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Electric vehicles for low-carbon transport

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There are three main energy options for decarbonising road transport: biofuels, hydrogen and electricity. While the 'hydrogen economy' and fuel-cell vehicles (FCVs) are often seen as the only viable long-term option, and liquid biofuels as the only short/medium-term option, the potential for battery-dominant electric vehicles (including 'plug-in' hybrids) charged by low-carbon electricity has tended to be neglected in recent policy debates. However, even if low-carbon hydrogen were available it is likely to be as efficient to convert it to electricity for battery electric vehicles and plug-in hybrids as to use it for FCVs. Low-carbon electricity (e.g. from renewables, nuclear) is more efficiently used directly in electric vehicles than via conversion to hydrogen. Electric vehicles also generally have less challenging technical, infrastructural, financial and commercial barriers. In particular, the electrification of road transport can 'piggyback' on existing grid and off-peak generation capacity as well as market-driven R&D on advanced batteries and other electric drive components. Electricity production is also a highly efficient route for using a wide range of biomass materials in transport. Adding carbon dioxide capture and storage would give a further negative carbon dioxide emission of about 125 g/km to set against other lifecycle emissions.

1. INTRODUCTION

Large reductions in carbon dioxide (CO_2) emissions from road transport can only be obtained by replacing conventional fossil-derived liquid fuels with low-carbon energy, which will have to come in the form of biomass, hydrogen or electricity. It is obviously necessary that this biomass, hydrogen or electricity is produced with low lifecycle CO_2 emissions, but there are many ways of achieving this. The question still remains of how best to transfer this low-carbon energy to vehicles. It might be assumed that these low-carbon energy sources would be used in the form in which they are available, as liquid biofuels, hydrogen or electricity. Biomass can, however, also be converted into hydrogen or electricity, and hydrogen can be converted to electricity, and electricity to hydrogen.

Electricity has, however, been largely neglected as a possible transport 'fuel'. The 'hydrogen economy' and fuel-cell vehicles (FCVs) have generally been assumed to be the long-term option, with liquid biofuels preferred in the short to medium term. This paper examines some key differences between battery electric vehicles (BEVs) and FCVs, including their relative efficiency for using different forms of energy and the technical and infrastructural challenges associated with their introduction. BEVs, in the context of the comparisons made in this paper, may be either pure electric or plug-in hybrid electric vehicles (PHEVs) operating exclusively or mainly on electric power. PHEVs with even a relatively small 'range extender' internal combustion engine or solid oxide fuel cell (SOFC) using hydrocarbon fuel may obviously offer a very useful transition option, either to full BEVs, as battery capacity and charging rates increase, or to PHEVs based on hydrogen fuel cells which also have the capacity to use readily available electricity without electrolysis or fuel cell conversion losses.

BEVs, unlike hydrogen vehicles, can also be envisaged as a near-term option, with several models already being sold and on the roads, and so might therefore offer an alternative to liquid biofuels for getting biomass (and other renewables) into transport. Biomass used with CO_2 capture and storage (CCS) can also remove CO_2 from the atmosphere and provide a negative offset for the rest of the lifecycle.[1] Indicative efficiencies for these options are compared in this work.

Given these advantages, it is important that BEVs are not treated less favourably than biofuel or hydrogen vehicles in policy and incentive design. Some measures are suggested.

2. BEV AGAINST FCV EFFICIENCIES STARTING WITH ELECTRICITY AND HYDROGEN

This comparison covers cases where low-carbon electricity or hydrogen is available, from renewables, nuclear or fossil fuels with CCS.[1] Renewable and nuclear power plants generate electricity, so converting this to hydrogen requires an additional step (electrolysis). Primary hydrogen production from photochemical processes or high-temperature nuclear reactors is also theoretically possible, but is not discussed here due to the very small scale of research and development (R&D) activities in these areas. In contrast, low-carbon hydrogen is the initial product from coal gasification and natural gas reforming plants with pre-combustion CO_2 capture. Generating electricity from such plants requires a further step (hydrogen combustion).

The main processes to consider are thus those that convert electricity to hydrogen and vice versa. For the indicative cases reported, electrolysis process efficiencies of 80% are assumed; this is the mid-point in the range given by Suppes *et al.*[2] and below the 90% efficiency that can theoretically be achieved.[3] It is also assumed that electrolysis efficiency is independent of scale. For

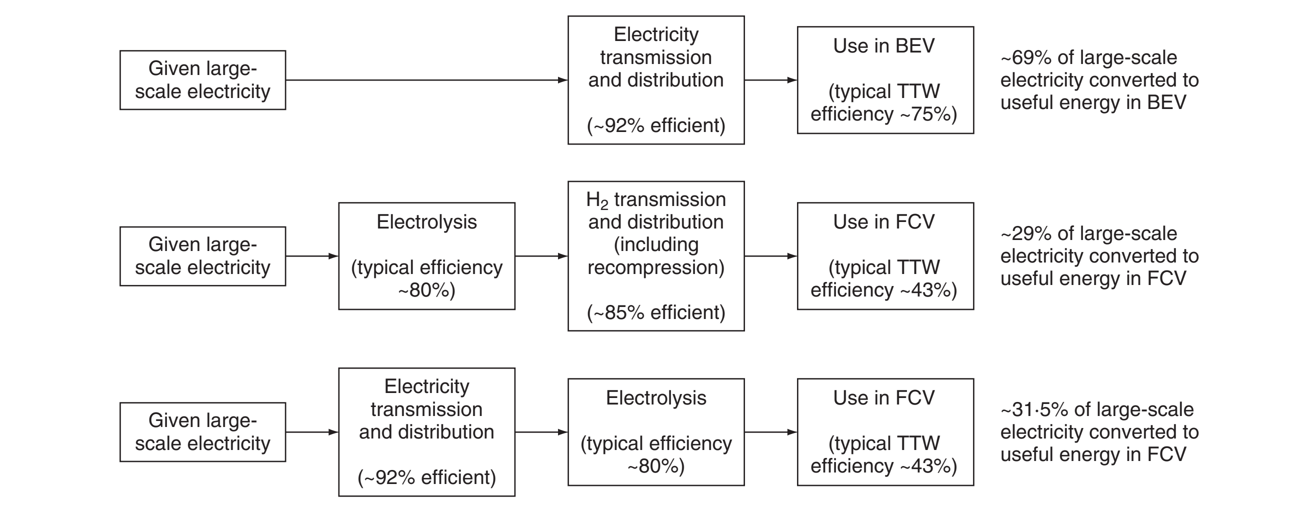

Fig. 1. Some examples of large-scale electricity use for BEVs and FCVs

small-scale distributed conversion of hydrogen to electricity, a stationary hydrogen fuel cell with 65% efficiency is assumed. This follows the efficiency reported by Pehnt[4] for a SOFC with no co-generation of heat assuming a hybrid system with gas turbine; it is towards the upper end of the efficiency range for SOFCs reported by Edwards *et al.*[5] In reality, current efficiencies reported by FCV developers (which are almost exclusively focused on proton-exchange membrane (PEM) fuel cells) tend to be in the range of 50–60%. Large-scale electricity production from hydrogen is assumed to take place in a gas turbine combined cycle with a very conservative efficiency of 50%. This does not allow for future improvements in conventional gas turbine technology and the scope for large-scale fuel cell/turbine hybrids.

Losses for transmission and distribution of electricity are frequently given in the range of 7–10% and the mid-value of this range has been used for the cases reported here. Losses for transmission and distribution of hydrogen are more difficult to define since fewer references and less operating experience are available. A value of 15% has been chosen, including re-compression (and/or other gas conditioning) at the point of supply. A discussion of the losses associated with transmission and distribution of electricity and hydrogen can be found in the literature.[3]

For the examples reported in this work, vehicle efficiency is defined with a tank-to-wheels (TTW) value, which includes drive system losses as well as battery or fuel cell efficiency. Both battery and FCVs use electric drive trains that have typical reported efficiencies of 80–90%. For the cases here, it is assumed that lithium ion batteries are available with efficiencies of 90–95%. This suggests a range for BEV TTW efficiency of 72–85%, with a relatively conservative value of 75% used in this analysis. For FCVs, fuel cell efficiencies of at least 50% are reported by many studies, with a typical range of values of 50–55%. This leads to a range of FCV TTW efficiencies of 40–50%. Again, a relatively conservative value of 43% is used in this analysis.

Figure 1 shows indicative results for the efficiency of electricity as the original energy source for FCVs and BEVs. Even allowing for the approximations included in the calculations, it is clearly better to use electricity directly in a BEV. Many critiques of hydrogen have emphasised this result,[3] which is an obvious conclusion since BEVs avoid conversion losses to and from hydrogen with FCVs.

Figure 2 shows routes starting from the basis of large-scale hydrogen availability. CCS has been highlighted in a number of

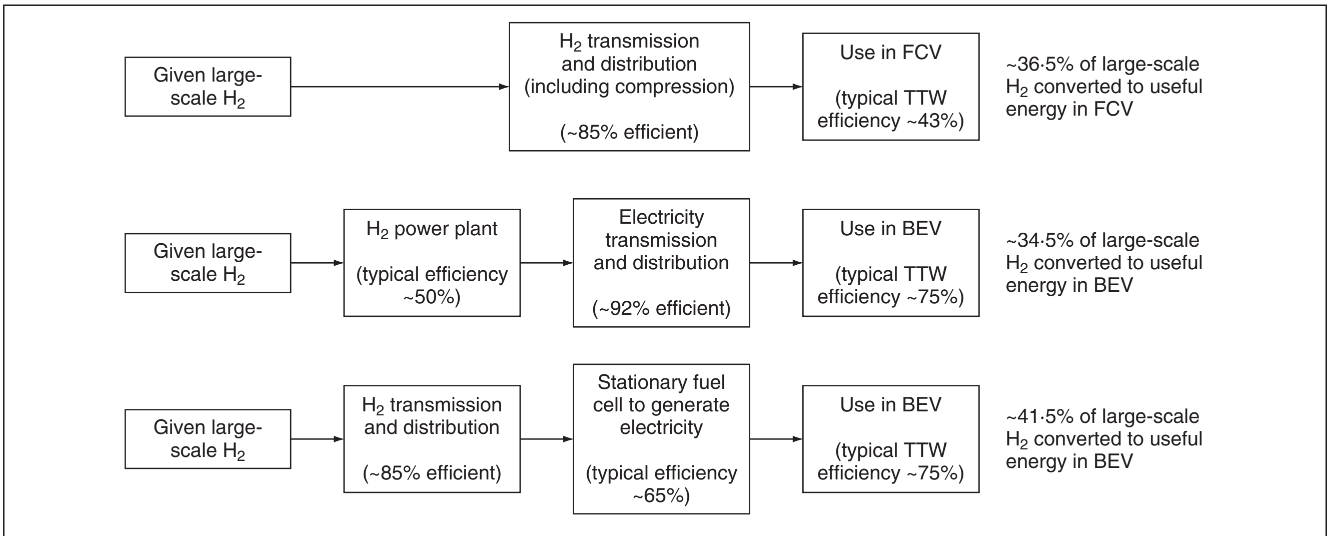

Fig. 2. Some examples of large-scale hydrogen use for BEVs and FCVs

studies as a relatively low-cost, low-carbon pathway for producing hydrogen (e.g. the work of Ogden *et al.*[6]). However, these studies have generally excluded BEVs in their analysis. Rather than distribute the output hydrogen to FCVs via hydrogen distribution and refuelling infrastructures, the hydrogen could be converted to electricity on site and then distributed to BEVs via conventional grids and charging facilities. From the indicative results shown in Fig. 2, it is possible that the latter ('hydrogen by wire') route would be more efficient. This is explained by the higher end-use efficiency of BEVs, which can outweigh the greater losses assumed to be associated with converting hydrogen to electricity in large central power plants instead of using onboard or local stationary fuel cells. Of course, this result depends on assumptions regarding the relative future performance of these technologies and so can only be conjectural. However, it does indicate that further work to understand options and trade-offs in this area might be worthwhile.

3. BEVs (AND FCVs) AS SHORT/MEDIUM-TERM ALTERNATIVES TO BIOFUELS IN ROAD TRANSPORT

Biomass utilisation efficiency is of interest because supplies are inherently limited. The types of biomass that can be used for biofuels generation are also currently limited, although this will be extended with 'second-generation' processes. Even these, however, are unlikely to exceed the feedstock flexibility of combustion routes for electricity. For the indicative cases considered in Fig. 3, it is assumed that second-generation biofuels processes will approach thermal processing systems in their ability to use cellulosic biomass substrates, making this comparison valid, and achieve an overall energy efficiency of 50%. It is also assumed that the biofuels processes are not net users of other sources of energy and do not emit (or capture) any additional CO_2.

Timing issues are also of interest. FCVs are not likely to be available within the 2020 deadline set by the EU for supplying 10% of transport energy from biofuels.[7] BEVs could be, and there may be strategic reasons to encourage this. The conversion of biomass to electricity is a well-proved technology (i.e. much more mature than second-generation biofuels). Co-firing biomass with coal at large central power plants is proved as a highly efficient option compared to direct use in smaller dedicated plants. Additionally, within the 2020 time horizon, CO_2 capture may be applied to these plants. CO_2 removed from the atmosphere as the biomass grew could then be placed into secure geological storage. For vehicle energy consumption at the wheels of 0·4 MJ/km, a biomass specific emissions factor of 93 g/MJ (LHV basis), 85% CO_2 capture (including storage) and a biomass-to-wheels efficiency of 25%, this would result in additional CO_2 removal from the atmosphere of 127 g/km (i.e. −127 g/km of emissions).

Although significant numbers of FCVs are not expected by 2020, they are included here for completeness. The examples shown give a preliminary indication that it may be more efficient to use biomass to generate large-scale electricity for use in a BEV rather

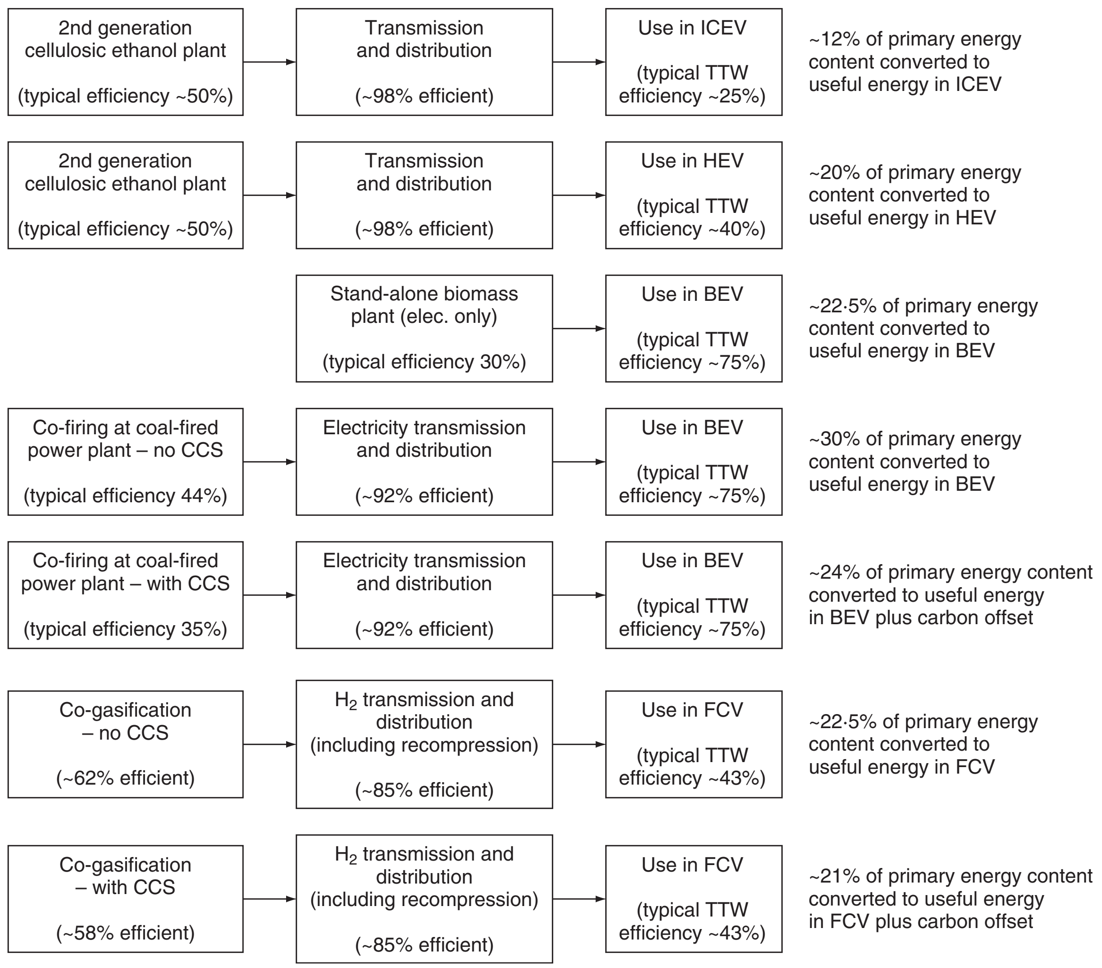

Fig. 3. Some examples of biomass use in vehicles

than hydrogen for use in a FCV or to process biomass as a second-generation biofuel. If biomass is used to produce electricity at a small-scale dedicated biomass plant, the generation efficiency is significantly reduced and there is little difference between all three options. It is also unlikely that CCS would be used at a small-scale biomass plant. It should be remembered, however, that the cases used here show only one set of indicative results out of a range of possible future performance characteristics for each of the steps shown. Again, however, the trends indicate that further examination of BEV routes for biomass may be merited, particularly if they involve CCS.

4. INFRASTRUCTURE AND TECHNOLOGY REQUIREMENTS OF BEVs AND FCVs

Although BEVs are likely to enable more efficient use of biomass than biofuels, efficiency is only one consideration in determining technology choice for producers and consumers. Another important issue is whether safe and reliable infrastructures are available to supply and distribute the required energy to vehicles. Biofuels can make significant use of existing infrastructure, so their requirements will not be discussed in detail in this paper. Instead, focus is placed on the relative requirements and impacts for FCVs and BEVs.

Generally speaking, road transportation is characterised by deep technological inertia as a result of technological and institutional 'lock-in' around internal combustion engine vehicles (ICEVs) and hydrocarbon fuels. This lock-in is caused by a number of factors, including the inter-dependency of vehicles and filling stations and the massive scale economies enjoyed by conventional vehicles and fuels.[8] The feasibility of getting around this lock-in should be a key criterion for any low-carbon technology, as well as other attributes such as environmental impact.

One of the most significant challenges facing FCVs in this regard is the need to deploy new energy infrastructures more or less simultaneously with the vehicles. This is a typical 'chicken and egg' problem where it only makes sense to invest in infrastructure after a significant number of vehicles are on the road, and vice versa. In theory, original equipment manufacturers (OEMs) and energy suppliers could overcome this problem by committing to a coordinated vehicle-infrastructure deployment schedule, based on a common 'roadmap' put forward (or sponsored) by governments and public–private partnerships. The deployment path could either be an 'Apollo project' style leap to a hydrogen economy (as called for by several hydrogen proponents) or, as is more likely, a gradual deployment strategy such as the EU's Lighthouse projects. In the latter case, OEMs, energy suppliers and governments commit to deploying hydrogen refuelling stations and FCVs within a given area, ideally one where there is already an established source of hydrogen (e.g. the by-product of chemical plants) and a high density of potential users. This strategy mitigates the risk of energy suppliers and automotive OEMs being left with large stranded investments in the case that FCVs fail in the market. Whatever deployment pathway is chosen, however, its long-term cost will be very high given the need for new hydrogen generation, distribution and dispensing equipment.[9] Moreover, complex coordination structures will still be needed.

It could be argued that many of the large-scale hydrogen infrastructure issues can be avoided by alternative on-site methods for producing hydrogen. This approach also faces serious problems, however. Small- to medium-scale electrolysers are a relatively mature technology, but the electricity requirements are likely to be roughly twice those of a BEV. High energy costs are the main reason why electrolysis is rarely used in the industrial gas industry, where steam methane reforming (SMR) accounts for over 90% of global hydrogen production. On-site SMR is technically feasible, but the technology is not yet commercially mature. Moreover, CCS would be difficult to use at this scale, making it unsuitable for achieving large cuts in CO_2 emissions. This approach is best seen as a transition strategy; large-scale investments in generation and distribution by pipelines would be needed eventually.

The various investment costs and temporary environmental trade-offs relating to hydrogen and FCVs might be justified if hydrogen were the only alternative to petroleum. There is, however, another alternative 'fuel', electricity, which already has a well-developed infrastructure that could be cost-effectively modified to accommodate a substantial number of vehicles. For example, according to the Pacific Northwest National Laboratory, current US off-peak electricity production and transmission capacity is sufficient to fuel up to 166 million PHEVs, or 84% of the 198 million US cars, pick-up trucks and sport utility vehicles.[10]

Some investment will be required to introduce distributed street charging facilities for the many users without private parking spaces, but units could be fairly technically simple and perhaps be combined with other facilities such as parking meters. Moreover, many early users will be content with home charging; consumers are now used to charging phones and other appliances on a daily basis. Still, looking forward, deeper penetration of BEVs is likely to require substantial investments including more power plants, strengthening of transmission networks, the introduction of demand-side management systems (e.g. to encourage off-peak recharging) and possibly rapid-charging systems. As with many other infrastructure projects, many of these investments will face social, political and regulatory barriers (e.g. so-called 'not in my back yard' (NIMBY) barriers). Whether these barriers will be higher or lower for hydrogen is an open question. It is important to remember, however, that such investments will not be required during the initial deployment of PHEVs and BEVs, allowing facilities to be added piecemeal and at a grass-roots level. After all, several thousand BEVs are already on the road throughout the world, often operating without any direct involvement of electricity suppliers.

Another significant feature of an electricity network using PHEVs and BEVs is likely to be 'vehicle-to-grid' (V2G) systems. In these systems, PHEVs and BEVs would be remotely managed by utilities for electricity storage and peak power supply, so could play an important role in the electricity system. In addition to balancing demand and supply (e.g. peak shaving), V2G networks could help stabilise frequency and voltage, support distribution networks in weak areas, provide peak power for urban transit systems and provide emergency back-up power and reserve services. V2G could also provide storage for intermittent renewable electricity sources. Hydrogen storage associated with FCVs or other aspects of a future hydrogen economy could also play an analogous role, but the conversion losses into and out of hydrogen would be much higher.

Infrastructure lock-in and its impact on FCVs has been discussed before (e.g. by Romm[11]). Lock-in is, however, also related to the cost of the vehicles themselves. Large reductions in costs and improvements in performance (e.g. durability) are needed before commercial production of FCVs begins. PHEVs, BEVs and even HEVs are still expensive relative to conventional vehicles, even when fuel savings are factored in. Much of the added cost stems from the battery. Moreover, batteries continue to suffer from limited energy densities, which result in driving ranges below 200 miles, and usually below 100 miles. In the 1990s, BEVs failed to penetrate mainstream markets in the USA, Japan and Europe despite many efforts by governments and automobile manufacturers.

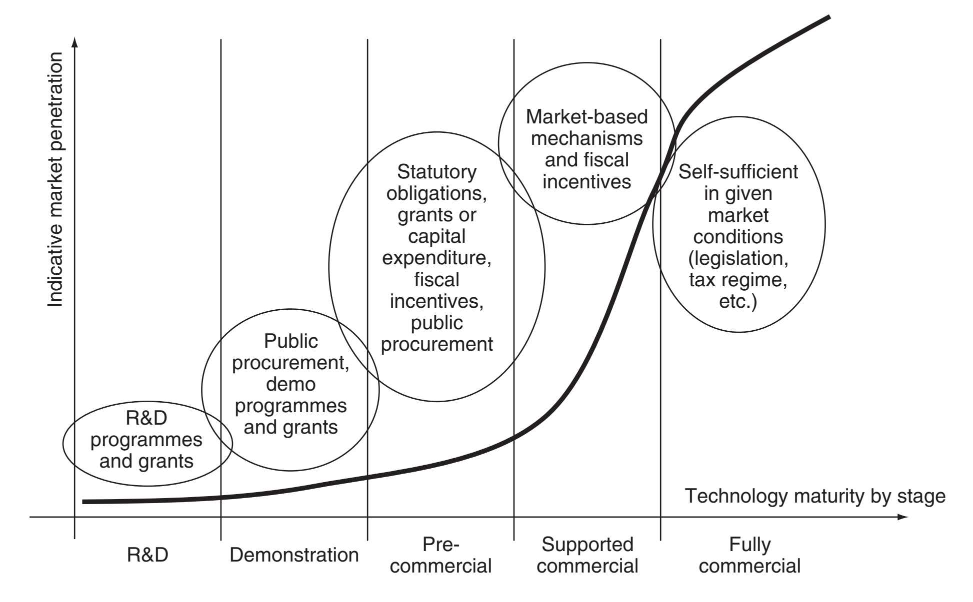

Fig. 4. Typical stages and support mechanisms for innovation (after Foxon *et al.*[12])

Encouraging technologies to move from research, development and demonstration (RD&D) to fully commercial deployment is another chicken and egg situation since manufacturers need high volumes and 'learning by doing' to reduce costs, but volumes will not increase until costs fall to reasonable levels. In this context, the problem facing low-carbon vehicles, including both BEVs and FCVs, is that their markets are currently small or non-existent, and commercialisation timelines and hence returns on R&D investments are uncertain. Although automotive manufacturers still invest considerable amounts in these technologies, the investments are modest in comparison with spending on ICEVs and petroleum. It is also likely that some of this research expenditure is slanted towards publicity purposes. The risk is, therefore, that these technologies remain forever stuck in demonstration programmes, '10 years' away from commercialisation.

Figure 4[12] illustrates one established model for technology innovation, indicating five stages of technology development from R&D to fully commercial. As market penetration increases and technology matures, appropriate mechanisms for incentivising technology development and encouraging deployment also change. Given current technology development, funding for low-carbon vehicle RD&D can play a critical role. However, such support cannot be sustained forever and demonstration programmes only partly compensate for the lack of 'real' user feedback, which plays a key role in technological innovation. Last but not least, the small volumes characterising prototype and demonstrator activities preclude the scale and scope of economies required for cost reduction.

In contrast to other options, however, BEVs and PHEVs may be more likely to progress beyond R&D, among other reasons because future cost/performance improvements are not wholly dependent on either government subsidies or automobile manufacturers' R&D budgets. A key advantage of PHEVs and BEVs is that their critical technologies (mainly batteries) are being developed not only for low-carbon vehicles but also for numerous other applications, many of which are commercial and rapidly growing. Advances in lithium batteries, for example, have and still are being driven by consumer electronics markets with little to no involvement of governments. Although they remain expensive for automotive applications, a number of companies including GM, Nissan and Tesla Motors are planning to or are currently applying them to BEVs and PHEVs. Indeed, the remarkable advances in lithium batteries is one of the main reasons why BEVs (and PHEVs) have come back in favour (at least in some circles) since automotive OEMs largely abandoned BEVs in favour of FCVs in the late 1990s. Although there are many uncertainties relating to their use in mainstream vehicles, many observers are confident that substantial improvements in lithium ion cost, performance, durability and safety will continue as a result of advances in materials, chemistry and manufacturing techniques.[13]

Another trend working in favour of BEVs and PHEVs is the continued growth of 'conventional' BEVs in niche markets such as urban transport. This provides further impetus for technology development, among other reasons due to increased user feedback. Market niches have often played a critical role in the early stages of successful technologies including photovoltaic power and the ICEV itself.[14–16]

Last but not least, the rapid growth in HEVs is driving developments in all critical BEV technologies including advanced lithium batteries. Indeed, a natural evolution from HEVs to BEVs via PHEVs can be envisaged. Technology 'hybridisation' was a key phase in many technological transitions, such as the transition from sail to steam in marine transport,[14] so the significance of HEVs cannot be understated. The Toyota Prius HEV was first commercialised in 1997 and significant progress is being made towards commercial deployment of PHEVs with increasingly large battery packs. As battery and electric motor costs and performance improve, full-powered BEVs may become increasingly attractive, although PHEVs (and perhaps FCVs) are likely to continue to be used in certain applications, such as long-haul travel.

It should also be noted that since FCVs use electric drive trains, the development of HEVs and PHEVs could also make a useful contribution to FCV development. For the other critical technologies for FCVs, however, the prospects are not very good. Early markets for PEM fuel cells include stationary and back-up power, but so far only limited commercial sales have been achieved in this area. Synergies from other types of fuel cells (SOFC, etc.) will be limited due to very different requirements in terms of specifications, materials and so on. Hydrogen storage, which is generally seen as the weakest point of the FCV innovation chain,[13] also suffers from a lack of potential early markets; hydrogen ICEVs, for example, lack industry support with only BMW committing significant funds to this option. Kalhammer *et al.*[13] note that none of the storage systems under development are expected to meet weight or cost targets in the next 10 years, even assuming large production volumes. It is also very difficult to imagine an affordable hybrid hydrogen–gasoline vehicle, let alone one with both a fuel cell and internal-combustion engine (which would also require batteries!).

That said, hydrogen and fuel cells continue to attract considerable interest from big OEMs and oil companies as well as a wide range of other industrial sectors. This wide support base is one of the strengths of the FCV and hydrogen innovation system, especially when compared to previous alternative fuel technologies.[17] The combined impact of these investments may compensate, to a certain degree, for the lack of early markets. However, previous experience with technological transitions suggests that in decentralised market-based economies, coordinated, vision-guided technological transitions are very rare (except in times of war). Transition failures are much more frequent, such as the case of nuclear power in the 1970s, compressed natural gas in the 1980s and many other alternative fuels that failed to attract sufficient users. A general problem with the planned transition concept is that it faces a fundamental dilemma: while uncertainty implies the need to support a wide range of options and to avoid premature technological lock-in, major technological transitions, such as those envisioned by hydrogen proponents, require governments and firms to make large and often irreversible commitments.[18] If evidence in favour of BEVs and PHEVs continues to build, then a common, unifying vision around hydrogen may be difficult to sustain.

In contrast, the strength of the BEV/PHEV vision is that it does not require any major infrastructure investments to begin (although some might be needed later), nor any publicly funded ‘strategic niches’ or vision-guided transition ‘master plans’. It builds on much more *evolutionary*, bottom-up dynamics than the planning-intensive FCV agenda. Indeed, it is possible to imagine a largely market-driven transition from HEVs to BEVs accompanied by the decarbonisation of power generation (which is already under way, with significant progress likely within the EU by 2020[7]).

Unfortunately, the reality is, as usual, more complicated. As with many early fuel cell applications, differences in requirements and other factors will limit possible spillovers between battery applications (e.g. between consumer electronics and BEVs, and even between HEVs and PHEVs). A key point is that PHEVs and BEVs have different, more demanding requirements than HEVs in terms of power and energy, with negative implications for battery lifetimes. A ‘natural’ evolution of electric drive vehicles from HEVs to BEVs is thus far from guaranteed; continued RD&D on all components and probably publicly funded research on ‘post-lithium’ chemistries will be necessary.[19] Government will still have to play a key role in a transition to PHEVs and BEVs, although its involvement need not approach the level required by a transition to hydrogen.

5. POTENTIAL POLICY BARRIERS TO BEV/PHEV DEPLOYMENT BY 2020

Some key barriers to the take-up of BEVs and PHEVs are summarised in Table 1; a more detailed discussion is presented in this and the preceding section. Although there are a number of technologies that can help to drive down near-term emissions, including advanced diesel vehicles, not all of them will lead to decarbonised energy systems. HEVs can deliver both near-term emission reductions, through improved fuel consumption, and a bridge toward zero-carbon mobility. Every HEV sold sends a signal to the industry that electric drive technologies (including advanced batteries and electric motors) are a growing market. BEVs sold today can also contribute to reducing near-term carbon emissions, but current limitations on battery technology restrict their use to either micro urban car segments or high-end performance car segments. The adoption of PHEVs to combine the advantages of HEVs and BEVs could lead to larger take-up. If BEVs/PHEVs are available to provide an equivalent oil demand reduction, the UK’s limited biomass supplies might be better applied to the production of low-carbon (or negative-carbon with CCS) electricity than liquid biofuel production.

A major barrier to the development of BEVs/PHEVs as a low-carbon transport option in the short/medium term, characterised by the 2020 date set for EU targets in this area, is that electricity is not currently recognised as a route to get low-carbon energy into vehicles. Biofuels have a clear origin and (in many cases) a traceable supply chain so their low-carbon credentials are recognisable. In contrast, electricity is often taken as having the average specific CO_2 emissions of the generating mix. Although ‘green tariffs’ are available to source specifically low-carbon electricity, under present arrangements there is no guarantee that BEV users would use these tariffs, or that low-carbon electricity supplied for transport use had in fact been used for that purpose.

It seems a pity, however, that the advantages of developing electricity use in transport may be lost simply because new accounting methods and monitoring technologies might be required. One theoretical possibility is that ‘trusted’ corporate fleet operators could be used to operate low-carbon BEV/PHEV fleets. This might also assist with initial BEV deployment, as fleet operators form an important element in new car sales. Other approaches could use secure onboard metering of electricity use (as is now used in buildings), which would have to be matched to corresponding low-carbon electricity purchases to obtain a ‘renewable transport’ rebate. Electricity sales from vehicle charging points could also be from low-carbon electricity supplies.

It is also worth considering whether transport is the best use for biomass. A detailed examination is beyond the scope of this paper, but it is at least possible that it would be advantageous to retain biomass for heating purposes and use off-peak wind generation in transport instead.

In any case, however, for PHEVs/BEVs to offer a significant contribution to delivering 2020 policy targets, a minimum market

Barrier	Comments	Possible fixes
Battery cost and lifetime	Current lithium batteries, for example, offer many performance advantages over lead-acid batteries but cost far more	Advanced lithium batteries and possibly 'post-lithium' batteries. For example, lithium iron phosphate batteries, as developed by US firm A123 Systems (tied with GM) and others, avoid many of the risks (and have much longer lifetimes)
Battery energy density	Higher specific and volumetric energy densities are needed to achieve 'acceptable' driving ranges, beyond the current 160–320 km	
Battery safety	'Thermal runaway' risks with conventional lithium ion batteries	
Lack of electric vehicle models	In the short term, most BEV offerings will come from specialist firms such as Reva (India), Tesla (US), Modec (UK) and Think (Norway)	Toyota and GM have announced plans for PHEVs, Subaru, Mitsubishi Motors and Nissan are working on BEVs
Electric motor cost	Expensive, although both cost and performance have improved significantly over the past decade	Improvements benefiting from growth in HEVs, with similar components
Lack of home charging access for some users	Home charging is the most straightforward way to recharge a PHEV or BEV, but not all drivers have access to a dedicated/private parking space (as in most European cities)	Public or commercial charging points located on streets, car parks, shopping malls, and so on—the cost of these may be significant, but much less than for hydrogen infrastructure
Need for rapid-recharging stations	Rapid-charging stations would be attractive for longer drives; this will require more substantial investment	Subaru's latest BEV model is designed to recharge in 15 min, so this is no longer a technical barrier
Increased power generation capacity	May be needed in certain areas in the longer term, although current off-peak capacity can cope with large increases in electricity demand in many countries	Develop flexible charging and vehicle-to-grid to minimise impact on electricity supply system
No recognition for low-carbon electricity use in EVs	Low-carbon electricity is available for purchase and use in EVs but if this is not recognised as a low-emission transport option then transitional support measures (e.g. EU biofuels target) are not applied to EVs	Credit low-carbon electricity used in EVs on a consistent basis with other emerging low-carbon transport options; put suitable accounting systems in place

Table 1. Key barriers to the take-up of BEVs and PHEVs

penetration of the order of 1% of the car/light van fleet is required. It is probably reasonable to assume that PHEVs/BEVs would achieve at least the average annual miles travelled per car, since lower running costs are their principal economic attraction; if so, these vehicles would then be achieving 10% of the 10% EU 'biofuels' target[7] for that sector. Fig. 5 shows a theoretical growth trajectory to 1% fleet penetration by the end of 2020, which would require sales to increase from 0·1% of new vehicles during 2010 to 3·1% in 2020, that is an annual growth rate in sales of around 40% per year (conservatively assuming that no BEVs/PHEVs are on the road at the start of 2010 and that the total number of vehicles on the road grows by 2% each year). Although challenging, this level of growth is of a similar order of magnitude to that seen for HEVs in the USA.

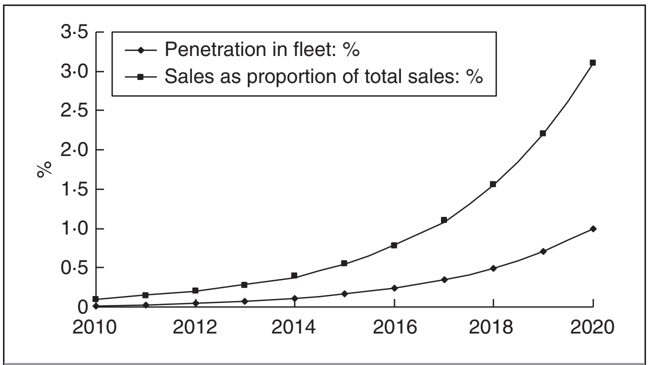

Fig. 5. Illustrative growth trajectory for BEV/PHEV to achieve 1% of fleet by 2020

Consumer uptake of these new vehicle technologies is crucial to achieve such rates of growth. A technological transition toward low-carbon vehicles cannot be forced, so it is vital that technologies are developed with consumer needs and wants taken into consideration. It appears likely that the key factors driving consumer choice will be cost and performance. If these progress sufficiently, consumers will adopt the new technologies just as they switched from gasoline to diesel, from landlines to mobile phones and so on.

London is already a significant niche market for BEVs. Sales are being driven by the London congestion charge as well as a number of tax, parking and charging privileges offered by councils such as Westminster. Combined with the relatively high environmental awareness of UK drivers, these policy instruments have the potential to make London (and possibly other UK cities) a prime showcase or 'boutique market' for BEVs and possibly PHEVs. In such a case, suppliers from around the world, including China, can be expected to target this market and are likely to invest in local distribution and repair facilities.

This brings us back to the technology development/commercialisation pathways discussed earlier. Low-carbon technologies need to be 'nurtured' in early markets (such as London) to drive further improvements in cost and performance, enabling more mainstream buyers as well as industrialising countries to adopt these vehicles.

6. CONCLUSIONS

It appears that even if a source of low-carbon hydrogen were available it would be just as effective to convert it to electricity for use in BEVs and PHEVs as to use it directly in FCVs, and any source of low-carbon electricity is, of course, much more efficiently used in electric vehicles than in FCVs (by at least a factor of two). Turning biomass into electricity for electric vehicles would also be at least as efficient as using it in second-generation biofuels processes. In addition, if the biomass were to be used in larger power plants with CCS, a negative emission of about 125 gCO_2/km would be obtained (for CO_2 removed from the atmosphere) to set against the other lifecycle emissions.

Moreover, the introduction of PHEVs and BEVs will be significantly less challenging than that of FCVs, given the possibility of 'piggybacking' on existing grid and off-peak generation capacity as well as industry-driven technical developments relating to batteries and electric drives. In contrast, FCVs require strong and long-term government involvement for both vehicle and fuel infrastructure development—a transition strategy that is not only expensive but largely unproved.

Although breakthroughs in fuel cell costs and hydrogen storage might make FCVs eventually the 'better' option, the commonality of electric drive technology and the advantages for direct use of primary electricity mean that BEV/PHEV technology developments are unlikely to be wasted.

In the medium term, it appears feasible that BEVs/PHEVs could make a noticeable (order 10%) contribution to achieving 2020 low-carbon transport targets, but this would require traceability for the low-carbon electricity supplied and its recognition on the same basis as is currently given to 'biofuels'. It would be inconsistent to require that all electricity be decarbonised before EVs can get credit for using low-carbon electricity to achieve low-carbon transport. The analogy would be to require that all liquid fuels be produced from low-carbon biomass sources before some ICEVs achieve low-emission transport using specially purchased biofuels. The fact that low-carbon electricity shares a distribution network with 'generating mix' electricity with significant specific carbon emissions is irrelevant, provided a proper accounting system (of which examples already exist) is in place.

In the shorter term, HEVs are developing the necessary technologies and giving market confidence. As well as national policies, local measures such as exemption from the London congestion charge and tax, parking and charging privileges offered by councils such as Westminster are providing significant encouragement. These local 'boutique markets' could have a very important role in the early commercialisation of new technologies, providing an income stream and real customer feedback to manufacturers.

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