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Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system

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ABSTRACT

This paper compares battery electric vehicles (BEV) to hydrogen fuel cell electric vehicles (FCEV) and hydrogen fuel cell plug-in hybrid vehicles (FCHEV). Qualitative comparisons of technologies and infrastructural requirements, and quantitative comparisons of the lifecycle cost of the powertrain over 100,000 mile are undertaken, accounting for capital and fuel costs. A common vehicle platform is assumed. The 2030 scenario is discussed and compared to a conventional gasoline-fuelled internal combustion engine (ICE) powertrain. A comprehensive sensitivity analysis shows that in 2030 FCEVs could achieve lifecycle cost parity with conventional gasoline vehicles. However, both the BEV and FCHEV have significantly lower lifecycle costs. In the 2030 scenario, powertrain lifecycle costs of FCEVs range from \$7360 to \$22,580, whereas those for BEVs range from \$6460 to \$11,420 and FCHEVs, from \$4310 to \$12,540. All vehicle platforms exhibit significant cost sensitivity to powertrain capital cost. The BEV and FCHEV are relatively insensitive to electricity costs but the FCHEV and FCV are sensitive to hydrogen cost. The BEV and FCHEV are reasonably similar in lifecycle cost and one may offer an advantage over the other depending on driving patterns. A key conclusion is that the best path for future development of FCEVs is the FCHEV.

1. Introduction

Road transport today is responsible for a significant and growing share of global anthropogenic emissions of CO_2. Moreover, it is almost entirely dependent on oil-derived fuels and therefore highly vulnerable to possible oil price shocks and supply disruptions. Finally, using oil-derived fuels in internal combustion engines generates tailpipe emissions of pollutants such as PM_{10}, NO_x and VOCs which are harmful to human health.

Improving road transport requires all these issues to be addressed. Managing demand and promoting co-modality can provide a partial solution, however introducing alternative transport fuels and vehicles will also be necessary in order to achieve the objectives of decarbonisation, energy security and urban air quality.

In this paper two of the three alternative powertrain technologies considered by the International Energy Agency (IEA) as being capable of delivering a sustainable road transport system with near-zero emissions are addressed (IEA, 2008). The first is the battery electric vehicle (BEV) and the second is the hydrogen fuel cell electric vehicle (FCEV). Since the focus of this study is exclusively electric drive trains, the third option, biofuels, is not addressed.

The King Review in 2007 (King, 2007) and 2008 (King, 2008) suggested that electric vehicles have the potential to substantially decarbonise road transport in the UK by 2030 (King, 2007); the same conclusion should also apply to other EU Member States. Well-to-wheel (WtW) CO_2 emissions of battery electric vehicles depend upon the power grid generation mix of the country considered; the King Review estimates that with the current UK mix these would be of the order of 80 $gCO_2\,km^{-1}$ and could be reduced to 30 $gCO_2\,km^{-1}$ by 2030 for a predicted mix which includes increased renewables, nuclear and the use of carbon capture and storage with coal (King, 2007).

The EC co-funded project HyWays investigated a range of hydrogen scenarios for the EU and concluded that, by 2050, if 80% of road vehicles were hydrogen-fuelled this would result in 50% less CO_2 emissions compared to a business-as-usual scenario (HyWays, 2008); the portfolio of hydrogen production and distribution pathways on which this estimate relies was defined based on input from key stakeholders from 10 EU Member States.

Although these two studies are not directly comparable, they both demonstrate the potential of electricity and hydrogen as fuels to significantly contribute to the decarbonisation of road transport.

Moreover, both electricity and hydrogen can be produced from any primary energy source, including biomass, wind and solar energy, nuclear energy and decarbonised fossil fuels and therefore offer the opportunity to break the link between oil and transport,

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opening up options to improve energy security. Efficient pathways for the production and transmission of electricity and hydrogen combined with the inherent efficiency of electric vehicle powertrains could have the additional benefit of reducing total energy consumption from the transport sector. Finally, both BEVs and FCEVs produce zero emissions of pollutants from the tailpipe and therefore could significantly contribute to improved urban air quality.

However, there are currently various barriers to the widespread adoption of both BEVs and FCEVs; the most important being technical, economic and infrastructural. For BEVs technical barriers are mostly associated with battery technology (Tollefson, 2008). A significant challenge is the relatively low energy density of batteries, which means that, for a reasonable range, they have to be large, heavy and expensive. For example, with present technology a range of 200 km requires roughly 150 kg of lithium ion cells or more than 500 kg of lead acid batteries. This is a fundamental problem because the chemical storage of energy and its conversion into electric power are combined in a single device. In order to double the range, the power, weight and cost must also be doubled. Energy density and hence range is less of a problem for FCEVs, where chemical energy is converted into electric power in the fuel cell but the hydrogen fuel is stored in a tank. However, hydrogen tanks are characterised by good specific energy (gravimetric energy density) but the energy density (volumetric energy density) is not so good, so achieving the range of a conventional gasoline vehicle with a pure FCEV requires a bulkier hydrogen tank than the equivalent gasoline tank.

The cost of batteries and the logistics of recharging which provide additional barriers, could at least be partly overcome by mass production of battery systems for road vehicles (IEA, 2008) and with schemes such as battery swapping (Charters, 2008). Fuel cells are also expensive and currently produced in very small numbers, but mass production should reduce their cost by an order of magnitude (IEA, 2007a). Refuelling a hydrogen tank only takes minutes whereas fully charging a battery may take hours, depending on the battery technology and the local electrical power limitation. However, electricity is already a widely used energy vector and building a recharging infrastructure for BEVs on top of the existing power grid is likely to be significantly faster and of lower risk than building a hydrogen production, transmission and refuelling infrastructure of which very little exists today.

Both BEVs and FCEVs can contribute to making road transport more sustainable but the barriers they face are somewhat complementary. Although the advantages and disadvantages of battery and hydrogen fuel cell technologies have all been identified and discussed elsewhere (IEA, 2004, 2008; King, 2007, 2008; Tollefson, 2008), there is limited awareness of the strong synergies between them in road vehicle applications. Despite limited analysis comparing fuel cell and combustion engine range extenders for electric vehicles (Burke, 2007), BEVs and FCEVs are still largely seen as mutually exclusive future options. Moreover, the most recent high profile assessment of low carbon cars in the UK, the King Review (King, 2007), does acknowledge that a fuel mix including hydrogen and electricity is likely, but it implicitly assumes that this will be via different vehicle platforms, and not by a single vehicle with the capability to use both electricity and hydrogen. The fuel cell plug-in hybrid appears to have been mostly overlooked in the literature, although vehicles of this type are being developed and demonstrated by a number of major automotive manufacturers (such as the Ford HySeries Drive or the Mercedes BlueZero platform).

Furthermore, despite studies comparing conventional, hybrid, electric and hydrogen fuel cell vehicles (Granovskii et al., 2006), there is limited literature on cost comparisons between fuel cell and fuel cell hybrids (Burke, 2007; Suppes, 2005, 2006; Van Mierlo and Maggetto, 2005). Suppes (Suppes, 2005, 2006) considered using a regenerative fuel cell to replace some of the batteries in a combustion engine hybrid configuration. However the regenerative fuel cell is used in a closed loop to generate hydrogen on the vehicle from electricity to augment battery charging, rather than refuelling with either electricity or hydrogen. Whilst this differs from what we present in this paper, Suppes does demonstrate that combining fuel cell and battery technologies can deliver significant advantages in certain applications.

In this paper it is demonstrated that a combination of electricity and hydrogen as a transport fuel could bring additional benefit to the end user in terms of both capital and running costs. A cost comparison is made between BEVs, FCEVs and FCHEVs. In order to achieve decarbonisation of road transport, aspects such as WtW efficiency and CO_2 emissions of fuel/vehicle platforms as well as the practical and commercial viability of building up alternative fuel infrastructures are also very important. However, overcoming the vehicle's technical and economic barriers is one important prerequisite for their large scale adoption and therefore this paper focuses on the potential economic and practical (i.e. range, refuelling time, etc.) advantages to the end-of the different vehicle platforms mentioned above.

2. The technology

Pure BEVs and FCEVs present differences in attributes such as range, efficiency, cost, and recharging methods. A comparison of the two vehicle platforms should not be based solely upon WtW efficiency and CO_2 emission analysis (Bossel, 2006). In addition it is essential to consider the relevance of the technologies to the application. A typical private vehicle is a complex consumer product which has been optimised for multiple performance criteria e.g. peak power (acceleration), average power (cruising efficiency), and energy density (range). An internal combustion engine has to deliver the peak and average power, with a trade-off compromising acceleration for cruising efficiency or vice versa. However, the range is determined by the fuel tank size and is decoupled from the energy conversion device, significantly reducing this trade-off. The extremely high energy density of the tank of liquid fuel mitigates the use of an inefficient energy conversion device. A BEV is capable of delivering peak power and average power at excellent efficiency but has a relatively low energy density. Typical BEVs achieve roughly 3–6 mile kWh^{-1} (INL, 2006) depending upon vehicle design and driver behaviour. The range is very sensitive to the energy density. A FCEV is capable of delivering average power at much better efficiencies than a combustion engine, and like the combustion engine the range is decoupled and determined by the fuel tank size, with FCEVs potentially delivering roughly 50–100 mile kg^{-1} H_2 (Granovskii et al., 2006). However in order to deliver the peak power, the fuel cell must be large and therefore expensive.

As both the BEV and the FCEV rely upon an electric powertrain, and thus the remainder of the vehicle can effectively be identical, it is evident that the two technologies should be considered together rather than separately, in a hybrid solution. In this paper three options are explored: BEV, FCEV and FCHEV from both a tank-to-wheel (TtW) efficiency and cost basis, in 2010 and 2030. WtW CO_2 emissions and efficiency are not explicitly investigated as they are affected by the means of production or type of energy carrier.

3. Cost prediction analysis

The technology cost predictions for fuel cells (IEA, 2007a) and hydrogen production and distribution (IEA, 2007b) provided by the International Energy Agency (IEA) are considered to be a reasonable assessment of the prospects for hydrogen fuel cells in a mass production scenario. Unfortunately, there are no equivalent technology cost predictions for batteries provided by the IEA. However, there is a report published by BERR and the DfT in the UK (DfT, 2008) which includes an assessment of the cost and performance requirements for BEVs and plug-in hybrid EVs, and also includes an assessment of the current and projected costs of lithium ion battery technologies.

The IEA cost predictions for fuel cells (IEA, 2007a) assume a technology learning rate of between 0.78 and 0.85, equivalent to cost reductions of 22% and 15%, respectively, with each doubling of cumulative production. Justification for the costs of individual components of the fuel cell powertrain is described in detail by the IEA. The IEA predictions suggest that a fuel cell cost of \$35–75 kW_e^{-1} should be anticipated by 2030. Adding the costs of the electric powertrain and hydrogen storage, an 80 kW_e fuel cell powertrain in 2030 would cost \$4.9k–\$10k compared to \$2.4k–\$2.5k for a conventional 80 kW_e powertrain. However, these predictions are based upon a crucial assumption, that the fuel cell system must provide the peak power of the vehicle. Considering the benefits of hybridisation with batteries, the key question answered in this paper is: would reducing the size of the fuel cell deliver a saving greater than the cost of the batteries, and how does this affect the cost predictions?

In this analysis the capital cost of the powertrain and the fuel cost at point of sale of the various fuel options are compared. Any mark-up that may be applied at the point of sale, such as profit, inflation, taxes, fuel duty, cost of capital and carbon costs have been excluded. This enables the technologies to be evaluated on a level playing field representing the marketplace in 2010. Note that, in this paper, all costs are relative to 2010. Exchange rates of 0.7 GBP equals 1 USD and 1 GBP equals 1 Euro have been used to compare reports prepared in different currencies.

3.1. Capital cost

The key assumptions that have been made are summarised in Table 1:

- The IEA cost predictions are used for the fuel cell and conventional powertrains in 2010 and 2030 (IEA, 2007a), summarised in Table 1.
- In order to compare to the IEA cost predictions, a single vehicle platform is assumed with the following requirements:
  - Of about 80 kW_e peak power (as used by the IEA (IEA, 2007a)).
  - Of about 20 kW_e mean power, estimated based on a saloon car with a frontal area of 2.2 m^2, drag coefficient of 0.35 cruising at 70 mph with an appropriate rolling resistance.
- The FCHEV was assumed to be a plug-in hybrid with the capability to recharge the batteries when possible and a hydrogen fuel cell range extender.
- For the FCHEV, a battery size of 6 kWh was assumed, as the lower limit considered acceptable for a plug-in hybrid vehicle (DfT, 2008).
- For the BEV a battery size of 25 kWh was assumed, as the lower limit considered acceptable for an electric vehicle (DfT, 2008). This assumption is probed further below.
- Battery costs of \$1000 kWh^{-1} were assumed for 2010 based upon the lowest boundary from current price data (DfT, 2008).
- Battery costs of \$300 kWh^{-1} were assumed for the 2030 pessimistic scenario based upon the projections for 2020 (DfT, 2008).
- Battery costs of \$200 kWh^{-1} were assumed for the 2030 optimistic scenario assuming some improvement on the predictions for 2020 (DfT, 2008).
- The effect of the useable state of charge (SOC) of the battery has not been included, but this would reduce the range of the vehicle, or increase the capital cost for a given BEV range.

Table 1 expands the IEA cost predictions for conventional and fuel cell powertrains to include battery electric and fuel cell electric hybrid powertrains. The hybrid option appears to be favourable in all scenarios, outperforming both the electric and the fuel cell option on a capital investment basis. This benefit is immediate, and it is suggested that significant capital cost savings could be achieved in the development of current prototypes simply by switching to a FCHEV platform rather than developing all fuel cell or all battery vehicles.

3.2. Running cost

In order to assess the viability of the various powertrains, it is necessary to consider not just the capital cost but also the running costs. The key assumptions that have been made are summarised in Table 2:

- It is difficult to obtain an accurate picture of future hydrogen costs. In addition the costs are inherently coupled to the costs of the fuel or feedstock, and this further complicates matters due to price variability. The current (2010) cost of hydrogen is

Table 1
Summary of the capital cost input data.

	2010	2030 Optimistic	2030 Pessimistic	2030 Average
Powertrain cost				
20 kW_e fuel cell	\$10,000[b]	\$700[b]	\$1500[b]	\$1100
80 kW_e fuel cell	\$43,700[a]	\$4900[a]	\$10,030[a]	\$7465
6 kWh battery pack	\$6000	\$1200	\$1800	\$1500
25 kWh battery pack	\$25,000	\$5000	\$7500	\$6250
Electric motor and controller	\$1700[a]	\$1200[a]	\$2030[a]	\$1615
Hydrogen storage	\$2000[a]	\$900[a]	\$2000[a]	\$1450
Conventional (ICE)	\$2200[a]	\$2400[a]	\$2530[a]	\$2465
Total cost				
ICE	\$2200	\$2400	\$2530	\$2465
FCEV	\$47,400	\$7000	\$14,060	\$10,530
BEV	\$26,700	\$6200	\$9530	\$7865
FCHEV	\$19,700	\$4000	\$7330	\$5665

[a] Denotes those used from the IEA report (IEA, 2007a), and
[b] Denotes those adapted from the IEA report (IEA, 2007a).

Table 2
Summary of the running cost input data, normalised to \$ GJ^{-1} for comparison.

Fuel cost	2010 (GJ^{-1})	2030 Optimistic (GJ^{-1})	2030 Pessimistic (GJ^{-1})	2030 Average (GJ^{-1})	Miles (GJ^{-1})	Typical units
Gasoline	\$12.7	\$19	\$38	\$28.5	253	40 mpg
Hydrogen	\$42	\$14	\$56	\$35	506	72 mile kg^{-1}
Electric	\$36	\$27	\$45	\$36	1013	3.6 miles kWh^{-1}

assumed to be \$6 kg^{-1} (equivalent to \$42 GJ^{-1}) taken from a review of the various hydrogen production technologies in 2005 by Haryanto et al. (Haryanto et al., 2005), which is commensurate with the IEA estimate for current production in 2007 (IEA, 2007b). The cost in 2030 is assumed to be between \$8 kg^{-1} (pessimistic) assuming production by electrolysis (Haryanto et al., 2005) and \$2 kg^{-1} (optimistic) (\$56 and 14 GJ^{-1}, respectively) assuming production by steam reforming of natural gas with carbon capture and storage using the IEA cost predictions (IEA, 2007b).

- A current (2010) gasoline price of \$2 gal^{-1} is assumed for comparison, which is equivalent to \$13 GJ^{-1}. The cost in 2030 is assumed to be between \$6 and 3 gal[1] (\$38 and 19 GJ^{-1}, respectively) for the pessimistic and optimistic scenarios, respectively.
- Cost estimates for electricity generation vary widely and also seem to be highly subjective. A review of the unit cost estimates by the UK Energy Research Centre (UKERC) is used. The current (2010) cost of electricity is assumed to be \$45 MWh^{-1} (equivalent to \$12.6 GJ^{-1}) based upon the UKERC assessment for the predominant technologies of coal, gas and nuclear. Wind is \$56.5 MWh^{-1} (Heptonstall, 2007) (equivalent to \$15.7 GJ^{-1}). Therefore the current cost of wind energy is used as the pessimistic assumption for 2030. The 2030 optimistic scenario is arbitrary and assumes a 25% reduction in costs to \$34 MWh^{-1} (equivalent to \$9.4 GJ^{-1}). However, this does not represent the cost of delivery and transmission and this must be taken into account. The retail cost of electricity in the UK as reported by Eurostat in 2008 (Eurostat, date of extraction, October 2008) was \$129 MWh^{-1} (equivalent to \$36GJ^{-1}) without tax for high usage users, a factor of 2.85 increase in cost. Therefore we have applied a fixed ratio of 2.85 to the production cost predictions to generate the retail cost predictions.
- None of the cost assumptions include taxes or local charges allowing other policy tools such as feed-in tariffs and local taxation to be ignored.
- A conventional powertrain efficiency of 40 mpg is assumed.
- The fuel cell powertrain is assumed to be twice as efficient (Burke, 2007), i.e. 80 mpg, or 72 mile kg^{-1} of hydrogen.
- The battery powertrain is assumed to be four times as efficient, i.e. 160 mpg, or 3.6 kWh^{-1}.
- The fuel cell hybrid powertrain is assumed to be operated on hydrogen 50% of the time (King, 2007).
- Finally, the lifecycle of the vehicle was assumed to be 100,000 mile.

A sensitivity analysis on the various input assumptions shows those which are critical to our conclusions.

The assumptions for the energy cost of gasoline are very similar to those used by Granovskii et al. (Granovskii et al., 2006) who compared conventional, hybrid, electric and fuel cell vehicles (but not fuel cell hybrid vehicles), but assumptions for hydrogen and electricity cost are much higher than those used by Granovskii et al. (Granovskii et al., 2006.) This is because all the costs associated with delivering the fuel to the consumer, rather than just the production costs, have been included.

In addition, assumptions for vehicle range are roughly the same as those used by Granovskii et al. who assumed a range of 262, 480 and 925 mile GJ^{-1} compared to our 253, 506 and 1013 mile GJ^{-1} for gasoline, hydrogen and electric powered vehicles respectively. However, Granovskii et al. assumptions for the capital costs of the various technologies are not rigorous, in particular the fuel cell vehicle capital cost which was based upon a single magazine article in 2002.

3.3. End-of-life cost

End-of-life costs are not addressed in here, nor are the durability and lifetime of the various components accounted for. Therefore it is implicitly assumed that the end-of-life costs are all equal, and that all components will have acceptable lifetimes. This is a very important consideration and must be addressed in order to accurately predict complete lifecycle costs, but at the present time there is insufficient reliable data on the recycling and/or disposal costs of vehicle batteries and fuel cells to make an objective assessment.

3.4. Results and discussion

3.4.1. Powertrain technology options

Fig. 1 presents the cost predictions for 2030 for the four powertrain technology options as a sensitivity analysis. The results show that if the cost predictions for fuel cell, battery and hydrogen and electricity costs are correct, then for this scenario both the FCHEV and BEV option are the cheapest by 2030 in terms of lifecycle costs. The results also show that by 2030 the FCEV costs have approached parity with the ICE costs. The results are sensitive to the capital costs (in particular the fuel cell) and the hydrogen cost, reflecting the large variations in cost assumptions. However, the gasoline combustion engine is most sensitive to the fuel cost rather than the capital cost, which is unsurprising considering the maturity of the technology and the variability in gasoline prices. It should be noted that the capital costs for the FCHEV include both the battery and fuel cell costs, and they are coupled in this analysis. It is therefore unlikely that the FCEV option will ever be competitive as a stand-alone solution given that any FCEV can easily be made cheaper by downsizing the fuel cell for mean power and using batteries and/or supercapacitors to provide peak power. In addition the FCHEV has additional benefits to the consumer of fuel choice, faster refuelling and extended range.

There are other crucial assumptions which have not been probed in this scenario, which could potentially influence the analysis.

3.4.2. BEV range

Perhaps the most important assumption to test is the range of the BEV. In the scenario shown in Fig. 1, the BEV has a battery size of 25 kWh and an efficiency of 3.6 mile kWh^{-1} giving a range of 90 mile. Improving the vehicle efficiency (for example reducing drag, weight and rolling resistance) will increase the range without increasing cost in this model, whereas increasing the battery size will increase the cost.

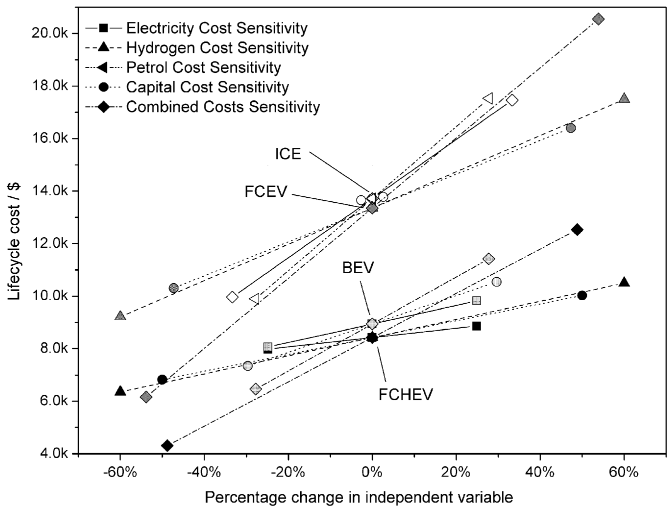

Fig. 1. Normalised sensitivity analysis of the lifecycle costs of the powertrains for the three sustainable transport options based upon the assumptions for 2030. The bounds of the sensitivity analysis represent the costs assumed for the pessimistic (positive) and optimistic (negative) scenarios described in Tables 1 and 2. ICE (white), BEV (light grey), FCEV (dark grey), FCHEV (black).

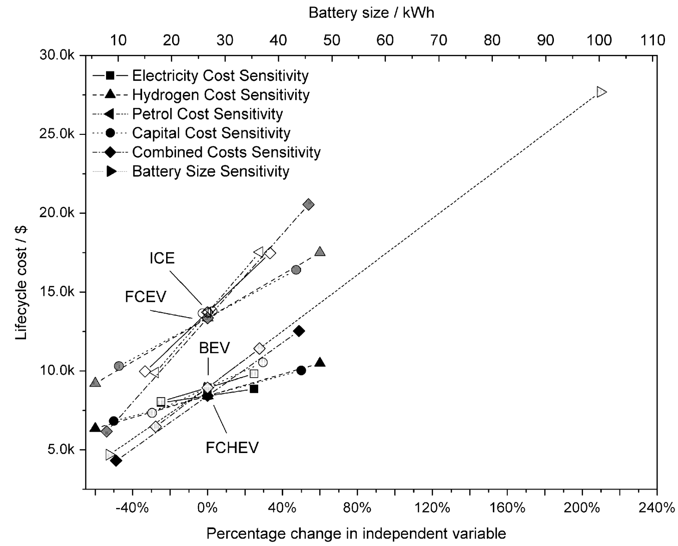

Fig. 2. Sensitivity of analysis to the battery size of the BEV overlaid on the results from Fig. 1, using a battery cost of \$250 kWh^{-1}. ICE (white), BEV (light grey), FCEV (dark grey), FCHEV (black).

Table 3
Calculations showing boundaries of battery size for the BEV adjusting efficiency and range.

		Range/miles	
Efficiency/mile kWh^{-1}		50 mile	300 miles
	3 mile kWh^{-1}	17 kWh	100 kWh
	6 mile kWh^{-1}	8 kWh	50 kWh

In order to test the coupled effect of the efficiency and battery size on the BEV, the efficiency was varied between 3 and 6 mile kWh^{-1} (INL, 2006) and the range between 50 and 300 mile. As shown in Table 3, this gives a range of battery sizes from 8 to 100 kWh.

Fig. 2 presents the results of varying the battery size between 8 and 100 kWh. It demonstrates that the scenario that uses the lower limit considered acceptable for an electric vehicle (25 kWh) (DfT, 2008) is comparable in performance to the FCHEV, but that the lifecycle costs of the BEV are highly sensitive to the size of the batteries. Even with the most efficient BEV, achieving a range of 300 mile would require 50 kWh of batteries and the lifecycle cost would then be the same as the ICE and FCEV. However, for the most efficient BEV, if a range of only 50 mile is required, the lifecycle cost could be below \$5000, considerably less than any other option. Therefore, for a city car, the BEV may well be the cheapest option if the battery size can be kept to a minimum.

3.4.3. *Other considerations and sensitivities*

In this paper a high level cost analysis has been conducted using credible assumptions. Some of the assumptions that would be interesting to address in more detail are the following.

It was assumed that the FCHEV used H_2 as a fuel, 50% of the time. However this will be hugely dependent upon driver behaviour in particular the distribution of trip lengths. This is also coupled with the size of the battery of the FCHEV which was assumed to be 6 kWh. This would enable the FCHEV to travel 22 mile on electric power alone, which assumes that this is enough to use electricity for 50% of the miles driven. A more rigorous assessment should optimise the distribution of journey lengths versus capital cost and running costs to suggest the most effective electric range for specific driving patterns.

An area of BEV research that is seldom explored in the costing and evaluation is the power electronics. These are typically inverters that take DC from the battery and turn it into multi-phase AC for the motor(s). At present they can be almost as expensive as the battery on a kW_e basis: this is an area where there is potential for huge cost savings. In this paper, the base electric vehicle powertrain was taken as the same for each case, and therefore these costs do not affect the relative costs.

Vehicle size, weight and drag will also contribute significantly to any assessment. In this analysis all these factors have been considered to be equal in each vehicle.

In addition a comparison with an internal combustion engine plug-in hybrid has not been made, and the authors would expect this option to compare quite favourably, although we have excluded it in this paper because it does not qualify as a long term sustainable road transport option. However, biofuel powered combustion engines (BICE), and BICE hybrids should both be considered in this context.

We have also assumed that the fuel cell type is a polymer electrolyte membrane fuel cell (PEMFC), and have not considered other types of fuel cell which are also suitable for vehicle applications, such as solid oxide fuel cells, which are particularly suited for vehicles with well defined duty cycles in a hybrid configuration (Brett et al., 2006a, b).

Other factors associated with the different technologies that should also be considered, and where appropriate allocated a cost, might include a value associated with fossil fuel supply and energy security, or costs associated with other emissions such as NO_x, SO_x, and particulates. For example, it has been shown that converting all US road vehicles to FCEVs could save from 3700 to 6400 lives in the US annually through improvements in air quality and health (Turner, 2004), and would have a negligible effect on tropospheric water concentrations (a common misconception about FCEVs).

For mass production of fuel cells, the implications of platinum supply should be considered. The IEA assumed that a 100 million vehicles a year (with 80 kW fuel cell systems) would require 2000 ton of platinum per year, ten times current annual production (IEA, 2007a). Although growing demand could probably be met by increases in production and recycling it could still affect availability and limit production.

Other challenges such as hydrogen production and infrastructure, and hydrogen storage on the vehicle also still need to be addressed. Other hydrogen generation technologies could also change the hydrogen cost assumptions such as biologically produced hydrogen, direct solar to hydrogen, hydrogen production from baseload nuclear, or smoothing of renewables.

For batteries, the implications of lithium supply should be considered which could have an impact on the potential for BEVs to penetrate the vehicle market. Electricity production is also a consideration, although the total electrification of the UK's car and taxi fleet would only require 16% of current electricity demand (King, 2007). However, this does not address the need to decarbonise electricity generation in general which will require massive investment in renewable generation capacity and upgrading of infrastructure.

4. Conclusions

This paper has reviewed hydrogen fuel cell and battery electric vehicle options for a future sustainable road transport system, focusing on quantitative comparison of different platforms in terms of lifecycle costs in 2030.

A number of interesting conclusions can be drawn from the analysis:

Firstly, in terms of capital costs, in 2010 FCEVs, BEVs and FCHEVs are all far more costly than conventional ICE powertrains. However, by 2030 capital costs could drop significantly, with the FCHEV exhibiting the lowest capital costs, followed by the BEV and FCEV. The ICE powertrain is still cheaper in 2030, but when lifetime fuel costs are factored in the situation changes significantly.

Secondly, in terms of fuel costs, accurate prediction of future costs is not possible. Nonetheless, some reasonable assumptions have been made. The TtW efficiency of each powertrain has a marked effect on fuel costs per mile, electric vehicles achieving far higher miles per GJ than either hydrogen or gasoline vehicles. In 2030, BEVs and FCHEVs are relatively insensitive to fuel (electricity) cost changes, whereas FCEVs and ICEs exhibit marked sensitivity to hydrogen and gasoline costs respectively. This is partly due to the differing powertrain efficiencies.

Thirdly, regarding total lifecycle costs over 100,000 mile, FCHEVs appear to be slightly cheaper than BEVs but exhibit a wider overall sensitivity to combined (capital and running) costs. Both ICEs and FCEVs have much greater lifecycle costs than FCHEVs and BEVs, around 1.75 times higher.

Regarding the BEV in particular, a separate study of battery size in terms of range and vehicle efficiency was conducted. From this it is shown that BEV lifecycle costs are very sensitive to battery size and that BEV economics are cheapest if battery size can be minimised, for example in city cars with a range of only 50 mile.

Some recommendations can now be made based on this study:

1. Hydrogen fuel cell electric vehicles could have a part to play in future road transport, but the best platform for integration of fuel cells is the battery electric vehicle with fuel cell range extender. This platform also has the benefit of building on a technology roadmap that begins with plug-in ICE hybrids in the near future.
2. Capital cost reduction of BEVs, FCEVs and FCHEVs should be a key target for ongoing development, as well as minimisation and recycling of platinum, lithium and other precious raw materials used in these technologies.
3. Various range extender technologies (ICE in the near future, fuel cells in the long term) can compete for space in an electrified transport network, with economic, social and policy issues informing the consumers' choice of platform and recharging or refuelling.

Therefore, for policy-making purposes, our findings suggest that battery electric and hydrogen fuel cell vehicles should not be regarded as antagonistic, either/or options but that both should be pursued and supported.

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