
		Refuel cost	see below	
Mitsubishi i	Four seat (or five to the pub) city car. Aluminium space-frame construction to save weight, steel panels presumably to save cost.	Power source	Straight 3 petrol	
		Cost	£9 000	
		Lap time	not tested	
		Refuel time	c5mins	
		Refuel cost	£35.00	

Mitsubishi i MiEV	As above but uses lithium ion cells and an electric motor. Maximum range c160km. Paintjob optional.	Power source Cost Lap time Refuel time Refuel cost	Battery £15 000 not tested ½hour 3phase; 7hours single phase <£3.50	
Chevrolet Volt	Plug-in Hybrid Electric Vehicle (PHEV). Four/five seat family car. Operates as a BEV for the first 65km, then uses a petrol engine at constant velocity to charge the battery in series	Power source Cost Lap time Refuel time Refuel cost	Series ICE PHEV $32 000 not tested 3hrs single phase <£3.50 + petrol	
Audi A8 TDi	2000kg all aluminium luxury car. Included for comparison with the Fisker Karma. <6sec to 100km/h, top speed 250km/h. Can do a return trip London – Edinburgh on one tank of fuel.	Power source Cost Lap time Refuel time Refuel cost	V8 diesel £65 000 not tested c5mins £90.00	
Fisker Karma	2100kg all aluminium luxury car. <6sec to 100km/h, top speed 200km/h. Can operate as a BEV for 80km. Uses 2 litre turbocharged petrol in switchable hybrid mode for battery charging or for performance use.	Power source Cost Lap time Refuel time Refuel cost	Dual-mode series ICE PHEV $80 000 not tested 7hrs single phase <£3.50 + petrol	

With thanks to Top Gear, Autocar, Evo Magazine, Car Magazine, Fisker Automotive, General Motors and Honda for the information and images. For simplicity's sake fuel cost was assumed to be £1.00 per litre for petrol and diesel. These prices include tax on electricity and fuel, since fuel tax is supposedly in place to wean us off inefficient vehicles and fuels that pollute – hence the actual price disparity between LPG, petrol and diesel, in ascending order.

Getting away from oil

Efficiency

We need to get as far away from oil as possible, in as short a time as possible. The first step as always is efficiency. The forthcoming VW Chico will achieve 2l/100km [6], 141mpg (shown right). It will be powered by a version of the firm's existing 1.4 litre turbo-diesel ICE, feature mild hybrid technology, and is likely to be a lively performer. Modern crash protection standards mean that although it will be roughly the same size as the original Mini, it will be a strict two-seater with associated limitations for most families.

In a similar vein is the forthcoming four-seat Type 25 (shown left under bubble wrap) from Gordon Murray Design [7]. About as tall and wide as a Smart car, it uses novel design features to reduce manufacturing costs, and will be powered by a small petrol engine initially. Its eponymous and respected designer has been quoted as saying 'I don't give a monkeys what you power it with. You can run it with a fuel cell or reconstituted cockroach wings or whatever you like in the future. What we're selling is a whole new vehicle architecture. We're going to prove that you can significantly reduce emissions over the whole lifecycle of the vehicle, but still have fun driving it and still feel safe'.

Efficiency is supposedly a dirty word in the United States. 'Aggressive demand reduction' perhaps?

While essential, efficiency on its own does not move us away from oil. It does also leave us with private (and other) vehicles which are essentially smaller and – perhaps – poorer performing than we have at the moment.

Biofuels

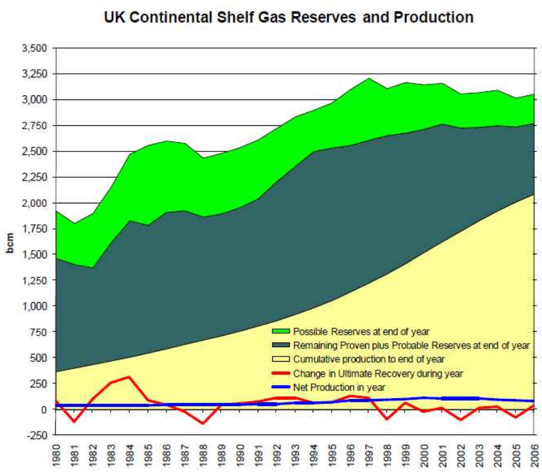
In theory, biofuels let us have our cake and eat it, except that experience has shown that while we may be eating cake, those in the developing world may be eating dirt – literally – to assuage their hunger [8].

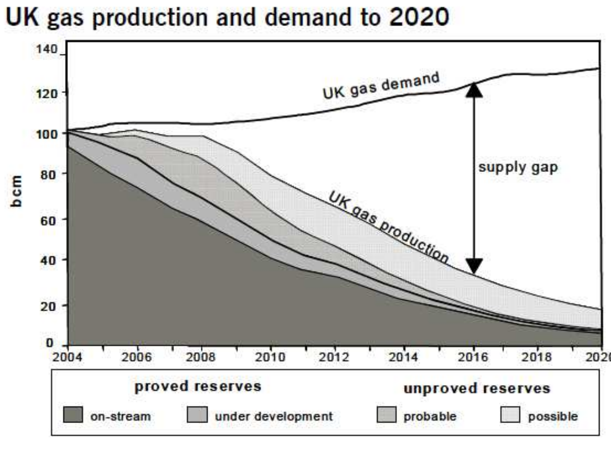
A direct and complete swap to biofuels – whether of the bioethanol or biodiesel variety – would seem unlikely without either significant technological breakthrough or creating havoc in the developing world; the UK certainly can't make enough of its own.

Natural gas

May filled up the Clarity at a Shell hydrogen refilling station in California during the show [9]. It was pointed out that hydrogen costs roughly the same as petrol in the States – well yes, but only when it's been split from natural gas, which is already the cleanest fossil fuel we have. In fairness he did later point out that hydrogen can be a bit difficult to obtain. Just how difficult will be examined later in the paper.

If one is going to be using natural gas in any case, as with fuelling the Clarity, why not the VW Passat Ecofuel, using an internal combustion engine specifically designed for gas? These would, for the moment at least, offer less expensive power units with considerably longer unit life. Other nations (Russia would be a good candidate) can make up their own minds on that one, though in the UK natural gas is under considerable demand pressure already. Adding massive extra demand is probably not the best of ideas at the same time as our production is metaphorically falling off a cliff (illustrated by POST and DBERR below). Renewable gas – whether from landfill or anaerobic digestion – is another matter.





Source: Modified from WoodMackenzie 2004, 'From surplus to shortage'

It is often taken as a given that natural gas can be used as a 'bridging' fuel between oil and the future since it is a relatively cheap source of hydrogen. Not in the UK.

Old King Coal

Critics of electric vehicles – or of vehicles operating in electric mode – often argue that the power mix from the grid includes coal-fired power stations. A wonderful illustration of this was given on Top Gear [10]. Yes, absolutely true. It does rather ignore two facts though – it is far easier to 'green' electricity production, and with oil prices as they were over last summer they would have very soon found themselves filling up at the pumps from a coal mine rather than an oil well. The Fischer-Tropsch coal to oil process is already being planned in many coal producing areas and is both expensive and dirty; likewise the gasification of coal for hydrogen. Remaining UK coal reserves are too expensive to consider except in the direst of circumstances. Related to this is the further criticism that extensive mining will be needed for battery (and fuel cell) materials, though it is already done for mobile phones and laptops, and there is a healthy recycling industry in place.

What then?

With the other two fossil fuels and biofuels excluded for large-scale UK use that leaves sustainable electricity in batteries or sustainable hydrogen as our immediate alternatives.

Batteries or hydrogen?

The vehicles

Clarkson and May [11] demonstrated that cars powered by either fuel cells or batteries can give us space and pace.

Without changing the vehicles, but rather only looking at fuels, the tables above suggested that there was 300TWh/yr that could perhaps be tackled immediately, from buses, white vans and cars. But could it? This is how it might work:

Buses — Buses are slow, heavy and stop a lot. That means that their inertia is high, and is a factor a lot of the time. Batteries could be incorporated into the floor-pan, and run in series hybrid mode with a small internal combustion engine or fuel cell for much higher efficiency than at present. Although the batteries would add more weight, Top Gear [12] ably demonstrated that superior torque from a standstill would overcome such a penalty, with the torque of the Tesla Roadster proving more than a match for a Lotus Elise in a drag race. Should racing at the lights not be the objective, it would seem that inertia will not be a hindrance to the efficiency of electric mode vehicles.

Routemaster concept

White vans — Although most white vans do a lot of miles in a day, some don't. Their duties are more in line with delivering flowers or trips to the cash and carry. Such vans could be operated as series hybrids with an ICE or fuel cell; more probably as pure

existing NGT Sprinter

electric vehicles.

Private cars The section of most interest to most people. Distance travelled is key, because neither batteries nor fuel cells can offer the same range as internal combustion engines at the moment. The Chevrolet Volt, a series hybrid, offers 65km, the Fisker Karma 80km. The Mitsubishi i MiEV, an electric vehicle, offers 160km. Why? About fifty and one hundred miles, or within range of 75% of American commutes or return commutes. The MiEV rather assumes that one wouldn't be able to re-charge at the office.

Ferrari MilleChili concept, a mild hybrid.

In the UK, more than 70% of the journeys we make in our cars are commutes, trips to the shops, trips to school, trips to see friends, trips out, other personal business [13]. All – usually – close to home.

Even allowing for all of the above 300TWh/yr would probably not be possible to work with. Just for starters people who live at the tops of hills will still need to drive SUVs [14]. People who do a lot of mileage – sales reps etc. – might prefer a small diesel. Owners of PHEVs will be making journeys on engine power rather than battery. 200TWh/yr? 'Ambitious but rubbish'? The main issue is that most cars tend to last upwards of ten years these days. 200TWh/yr may very well be possible as we approach 2030. Ambitious yes, rubbish – no, it's probably achievable. 200TWh/yr is about one third of the UK's total transport energy requirement and equivalent to just over 18.5million tonnes of oil a year.

<u>The arithmetic of energy - baseline</u>

200TWh/yr then. First we need to work how much energy we need. Internal combustion efficiencies vary, so to assure erring on the high side 30% efficiency will be assumed for the existing fleet.

(200 x 0.3 = 60) 60TWh/yr is what is actually used by the vehicles to make them move. The rest gets wasted as heat.

(An associated point – heating and air conditioning. This could represent anything up to a 10% parasitic loss for battery mode and FC use, as with ICE. As it is a small and variable loss it has been ignored.)

<u>The power trips</u>

Sustainable hydrogen is made by the electrical decomposition of water into hydrogen and oxygen – so it requires sustainable electricity. Hydrogen therefore requires a round trip of electricity generator > electrolyser > delivery > filling station > compression > vehicle. Electrical energy goes directly; generator > electricity grid > vehicle.

Hydrogen		Electricity
60	At the wheels	60

Next we have to allow for efficiency losses in the drive-train. Fuel cells on their own are at best about 65% efficient, battery mode electric vehicles 75% efficient or better [15].

(60/0.65) 92.30	At the pump/plug	(60/0.75) 80

Hydrogen has to be compressed. This is at best about 85% efficient [16]

(92.3/0.85) 108.5	At compression	

Hydrogen has to be delivered to the filling station (pipe is most efficient), and electricity has to get from the power station to the recharging point. Both about 90% efficient

(108.5/0.9) 120.6	At delivery	(80/0.9) 88.9

Hydrogen has to be electrolysed from water. This is about 70% efficient [17], and it is assumed the electrolyser is right next to the power station

(120.6/0.7) 172.3	At electrolysis	

That gives us our totals for the amounts of energy needed

172TWh/yr	Total requirement	89TWh/yr

The improvements compared to our original 200TWh/yr and to the 620TWh/yr overall that the UK presently uses for transport

28TWh/yr	Total improvement	111TWh/yr
14%	% improvement	55.5%
4.5%	UK transport %	18%

For comparison, existing electricity production in the UK is about 350TWh/yr. This would seem to suggest that electric mode vehicle use has already won. It has, but it gets worse for hydrogen as can be seen below.

<u>Getting the energy sustainably</u>

Demand will be expressed as normal, but also as numbers of two types of sustainable generators – wind turbines and nuclear power stations. The proposed new nuclear stations are 1GW, most new wind turbines are 3MW. This is 'rated' capacity. Load factor is the average of the time spent at rated capacity, expressed in hours per year.

Wind turbines

Power source	Size of unit	Number of units	Load factor		Delivered Energy
	W	multiplied by	multiplied by (hrs/yr)	(%)	
Wind	3000000	13000	2365	27	9.2235E+13
Total					9.2235E+13
Target					8.90E+13
Power source	Size of unit	Number of units	Load factor		Delivered Energy
	W	multiplied by	multiplied by (hrs/yr)	(%)	
Wind	3000000	25000	2365	27	1.77375E+14
Total					1.77375E+14
Target					1.72E+14

Nuclear fission

Power source	Size of unit	Number of units	Load factor		Delivered Energy
	W	multiplied by	multiplied by (hrs/yr)	(%)	
Nuclear	1000000000	12	7446	85	8.9352E+13
Total					8.9352E+13
Target					8.90E+13
Power source	Size of unit	Number of units	Load factor		Delivered Energy
	W	multiplied by	multiplied by (hrs/yr)	(%)	
Nuclear	1000000000	24	7446	85	1.78704E+14
Total					1.78704E+14
Target					1.72E+14

Therefore giving us the total numbers for required generating technology

25 000	Numbers of wind turbines	13 000
24	… or nuclear plants	12

The efficiency of the plants themselves has been ignored since delivered energy is the concern, by means of displacing oil. Keeping things in round numbers, getting the extra energy for hydrogen means an extra 12 000 wind turbines or 12 nuclear power stations. That means at least an extra £12 billion for generation, plus the electrolysers and delivery network.

Interestingly, battery use favours both nuclear and renewable generation. Nuclear accentuates the 'night valley', the trough in demand vs. production for electricity at night time. Electric vehicles can make use of this. Electric vehicles – with little modification – can also provide juice back to the grid as a powerful active demand-side measure, so helping grid balancing and therefore especially renewables.

Why use fuel cells OR batteries?

Can't ordinary engines use hydrogen?

Certainly they can, Sir. Where would you like us to put the…

(200/0.85) = 235.29; (235.29/0.9) = 261.43; (261.43/0.7) = 373.480

Power source	Size of unit	Number of units	Load factor		Delivered Energy
	W	multiplied by	multiplied by (hrs/yr)	(%)	
Nuclear	1000000000	51	7446	85	3.79746E+14
Total					3.79746E+14
Target					3.73E+14

… extra thirty nine nuclear power stations?

I can't plug in anywhere…

Fair point. It excludes battery electric vehicles, and is probably the best argument for using sustainable hydrogen from the beginning, if the infrastructure and fuel cells weren't so expensive. Two solutions – either buy a small petrol or diesel (part of the excluded 100TWh/yr from the original 300TWh/yr) or perhaps buy a PHEV and don't plug it in, at least at home or work. That isn't quite as daft as it sounds, as explained below.

For a start one would be able to use public recharging points. Plug-ins spend all their time on electricity, with the other power unit used to provide power to the capacitor or battery pack as needed, so there is energy to be saved from regenerative breaking. Also, there are only three PHEVs out there at the moment, all brand new technology, one from China and also the Karma and Volt. Both GM and Henrik Fisker have twigged to this issue, in that while the Karma normally operates as a plug-in with the engine merely to extend range, you can also use the battery and engine at the same time for performance. Turn that on its head and the Volt uses a small engine that runs at constant output for maximum efficiency.

Want both?

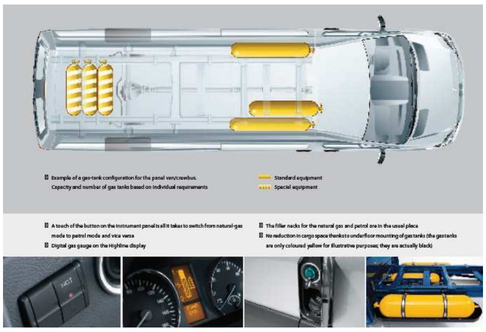
There's a technology called the DiesOtto cycle engine, recently developed by Mercedes. It's essentially a compression *and* spark ignition petrol engine that can operate with diesel efficiency at low revs and petrol power at high revs. Put one of those engines in a plug-in and you have an engine unit that can offer sustained (low efficiency) performance when needed; keep the batteries topped-off (high efficiency) when not.

And the rest?

What are you, some kind of Audi driver or something? Ok. This is what we've done so far – shown that by using private vehicles capable of operating in electric mode we can drop transport fuel requirements by nearly 20%, from about 620 to about 510TWh/yr. Dropped overall UK delivered energy requirements about 5%, from c2000 to c1900TWh/yr. Increased electricity demand by less than 30%. Saved the UK motorist a lot of fuel tax. Saved over 18million tonnes of oil a year, meaning lots of export revenue for the UK (and lots of tax for the Exchequer).

First we need to get the electricity from sustainable sources in the UK. Pick your own favoured source, that argument is not the purpose of this paper.

Beyond that trams – especially light trams – are more efficient than buses, and can draw electricity directly. On the routes where they are appropriate they'll cut energy use a bit further. As noted above, proposed PHEVs like the Volt and Karma use petrol engines, and that's because of the US market, which doesn't like diesel. Ten years ago Toyota used Atkinson cycle petrol instead of diesel on the Prius (mainly) because of the US market. It was astonishing economy over there but in the UK/EU everyone thought along the lines of 'what's the big deal?' and bought a Renault Clio instead. On the occasions PHEVs are being used on engine power a diesel (or DiesOtto) engine would make them more efficient, and that would also cut energy use a bit further.



The Sprinter van and Econic truck from Mercedes-Benz. Both of these already use compressed natural gas – not the best idea for the UK on a big scale, but it does also mean they *could* use renewable methane fuel with fuel cells (if the catalysers and FCs were available)

Beyond that? Things get costly. Reinforce the electricity grid in a big way. Shift the 150TWh/yr that goods vehicles use onto trains as far as possible – but for the moment that will make the goods themselves more expensive. Hope for advances in fuel cells that make them cheaper and longer lasting. Hope for advances in hydrogen storage. Hope for battery and capacitor advances that mean we need less range from other fuels. Start using fuel cells (perhaps sustainable ammonia, more likely sustainable methane or sustainable hydrogen) in PHEVs and series hybrids of all kinds – private transport and goods vehicles. Use bio-kerosene or sustainable synthetic kerosene for aircraft, making air travel hugely more expensive.

Translated without the waffle: that last paragraph means we have plenty of ideas but none of us knows what will happen for certain. If you're young and you're reading this then over to you.

Conclusions

The global oil market has become distinctly interesting of late. Electric mode vehicle use shifts transport in the UK away from oil towards sustainable low carbon solutions. It can be done quickly and inexpensively, with the technology we have right now and over a timescale of ten to twenty years (that is to say, hopefully before the next oil-price driven recession). Moreover it does so by switching demand to an efficient power source and therefore without – necessarily – sacrificing the comfort and real-world performance that we have come to expect.

In the United States things look even better. Their proportional savings remain about the same but they save upwards of 120million tonnes of oil per year.

Looking up to and beyond the next couple of decades James May got it right – he got it right six years ago when he drove the General Motors Hy-Wire concept [18] – in that hydrogen is going to be a big part of the automotive future. It has to be, one way or another. Just not the immediate future, and none of us can afford to wait.

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Jargon

- ICE – internal combustion engine, until the present time using the Otto, Atkinson or Diesel cycles, perhaps in future DiesOtto. The big noisy metal thing under the bonnet.
- Fuel cell – recombines hydrogen and oxygen to produce electricity and water
- Mild hybrid – stop/start with a larger starter motor and battery to reduce power consumption in traffic, energy recovery to the battery with regenerative breaking, meaning less parasitic losses from alternator use. Often accompanied by low rolling resistance tyres and slight aerodynamic improvements. Nearly all new BMWs are now mild hybrids, for a c10% efficiency increase.
- Hybrid – think Toyota Prius. As above, but uses an electric motor for very short distances, then an ICE which powers the car while recharging the battery.
- Parallel hybrid – again think Prius, though this is a stricter definition. The Prius operates only in this mode, with the car being directly powered by the engine at the same time as it also charges the battery.
- Series hybrid – uses a battery and electric motor to power the vehicle, while that battery is constantly charged by another means;
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usually ICE, occasionally fuel cell. The Clarity is a series hybrid with a low proportion of batteries to power unit. This mode of operation is also associated with cars (and buses) using a far larger proportion of batteries to power unit, which is then generally small and runs at constant RPM for maximum efficiency.

- Battery Electric Vehicle – a BEV uses batteries only. The Tesla Roadster is one such, though is essentially an expensive technology demonstrator, a direct comparison between two Mitsubishi models is given above.
- Plug-in Hybrid Electric Vehicle – a PHEV ('fev') uses an electric motor with a battery pack which can be plugged into the mains, plus another power plant. Existing and forthcoming PHEVs all use ICE technology, though it would be perfectly feasible to use a fuel cell. Once the battery power runs low they switch to either series hybrid mode – the Chevrolet Volt and Fisker Karma – or potentially parallel hybrid mode.

References

[1] May, James; *Top Gear*; Series 12 Episode 7; broadcast 14th December 2008 BBC2

[2] Clarkson, Jeremy, May, James; *Top Gear –Tesla and Honda FCX features*; Series 12 Episode 7; broadcast 14th December 2008 BBC2

[3] Clarkson, Jeremy; *Clarkson on: finance*; http://www.topgear.com/uk/jeremy-clarkson/clarkson-finance-2008-12-01; accessed 9th January 2009; ISBN N/A

[4] DBERR; *Regional and local authority road transport consumption statistics*; DBERR 2008; Publication URN 08/443c (2005, 2006)

[5] MacKay, David; *Without Hot Air*; http://www.withouthotair.com/; Draft 2.6.2 – August 12, 2008; ISBN N/A; pp25, 311, 326

[6] Kable, Greg; *Autocar - Exclusive: VW's Smart*; http://www.autocar.co.uk/News/NewsArticle/Volkswagen-Concepts/236168/; accessed 31st October 2008; ISBN N/A

[7] Pollard, Tim; *Car Magazine - Gordon Murray Design T25*; http://www.carmagazine.co.uk/Secret-new-cars/Search-Results/Spyshots/Gordon-Murray-Design-T25-city-car-the-scoop2/?content-block=0; accessed 26th November 2008; ISBN N/A

[8] BBC News; *Bioenergy: Fuelling the food crisis?*; http://news.bbc.co.uk/1/hi/world/europe/7435439.stm; ISBN N/A

[9] May, James; *Top Gear – Honda FCX feature* ; Series 12 Episode 7; broadcast 14th December 2008 BBC2

[10] Clarkson, Jeremy, May, James; *Top Gear –Tesla and Honda FCX features*; Series 12 Episode 7; broadcast 14th December 2008 BBC2

[11] Ibid

[12] Ibid

[13] Barratt, Mark; *TRANSPORT AND THE ENVIRONMENT an overview*, presentation given to the Claverton Energy Research Group 2008; ISBN N/A

[14] Clarkson, Jeremy; *Top Gear – Land Rover Disco in its natural habitat at the top of a Scottish mountain*; Series 3 Episode 3; broadcast 7th November 2004 BBC2. Also - Clarkson, Jeremy, Hammond, Richard; May, James; Stig, African; *Top Gear – African Challenge*; Series 10 Episode 4; broadcast 4th November 2007 BBC2

[15] Gibbens *et al*; *Electric vehicles for low-carbon transport*; Proceedings of the Institution of Civil Engineers; Energy 160; November 2007 Issue EN4 Pages 165–173; doi: 10.1680/ener.2007.160.4.165

[16] Quick, Martin, *personal communications 2009*; ISBN N/A

[17] Barratt, Mark, *personal communications 2008*; ISBN N/A

[18] May, James; *Top Gear – GM Hy-Wire feature*; Series 2 Episode 9; broadcast 13th July 2003 BBC2

no, I'm not normally this bad at designing a webpage - *luckyman*