The Royal Academy of Engineering

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charged with potential

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Executive Summary

Electric vehicles hold the promise, if widely adopted, of drastically reducing carbon emissions from surface transport and could, therefore, form a major plank in the UK's efforts to meet the binding emissions reduction targets enshrined in the 2008 Climate Change Act.

Most credible energy scenarios for the UK based on the earlier CO_2 emissions reduction targets of 60% compared to 1990 levels strategically allocated all emissions savings to other sectors of the UK economy, allowing the majority of road transport to be powered by fossil fuels. The revision of the emission reduction targets to 80% means that this is no longer an option and we now need radical changes in the way we power and use transport. Any likely future UK energy system will almost certainly involve the electrification of a significant proportion of the transport system. The most likely scenario for the development of electric vehicles is probably a mixture of Plug in Hybrid Electric Vehicles (PHEVs) and pure Electric Vehicles (EVs) on the roads.

Infrastructure, billing and ownership challenges

The automotive manufacturing industry appears to be very ready to take on the challenge of developing mass market electric vehicles but there are a number of prerequisites to truly mass market penetration. These include the development of an infrastructure for charging, functional standards for billing, a compelling consumer proposition and, potentially, new models of ownership for personal transport vehicles. Although these advances will come in time as the electric vehicle proposition develops, the market could be stimulated by the early adoption of standards, ranging from agreement on plugs and connectors through to protocols for billing both at home and en route. However, the major challenge is the provision of a charging infrastructure for EVs, which, in the UK, would require the active collaboration of national and local governments, car park operators, electricity distribution companies, bank card issuers, and many businesses not usually concerned with transport energy supply. The active collaboration of all these diverse parties will need to be carefully coordinated and it is not currently clear which body this coordinating role will fall to.

The present financial case for EVs is heavily dependent on the penalties for carbon emissions and the subsidies implicit in the lack of road fuel taxation on electricity. It is unlikely that these policies could be sustained were EVs to become as popular as diesel powered cars today. A crucial aspect of providing a stable framework for the development of EVs and PHEVs, will be for Government to indicate how it intends to replace fuel duty in the medium term.

Carbon saving

While EVs may hold a CO_2 emissions advantage over internal combustion engine vehicles, their limited range and relatively long recharging times will mean that the convenience of refuelling at petrol stations will favour internal combustion engine vehicles or PHEVs for some considerable time. In order to close this gap, research and development in battery charging cycles and fast charging needs to be funded.

In order to make a significant impact on CO_2 emissions, EVs and PHEVs must become a mainstream option for the majority of the motoring public and, while this is achievable, clear policy direction and development of standards, protocols and infrastructure for their widespread use must be a priority. Otherwise, their impact will be limited and the ability of the UK to reach its legally binding CO_2 emission reduction targets will be severely compromised.

Managing the electricity supply system for EVs

EVs and PHEVs can only be as 'green' as the electricity used to charge their batteries. Recent results from EV trials show a typical carbon dioxide emissions rating to be around 100g/km, when the car is charged from a typical power supply in the UK. Given that a brand new Volkswagen Polo turbo diesel injection has an emissions rating of 91g/km, it is difficult to see how electric vehicles fed from today's UK electricity generation supply are significantly better than petrol or diesel vehicles. To have a major effect, the introduction of electric vehicles must be accompanied by an almost total decarbonisation of the electricity supply.

The current contribution of renewable and low-carbon generation to the UK's energy supply is one of the lowest in Europe. If the UK is to meet its renewable targets, and ensure a 'greener' power supply to electric cars, a range of new low-carbon energy sources will be needed, including new nuclear power stations, wind farms and tidal barrages. Creating this new energy system will require a massive change programme and robust leadership by Government.

The challenge for those supplying energy to a fleet of electric vehicles is to match their varying charging needs to a fluctuating and unpredictable power supply, but not all renewable energy or embedded generation is readily controllable. In terms of annual energy consumption, the additional power requirements caused by a mass take-up of electric vehicles is manageable, but supplying sufficient low-carbon power at times of peak demand will be more difficult.

One solution is an 'intelligent' electricity network or 'smart grid'. In July 2009, the Department of Energy and Climate Change (DECC) outlined its proposal for a smarter grid that would "enable more dynamic real-time flows of information on the [electricity] network... [and] help deliver electricity more efficiently and reliably." An intelligent network could alleviate load issues from recharging batteries – a local smart grid could match generation to electricity use and manage loading on a street by street basis. Bringing together the energy and IT companies necessary to develop this will be a major feat of project engineering. However, the future overall grid architecture and network functionality for such a smart grid is yet to be worked through and what is being discussed bears little resemblance to the needs of a fleet of electric vehicles making up a very significant proportion of UK road vehicles. Without an optimised smart grid in place, the environmental case for electric car development becomes questionable.

Major growth in popularity of EVs would place significant strains on the electricity grid and distribution systems. Early adopters could be accommodated with little impact but, as the numbers increased, there could be a real possibility of local distribution networks being overwhelmed. Significant changes in the timing and size of electricity demand peaks could mean that more carbon-intensive generators lower down the merit order would have to be brought on-line to meet demand at times when carbon intensity would normally be expected to be low. The introduction of smart meters operating within a smart grid would alleviate this effect to some extent, but not entirely. Currently, plans to introduce smart meters to every household by 2020 do not include the functionality required to manage EV charging, potentially rendering the first generation of smart meters obsolescent as the EV market grew.

Recommendations

Electric vehicles and plug-in hybrid electric vehicles stand at a crossroads in terms of becoming viable, mass market options for the UK to radically reduce CO_2

emissions from transport. Technical development is proceeding, driven by an industry that sees their potential as the future of personal transport. However, their success will rely on a number of infrastructural improvements and early agreement on standards and protocols. Development of the technologies ahead of these decisions could reduce public acceptance of EVs, if different charging solutions are being offered, and ultimately require increased future investment in infrastructure to accommodate multiple standards.

1. Government needs to outline its long-term policy direction for EVs in order to provide the right incentives for early adopters as well as providing a stable policy environment for the EV market to develop over time. This policy needs to extend into strategies for the timely investment in the required infrastructure, the ownership of that infrastructure and the timescales over which it must be implemented so as not to delay the development of EVs and PHEVs as mass market solutions. Government also needs to map out intentions for the funding of road networks in the medium term as tax revenues from conventional road fuels reduces.

2. The introduction of electric vehicles on a large scale can only have a beneficial effect on CO_2 emissions if low carbon energy, universal broadband provision and smart grids can be delivered. There is an opportunity to integrate these policy areas and adopt a fully systems-based approach to ensure that that all work together and the critical links between them are explicitly recognised.

3. The automotive industry, with the support of other interested parties, including UK and European governments, must proactively develop international standards for charging EVs and billing protocols.

4. The Government, Ofgem and the UK electricity industry must develop protocols to integrate the long term needs of EV charging into current plans to roll out smart meters and smart grid technologies country wide. Not doing so will risk either stifling growth in the EV market or being faced with early obsolescence of the first generation of domestic smart meters.

5. Further research and development of EV batteries, energy management systems and fast charging is needed to maintain and increase the carbon advantage that EVs currently enjoy and to reduce costs of the battery and EV drive train relative to internal combustion engine vehicles. This needs to be achieved in parallel with continued decarbonisation of the UK electricity system.

1 Introduction

Until the end of the 20th century, petrol and diesel were the undisputed fuels for road transport. In the past 10 years, it has been recognised that the continued use of fossil fuels is unsustainable – partly because of the resulting CO_2 emissions but also because the long-term availability of affordable fuel is uncertain. The Climate Change Act 2008 sets national limits for emissions that would be unachievable with the anticipated levels of road traffic supplied by conventional fuels and the EU targets for average vehicle emissions require a radical downsizing of cars and their engines, a severe reduction in number of kilometres driven or a change in their energy supply.

At one time it was hoped that biofuels would solve both the issues of emissions and fuel availability without the need for significant changes to car technology. However, the 2008 Gallagher Review[1] showed that the sustainable limits on biofuel production are well below the levels needed to fuel the UK's transport system. Since then, electric vehicles, supplied by low carbon and renewably generated electricity, have appeared to be the preferred policy option to ensure long-term sustainable mobility. However, it seems likely that road transport of the future will be fuelled by a matrix of electricity, biofuels, synthetic fuels and possibly hydrogen (the last most probably for captive fleets of larger vehicles, such as buses).

This study has investigated the implications of the large-scale adoption of electric cars in Britain. To make a significant difference to CO_2 emissions, electric drive systems would have to replace internal combustion engines in a large proportion of 'family cars' and 'company cars' and could not be restricted to low-mileage niche markets.

While the report is primarily about cars, most of what is written applies to small vans derived from production cars and some of the discussion is also relevant to Transit-size vehicles. However, the report has not attempted to cover HGVs and long-distance freight transport which present a different set of challenges.

Present battery technology allows EVs a range of around 100 miles. Over the coming decade, other battery technologies will become available which could increase the range of an EV to several hundred miles. However, because of the trade-off between battery cost and additional range, only a minority of car users is likely to want the maximum range that is technically feasible. For others, a rechargeable "plug-in hybrid" (PHEV) would be more attractive and is likely to become the technology of choice for major market sectors.

A small EV with a range of 100 miles could be recharged in a few hours from a normal domestic socket. To recharge a high-performance, long-range EV would require a more powerful electricity supply. The widespread adoption of EVs would be manageable in terms of their effect on the 132kV electricity grid; but the same is not true for the local distribution network. The increased loading, particularly in affluent housing areas where high-performance vehicles might be more prevalent, could require wholesale replacement of cables in the streets or a local 'smart grid' to manage loading on a street-by-street basis by enabling electronic communication between consumers and electricity suppliers so that load and generation can be scheduled in as efficient a manner as possible.

In many residential areas, only a few homes have off-street parking where EVs could be recharged from domestic electricity supplies. Millions of cars are parked on the street at night and, were they to be replaced by EVs, a corresponding number of kerbside supply points would be needed. Whether these would be managed by the local authority, an electricity distribution company or some other body is far from clear but they represent a massive investment in infrastructure with a large behavioural impact. Changes to planning guidance to encourage off-street parking with charging points could make a major difference in some areas.

EV charging sockets are starting to be seen in car parks and at the kerbside in city centres. While there is only a low number of EVs in use, the effects on the electricity system are negligible. However, if EVs achieve a sufficient level of market penetration to make a real difference to national CO_2 emissions, the charging loads at locations such as out-of-town shopping centres, sports stadia, exhibition venues or multi-storey car parks could dominate the local electricity network. The extent to which charging at destination is needed will depend on the balance between short- and long-range EVs and PHEVs in the car fleet. Because charging at destination could take place at times of peak electricity demand, the additional energy would be unlikely to be supplied by renewable generation, which in turn would reduce the CO_2 benefits of the change to EVs.

Creating a pervasive network of public charging points would be a major but necessary investment if EVs are to achieve acceptability in mainstream market segments. However, the widespread adoption of PHEVs, rather than EVs would allow the low carbon market to develop without being tied to such a major infrastructure investment.

For EVs to achieve their maximum potential in reducing CO_2 emissions, they would require to be charged at times when the carbon intensity of electricity generation on the grid is low. Full integration of the UK's transport strategy with the smart metering strategy will be essential. However, merely arranging for EV chargers to switch on when a particular price signal is transmitted from a central facility risks overloading local electrical connections. To manage this would require a disaggregated smart grid with intelligence at the level of the 11kV/415V substation to balance local loads and carbon intensity together for an optimal solution. This bears little resemblance to what is currently being discussed and there is a narrow window of opportunity to ensure that the architecture of the smart grid takes proper account of the future needs of EVs.

Users of petrol and diesel cars pay for the road infrastructure through road fund tax and fuel duty: EVs are exempt from both. While this is a valuable subsidy to accelerate the introduction of the new technology, by the time significant penetration of EVs has occurred, government will need to find alternative means of funding road infrastructure. As it would be impractical to differentiate between electricity used for EVs and for other uses, large-scale adoption of EVs is likely to accelerate the need for a comprehensive system of road pricing or another mechanism for pay-as-you-drive taxation.

The motor industry is a truly international business and car owners expect to be able to drive from one country to another without costly technical or administrative problems arising. Although Britain has a large automotive sector, it is mainly concerned with manufacturing components, such as engines, rather than design and manufacture of complete vehicles. The widespread introduction of EVs will require close international cooperation in setting standards, including for charging interfaces, safety requirements and payment mechanisms.

Present government policies have provided a welcome incentive for the introduction of urban EVs. However many of them are difficult to scale up from the present trials of a few dozen vehicles around the country to the tens of millions that will be needed in the future. This study has identified some of the issues that need to be addressed if electric cars are to fulfil the expectation that they will maintain personal mobility in the face of diminishing and evermore expensive oil supplies and will contribute to the necessary limitation of CO_2 emissions.

It is important to remember that EVs are only as 'green' or 'low carbon' as the electricity that charges their batteries. While most electricity in Britain is generated by burning gas and coal, the difference between an EV and a small petrol or diesel car designed for low emissions is negligible. Establishing the EV or PHEV as the technology of choice for car transport is only one aspect of what is needed to reduce transport emissions.

2 Background

Figure 2 : 1970s electric vans – UK (above) and USA (below)

Electric vehicles have been on the roads for more than 150 years. In the 1830s, Robert Anderson, a Scot, developed an early electrically powered cart; in 1899, Belgian Camille Jenatzy set a land speed record of more than 100 kph in an electric car, *La Jamais Contente*. By 1897, the Electric Carriage and Wagon Company of Philadelphia had built a fleet of New York City taxis. The years 1899 and 1900 were the high point of electric cars in America, as they outsold all other types.[2] In 1910 in London there were some 6,000 electric cars and 4,000 commercial vehicles registered.[3]

In the early 1900s, electric vehicles had many advantages over their competitors. They did not have the vibration, smell or noise associated with petrol cars and, because the driver did not need the strength to swing a starting handle or the dexterity to operate a non-synchromesh gearbox, they were much easier to drive.

Figure 1 : Early electric car (Science Museum/SSPL)

In the 1860s, oil was discovered in North-Western Pennsylvania. During the second half of the century, production increased from a few tens of (whisky) barrels a month to thousands of barrels a day. The consequent reduction in the price of oil and improvements in the internal combustion engine meant that the dominance of electric vehicles was short-lived. By the middle of the 20th century, petrol cars were dominant and electric vehicles had been relegated to specialist uses, such as industrial trucks and milk floats.

In the 1970s, events in the Middle East triggered a five-fold increase in the price of crude oil and a renewed interest in electric vehicles on both sides of the Atlantic, particularly for commuter cars or light commercial vehicles.

During the 1980s, the price of oil fell back to its earlier level (in real terms) and the financial incentive for electric vehicles fell with it. In the 20 years following 1975 North Sea oil production (from the UK and Norway) grew from nothing to six million barrels a day, which eliminated most geopolitical strategic reasons for the UK seeking an alternative to oil based road transport fuels.

In the last five years, there have been two dramatic changes in the prospects for electric vehicles – the 'push' from new technology and the 'pull' of new demand.

The changes in technology centre round the battery. Up to the 1980s, there was really no choice – lead acid was the only sufficiently developed technology. The batteries were heavy; for long life cells, as used in milk float and industrial batteries, the tubular plate construction was almost universal which resulted in a specific energy of no more than 30kWh/tonne. In the last 30 years, there has been a revolution in battery technologies, led by the mobile phone and laptop market, which has made possible specific energy of 200kWh/tonne or more coupled with high cycle lives. New developments are expected to increase this by a further factor. A second breakthrough has been in the design of drive systems: for the first 100 years of EVs, the only choice was the dc motor, originally with very simple contactor control and, from the 1970s, with semiconductor control. Now software-controlled three-phase drives allow cheaper and more reliable AC motors to be used and high performance rare earth magnets have made smaller motors possible, increasing the flexibility of vehicle layout.

Apart from the push from new technology, there has also been the pull of the need to move away from oil-based transport fuels. Type the phrase 'global warming' into an internet search engine and it produces some 26 million results. In Britain, transport (including refuelling international carriers) is responsible for almost one third of CO_2 emissions, which have increased steadily over the past half century and show no indication of a permanent downturn. Because of the huge numbers of cars on the road, their use of oil and emissions dominate the statistics and finding an alternative to petrol and diesel to power the private car has become the key part of the drive to reduce transport emissions. There is also the strategic importance of 'peak oil'. Whether or not one accepts the predictions of an imminent physical shortage, there is little doubt that oil is a finite resource and, as the most accessible reserves are exhausted, prices will continue to rise.

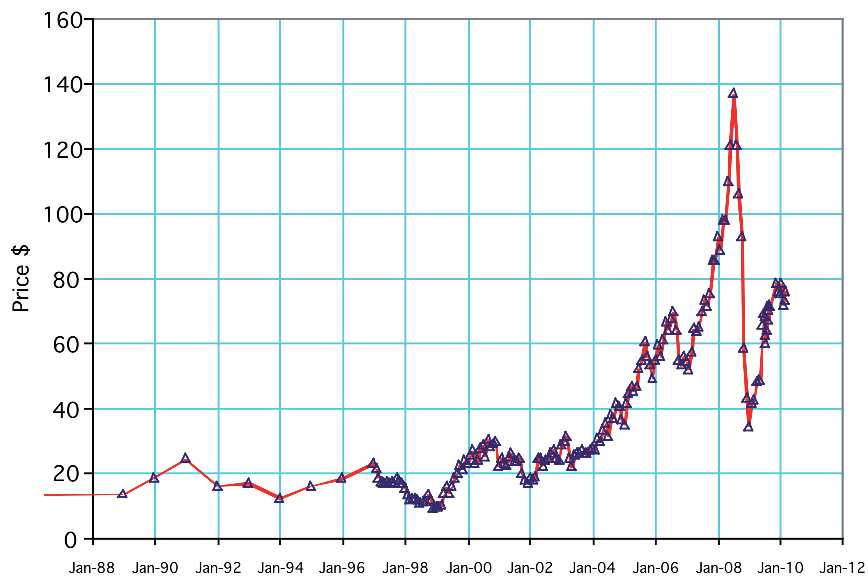

Figure 3 : Crude oil prices

3 Scope of the report

There are several current trials and studies on EVs financed by the EU or various UK bodies, many of which are planned to run for several years. The Academy's intention in commissioning this report is not to duplicate these but to contribute to public policy by focusing on those areas that could affect the overall strategic feasibility of the large-scale introduction of EVs.

To date, many trials and plans for limited EV introductions have involved small numbers of vehicles operating in restricted geographical areas. This is to be expected as it would not be appropriate to introduce a new technology requiring substantial infrastructure investment into a wide area where the infrastructure is too diffuse. To have a measurable effect on the UK's drive to reduce carbon emissions, EVs would have to achieve at least 30% penetration[4] by passenger-km; and, to meet the 2050 emissions target would require more than 60% penetration by passenger-km, even assuming the most favourable electrical generation mix.

In 2009, there were 32 million cars registered in the UK, more than double the number registered 30 years before. The total is increasing every year, with over 70 per cent of British households having regular use of a car. Over recent years, the number of households with the use of one car has remained stable at about 45 per cent, but the proportion with the use of two or more has risen to 28 per cent, almost doubling from 1981 to 2000. A few million small electric vehicles kept as second cars for shopping and the school run would have negligible effect on overall transport emissions; we therefore concentrate on vehicles likely to be used by the general population, not on vehicles from specialist suppliers destined for a niche market.

This report is about passenger cars and, by inference, car-derived vans. There will be many more applications of electric and hybrid technology – one of the most suitable applications for hybrids could be for refuse disposal lorries. The manufacture of light commercial vehicles with electric drive is already established and a longer report would have included more information from this sector. However, to cover all possible applications would constitute a major study in its own right. This report should therefore be seen as a snapshot of some of the issues, not a comprehensive and definitive study of the field.

Many bodies and individual researchers have been consulted in the preparation of this report: a list can be found at Appendix B. We have spoken to some of the largest international vehicle manufacturers, as well as niche suppliers, electricity grid operators and electricity retailers, local authorities, battery manufacturers as well as many academics and independent consultants.

3.1 Technical risks

In terms of technical risk and development potential, the drive system technology of EVs is low risk and is reasonably efficient (better than 90%) and the vehicle structure can use much the same technology as for one with an internal combustion engine. There are some technical risks in establishing a viable EV production infrastructure, discussed later in this report, but these are not the most important factors restricting the growth of the industry. The larger risks are upstream of these and include the energy supply and storage infrastructure which are discussed in subsequent sections.

In preparing this report, we have identified four major technical risks: the availability of high energy-density batteries at a price and with a sufficient cycle life for the EV to be economically viable; the charging arrangements – particularly for users without off-road parking and charging; the electrical distribution infrastructure to provide power to millions of charging points; and the 'smart grid' necessary to ensure that the energy demand of a fleet of EVs occurs at a time of day that matches the daily availability of low-carbon electricity.

3.2 Non-technical risks

To date, the EV has been considered either as a low-mileage commuter car or one fulfilling the same duty as a petrol or diesel-powered vehicle. Evidence suggests that the former would make inadequate impact on emissions and the latter is impractical at a reasonable cost due to the size of battery needed to achieve the required range.

At present, a customer purchasing a petrol or diesel car can select a vehicle of a size to meet their needs, with 4 or 5 stars in the Euro NCAP crash resistance rating, air conditioning, a range of accessories, capable of driving at the speed limit on every road in the land and effectively with an infinite range, with short, simple refuelling stops. Refuelling an EV, however it is achieved, is likely to be a more complex and lengthy procedure than for an petrol or diesel vehicle and be required more often.

The challenge to EV acceptance will be seen when the various subsidies which support electric vehicle growth are removed. At present, fuel duty raises more than £20 billion each year and it is unlikely that any administration will tolerate a significant loss in that revenue. It may, therefore, be necessary to find ways of taxing the energy used by electric vehicles. Similarly the Government scheme to fund 25 per cent of the new cost of EVs is scheduled to finish in 2014. In London, EVs are excused the Congestion Charge but that scheme has high running costs and it will be difficult to justify the exemption if such schemes become commonplace or EV numbers increase significantly. Once these subsidies are reduced, a consumer will choose between an internal combustion engine vehicle and an EV on their merits and unsubsidised price. There is a limited range of scenarios under which an EV would be fully competitive and only a committed group of potential customers would be prepared to purchase an EV that costs significantly more to own and operate than a competing internal combustion vehicle.

If EVs are to be the agents of change that allow a significant reduction in CO_2 emissions, it is likely to be in an environment that is different from that which has evolved symbiotically with the internal combustion engine over the last century. Ownership, funding and taxation models suitable for the traditional family car or company car may not be suitable for the new breed of vehicles and the use of public and private transport is also likely to change. Some of these societal, cultural and economic issues are addressed in the following section of this report.

4 The environment for the car in 2050

4.1 The car as an integral part of society

The growth of 20th century society went hand in hand with the development of the automobile.[5] Cars are iconic and aspirational in a way that most other energy-consuming goods are not and are central to much contemporary (and particularly youth) culture. In Britain, 6.4 million people do not tune in to TV programmes called *Top Domestic Appliances* or *Top Condensing Boilers* in the way they do for *Top Gear*.[6]

Cars have determined the development of cities and the relationship between town and country. Ribbon development of the 1930s and many communities of the post-war era owed their existence to the car and the evolution of the car was shaped by the communities in which they were used – sometimes conflicting with the dreams of their purchasers. Cars are also integral to the industrial development of countries. Cities like Detroit developed because of the car industry and much of Germany's industrial strength is based on its successful car companies.

4.2 Changes in society

Over the past 40 years, there have been major changes in society. In 1970, most school leavers looked forward to a working life in similar factories, dockyards, mills or offices to those in which their parents worked. Computers were owned only by the most progressive companies and were housed in special rooms, tended by their acolytes; copying a letter to someone involved an extra sheet of carbon paper. Britain was still a manufacturing nation and the word *globalisation* could not be found in the dictionary.[7]

The next 40 years promise even more dramatic changes. The need to reduce CO_2 emissions to mitigate global warming is coupled with peak oil – when rate of production peaks, which is expected sometime in the next 40 years, if it has not already done so. In the same period, world population is likely to increase from the present 6½ billion to more than 9 billion[8], which would exert increased pressure on land, water and food supplies, even without desertification, sea level rise and the increase in extreme weather events likely to be caused by climate change. Professor John Beddington, the government's Chief Scientific Advisor, has warned that a *perfect storm* of food shortages, scarce water and insufficient energy resources, due to come to a head in 2030, threatens to unleash public unrest, cross-border conflicts and mass migration as people flee from the worst-affected regions.[9]

Society in 2010 is very different from that in 1970 and society in 2050 could be quite unrecognisable compared with today. Some official studies assume a continuum, as was exemplified in the Stern Review which discussed the (small) detriment to growth caused by climate change mitigation.[10]

> *"For example, if mitigation costs 1% of world GDP by 2100, relative to the hypothetical 'no climate change' baseline, this is equivalent to the average growth rate of annual GDP over the period dropping from 2.5% to 2.49%. GDP in 2100 would still be approximately 940% higher than today, as opposed to 950% higher if there were no climate-change to tackle."*

Set against Beddington's *perfect storm*, Stern's hypothesis of steady economic growth with no shocks for the next 90 years seems more than a little implausible.

4.3 Innovations leading to a low-carbon transport system

The innovation challenge of bringing about the growth of electric vehicles involves maintaining the benefits of personal mobility without the downsides. Innovation can be non-linear, systemic and unpredictable and should not be considered solely in its technological, economic, social or political dimensions but across all of them. The level of innovation necessary for the widespread adoption of EVs requires a degree of as yet unprecedented synchronisation between technology, economics, politics and social factors.

The key question then for the widespread adoption of EVs is how such synchronisation can be made to happen across what can be an extraordinary array of agents involved in co-ordinated innovation? Probably the most important first step is to establish coherent visions of how society might develop and how the concept of the car can develop in parallel with the new views of society.

The implications of peak oil, increasing world population, changes in agricultural productivity resulting from climate change and the continued need to improve the sustainability of economic development point to EVs existing in a world very different to that at the end of the 20th Century. Thinking in terms of system developments rather than what individuals may or may not choose to do, leads us to consider three possible scenarios for the develoment of EV markets in the UK by 2050. This is not to say that these are the only scenarios, there is a range: at one extreme, a widespread decline in the number of personal vehicles, resulting from consumers being less willing to finance capital purchases through debt coupled with rapidly increasing energy prices and long queues at those petrol stations still open. At the other extreme, one can hypothesise the successful development of more sustainable and carbon efficient generations of biofuels allowing a secure, environmentally sustainable and affordable fuel for cars similar to those today.

4.3.1 Market scenario 1: competition

In this scenario, there is development of EVs by mainstream car companies which are sold and mostly used just like petrol vehicles. They are expected to cover long distances and so they are large vehicles with heavy batteries. Because of the intermittently rising cost of oil, EVs make a significant dent in the market through developing as mainly family cars (using charging points in private and workplace garages). They are something of a luxury with their quietness, greenness and immunity to petrol shortages. They are attractive to sectors of the middle class while petrol- and diesel-based cars continue as the mainstream owned vehicle.

4.3.2 Market scenario 2: complementarity

The growth of EVs occurs side-by-side with that of petrol-based vehicles. There are two systems, at least in the more affluent developed economies. Prosperous households own both vehicles. There may be a gender division of car ownership with women especially buying and using EVs (women generally show higher levels of commitment to 'doing something' about the environment/climate change)[11] 'Garages' develop charging as well as petrol distribution functions and EVs may enable personal vehicles to operate even in the event of local fossil fuel shortages brought about by increases in demand from China and India. The encouragement of such complementarity may be part of the energy diversification strategy of various governments.

4.3.3 Market scenario 3: substitution

EVs develop alongside many developments – deprivatisation (where shared car ownership or car clubs replace individual ownership), smart cards, virtual communications, non-metal bodies, some autonomous driverless vehicles, road redesign, smaller vehicles, smooth interchanges with mass transit and so on. This develops into a fully fledged EV system seen as smarter, quicker, more reliable and more fun. When introduced, it comes to replace petrol driven cars. These then come to appear as 'so 20th century': noisy, smelly, dangerous, and unreliable because oil supplies are intermittent. A tipping point occurs and many new uses for these deprivatised, smart, small vehicles develop. Major companies develop as leasers of huge numbers of such vehicles drawing on the commercial models first developed in El Bicing in Barcelona/Paris.[12] Garages convert into battery replacement centres.

Substitution happens first in relatively small, maybe island societies which are prosperous, with strong 'states' and with strong environmentally-oriented 'civil societies' which themselves initiate and experiment with emerging components of these systems (such as Singapore, Hong Kong, Denmark and Iceland). Some development will take place through disruptive innovation[13] and is associated with new models of social and economic progress that target far more than economic GDP.

These patterns for the development of EVs provide an underlying framework for the discussion of technological and strategic issues in subsequent sections of this report.

Figure 4 : Tesla Roadster

Figure 5 : Smart Move

4.4 Affordability

The above market scenarios indicate routes by which EVs might take a larger slice of the British transport market. However, for any of these make a significant impact on emissions, it will be necessary for the technology to be affordable. There will always be potential purchasers for a high-status 'green' car, such as the $130,000 Lotus-Tesla Roadster (figure 4), capable of 125 mph and less than 4 seconds from 0 to 60 mph.

JLR's development of a *Limo-Green* hybrid that will achieve 180km/h and emissions of less than 120g/km, while maintaining the ambience of a traditional Jaguar, will appeal to a niche market sector but will make a negligible dent in overall UK emissions.

At the other end of the scale, there will be a market for affordable city cars, such as the Smart Move (Figure 5) used for commuting and urban living. However, these will be used for low mileages and will not make a major difference to national emissions.

To make a significant difference to emissions, electric vehicles will have to appeal to the mainstream family car and company car sectors, which means they will have to compete economically with petrol and diesel models. The oil industry recognises that "the era of easy oil is over and, in future, oil will be dirtier, deeper and far more challenging."[14] However the overall cost of motoring using conventional fuels, which has been falling in real terms for several decades, is unlikely to see a steep increase and EVs will have to compete with vehicles having capital and running costs broadly similar to those seen today.

5 Climate change and CO_2 emissions

There is now little doubt that global warming is happening, that it is largely caused by CO_2 emissions from human activity, that the effects on some communities will be devastating and that a substantial cut in future emissions will be necessary to limit the damage.[15] EU policy has recognised the problem and has made ambitious commitments to reduce all greenhouse gas emissions, but it is not clear how these commitments will be fulfilled.

5.1 The commitment

The Kyoto Protocol, agreed in December 1997, aimed for a reduction in the 'aggregate anthropogenic carbon dioxide equivalent[16] emissions of the greenhouse gases' by at least 5 per cent by 2012, compared with 1990 levels; some European countries committed to greater reductions. In 2007, the International Panel on Climate Change (IPCC) reported that an 80% cut was needed from developed countries and European politicians have committed to achieve this by 2050.

This cut has been mandated in the UK by the Climate Change Act 2008 which places a legal duty on governments to meet steadily reducing targets for greenhouse gas emissions. At present, transport represents a third of total CO_2 emissions in the UK and, over the last decade, has increased faster than any other sector. Although, as yet, there are no formal targets for apportioning these reductions between sectors – other than for major emitters such as power stations – it is evident that an overall reduction of 80% will not be achieved unless there are significant reductions in emissions from transport.

5.2 Legal targets and incentives

The EU's New Car CO_2 Regulation[17] establishes a long-term framework for action by industry to develop lower emitting vehicles. In the UK, the Regulation is expected to reduce CO_2 emissions by 7 million tonnes of CO_2 a year in 2020. It is hoped that it will also stimulate innovation across all segments of car production. The targets for CO_2 emissions from cars are 130g/km driven from 2012, with full compliance by 2015, and 95g/km by 2020. When the regulation comes into force, manufacturers will have to ensure that the average emissions of vehicles sold will be below the target or pay the fine of €95/g per vehicle for exceeding this target.

At present, electric vehicles are deemed to be 'zero emission', irrespective of the carbon intensity of electricity generation. There are short term incentives and, for the first few years, selling one EV counts as equivalent to three zero-emission vehicles when calculating fleet averages. Producing EVs (even at a loss) could thus be attractive to manufacturers of larger or high-performance vehicles that could not readily meet the standards. These subsidies are likely to encourage the production of smaller vehicles, fitting into Scenario 2 (described on page 14), where the production of electric commuter cars runs in parallel with a vibrant internal combustion engine sector.

5.3 Emissions from UK transport

The previous paragraphs have identified the need for an 80% cut in emissions by 2050: what would a reduction in CO_2 emissions of 80% look like in the transport sector? Before projecting forward, we need to look at how emissions have increased over the years. The following chart, based on Netcen and DfT data, shows emissions from transport over the last 50 years. The blue line is land-based transport and the red line adds in data for air and sea bunker emissions (available only since 1990).

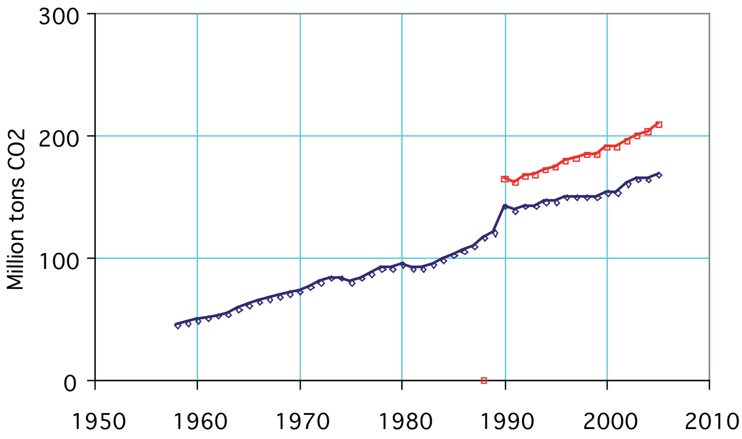

Figure 6 : Emissions from UK transport sector

If we project forward the trend until 2050, we can see that, with *business as usual*, emissions from the transport sector could be roughly double those in 2010. More importantly, an 80% reduction in comparison with 1990 is equivalent to a reduction of 92% compared with an extrapolation of this trend.

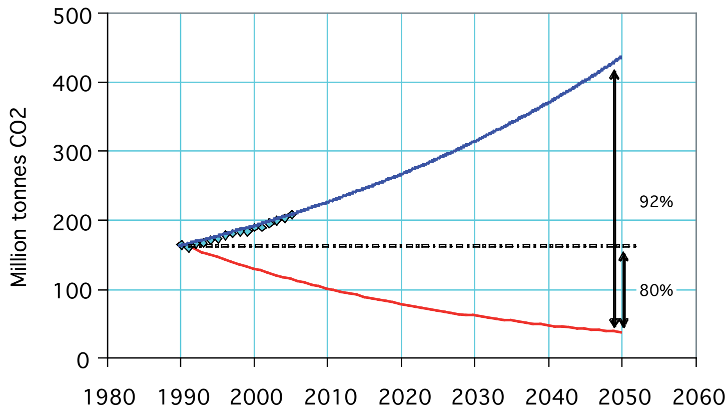

Figure 7 : Extrapolation of transport emissions trend

5.4 Can EVs reduce transport CO_2 emissions?

A car comparison website lists the CO_2 emissions for all of the UK's major new cars. The average CO_2 emissions rating is 173g/km (grams of carbon dioxide per kilometre driven), the lowest being 89g/km and the highest 500g/km.[18] The 2020 target for average emissions is 130g/km. It is expected that this figure will be reduced progressively and some experts are talking about a long-term target of around 80g/km for 4-seat internal combustion engine vehicles.

Results from electric vehicle trials show that EVs equivalent to a small petrol or diesel four-seat car use around 0.2kWh/km in normal city traffic. CO_2 emissions from power stations vary from year to year and also over the daily cycle as the carbon intensity of generation changes: in 2009 it was 544g/kWh. Thus the emissions related to an EV are about 100g/km. Trials on a small fleet of four two-seat *Smart Move* vehicles have shown average CO_2 emissions of 81.4g/km using electricity of the same carbon intensity.[19]

On this basis, it is difficult to see how EVs fed from the present UK electricity generation mix are significantly better in terms of carbon emissions than petrol or diesel vehicles.[20] To have a major effect commensurate with the 2050 target, the introduction of EVs would need to be accompanied by almost total 'decarbonisation' of the electricity supply. Under these conditions, they could provide the ideal solution of personal mobility without the environmental disadvantages.

The challenge of this should not be underestimated. In November 2009, in their joint response to the Department of Energy and Climate Change consultation on *Delivering Secure Low Carbon Electricity*, The Royal Academy of Engineering, the Institution of Engineering and Technology, The Energy Institute, The Institution of Chemical Engineers, The Institution of Civil Engineers and The Institution of Mechanical Engineers stressed the challenge of achieving government targets and set out the following key messages:

- The challenges to 2020, and onwards to 2050, are of an extraordinary scale and complexity, way outside 'business as usual'.
- We are of the view that the barriers are surmountable but the approach to the task must be bold, realistic, sustained and underpinned by determination from government.
- The scale of the technology challenges, the requirement for active consumer engagement, and the requirement for close interaction between sectors that today operate largely independently, mean that an honest assessment of downside risks is warranted.
- The approach adopted should have inbuilt flexibility for contingency out-turns and close government progress monitoring so that early action can be taken if the key deliverables are not being achieved on time.

Decarbonising the electricity supply system, to allow EVs to offer much lower emissions than internal combustion engine vehicles, is possible but will be very difficult. The additional generating capacity needed to provide energy for these vehicles will also add to the challenge of decarbonising the electricity supply. This challenge – building 1,000 offshore wind turbines per year, a one hundredfold increase in the rate of installing solar PV generation, harnessing wave and tidal energy and the deployment of many new nuclear power stations – is considered by many to be improbable without greater government intervention in the electricity supply industry.[21]

5.5 Energy scenarios

In March 2010, the Academy published a report on the challenges to decarbonising the UK energy system.[22] This looked at four energy system scenarios to obtain an 80% reduction in CO_2 emissions – constant demand, reduced demand with fossil fuels reserved for low grade heat (LGH – principally domestic and commercial space heating), reduced demand with fossil fuels reserved for transport and high demand reduction. In each case, the renewable energy and biomass contributions were the highest considered realistic, the fossil fuel input was limited by allowable CO_2 emissions and the balance was provided by nuclear or fossil fuels with 100% carbon capture and storage. The two most relevant to this study are the central scenarios, for which the Sankey Charts are reproduced in figures 8 and 9.

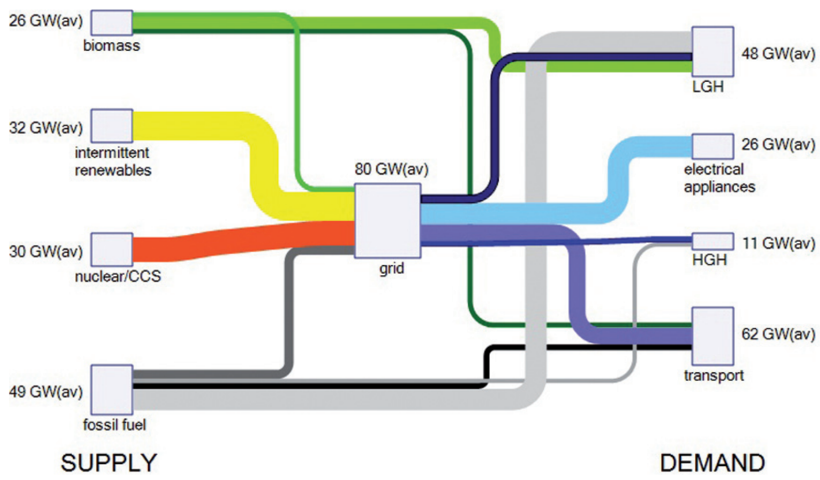

Figure 8 : Sankey chart – reduced demand: fossil fuels prioritised for heating

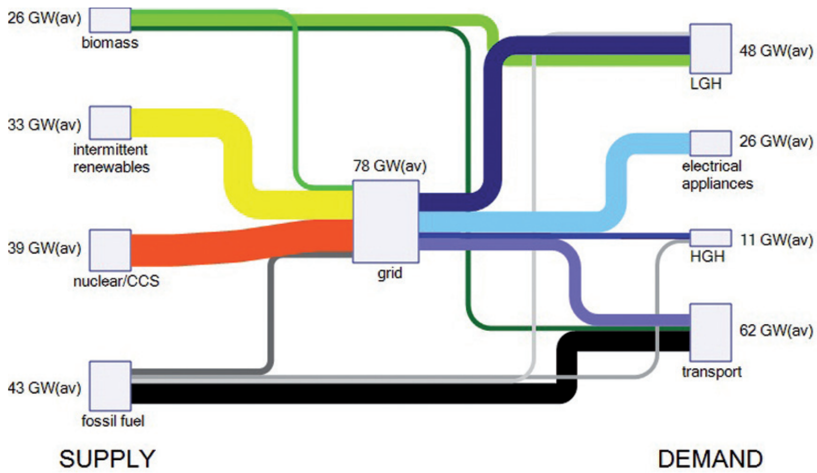

Figure 9 : Sankey chart – reduced demand: fossil fuels prioritised for transport

It can be seen that, even in figure 9 where fossil fuels are prioritised for transport, about one third of transport energy is provided by grid electricity. A small fraction of this use represents electric trains but even this scenario will need electrification of road passenger transport, bearing in mind that electrification of road freight is intrinsically more difficult.

In figure 8, where fossil fuels are prioritised for heating, transport is almost entirely electrified. In this case, almost all cars would have to be powered by electricity and all long-distance road freight moved to electric trains.

In practice, neither scenario is likely. Assuming the commitment to an 80% reduction is taken seriously, the outcome is likely to be somewhere between these two where there is not an outright ban on gas boilers but emissions from both the production of low grade heat and transport are cut dramatically by technologies like heat pumps and electric vehicles.

5.6 Alternatives to EVs as a route to reduced emissions

It seems likely that the production cost of an EV will always be more than an internal combustion engine car, because of the cost of the battery. An alternative to EVs would be to invest part of that extra cost in a radically different internal combustion engine capable of making a dramatic improvement in fuel consumption.

Organisations developing advanced engines are confident that it will be possible for a small internal combustion engine car to achieve CO_2 emissions of around 80g/km in the near future. This could be achieved by techniques such as intelligent turbo- or super-charging, low energy electric steering assistance, variable valve timing, charge stratification and switching off the engine when no power is required.

There are other options for reducing emissions from cars. Biodiesel and ethanol fuels are like-for-like (and, in the developed world, affordable) replacements for diesel and petrol. The limitations on their use will be not on their viability as fuels but on their impact on food availability and the environment, as outlined in the Gallagher report.[23]

DME (dimethyl ether, CH_3OCH_3), a readily liquefied gas, can be made from lignocellulosic biomass (such as agricultural residues or wood processing wastes) that are not in competition with food production, coal or hydrocarbons. It has been promoted as a lower-emissions alternative to conventional fuels and it is very clean, in terms of local pollution, easily meeting EURO5 emissions standards. However, the extent to which it is *low carbon* depends on what materials and energy went into making it.

Hydrogen has been trialled in London and is seen as a possible contender, particularly for larger vehicles such as buses. Although the energy transport and storage problems are different from those associated with EVs, the fundamental problem of providing low-carbon energy is much the same. The option of electrolysis and a fuel cell as a means of transmitting electrical energy from renewable sources, such as wind power, is generally a less efficient process than a battery.

If the objective of policy is to encourage the take-up of vehicles powered from freely available renewable energy by maximising their range and flexibility, then DME or hydrogen would be a logical option for all transport applications. But if, as seems more likely, we will be living in a world where supplies of renewable energy cannot satisfy more than a small fraction of the potential end uses, the greater efficiency of EVs will change the balance of many applications.

In the absence of a readily available, environmentally benign and affordable fuel, a range of transport energy supplies could be developed – synthetic diesel, hydrogen and biofuels as well as electric power. For the passenger car market, this would be a variant of complimentary described in market development scenario 2, in which the EVs are developed alongside advanced combustion technologies giving a wide range of alternative vehicle types for different applications.[24]

5.7 Competing policies

While considering how EVs might contribute to a reduction in CO_2, it is important not to forget the forces ranged against a reduction in mobility, and hence emissions. The website of the EU Directorate General for Energy and Transport quotes the founding principles of the Community:

> *Under the terms of Chapter XV of the Treaty (Articles 154, 155 and 156), the European Union must aim to promote the development of trans-European networks as a key element for the creation of the* ***Internal Market*** *and the reinforcement of* ***Economic and Social Cohesion****. This development includes the interconnection and interoperability of national networks as well as access to such networks.*

In other words, EU policy is to increase the movement of people and goods – which inevitably leads to an increase in CO_2 emissions.

It would be convenient if managing transport emissions could be considered in isolation from other policies, such as competition, immigration, education, employment or economic growth. All these strongly influence the amount of travel undertaken and thus emissions. For example, a policy of *best value procurement* that requires a local authority to invite competitive bids for all services, rather than operating a direct works department, is likely to result in contractors from neighbouring areas driving many kilometres to undertake jobs. Education policies that result in children being driven past a local comprehensive to a specialist college or faith school have a similar effect. It will be a challenge for government to reconcile these different policies.

It would also be convenient if a reduction in CO_2 emissions from transport had no effect on the amount of travel undertaken; unfortunately the inverse is often true. The Khazzoom-Brookes (K-B) postulate argues that 'if energy prices do not change, cost effective energy efficiency improvements will inevitably increase economy-wide energy consumption above what it would be without those improvements.' In other words, the greater the efficiency of a process, the greater the use of energy. This has been demonstrated in a recent UKERC publication[25] that quoted a study on the use of artificial light from 1700 to 2000 AD. As the efficiency improved over 300 years by a factor of 1000, the amount of light used per capita increased by a factor of more than 10,000.

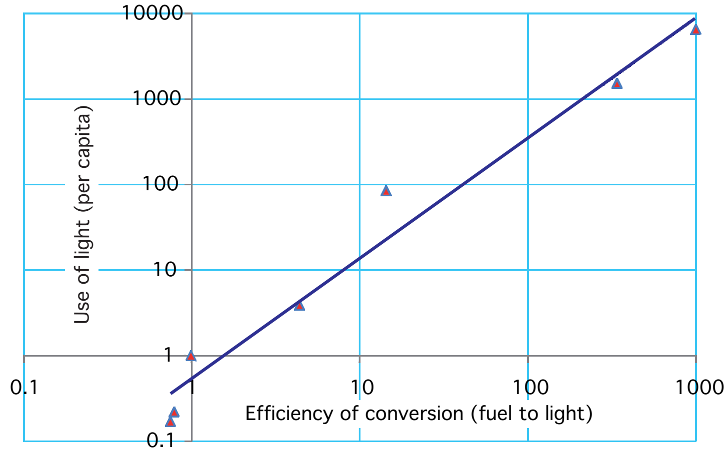

Figure 10 : Artificial light used 1700 - 2000

This suggests that, if CO_2 emissions per kilometre are reduced by a factor of five by 2050, the cost of energy should rise by the same factor – unlikely to be a popular policy.

Figure 11 : Mitsubishi I MiEV

Figure 12 : Citroën C1 Electric

Figure 13 : G-Wiz

6 The challenges of establishing an EV industry

6.1 Manufacturers' plans

As discussed in section 1, the technical development of EVs is not currently the main impediment to the widespread adoption of EVs – but that is not to say that all problems have been solved.

Many large vehicle manufacturers are developing EVs: Ford has a programme with Scottish and Southern Energy to develop an electric Focus; Citroën has developed the C1 electric (figure 12); Mitsubishi is also developing a range of EVs (figure 11). Toyota has a major programme of electric and hybrid vehicles; TATA (the owners of Jaguar Land-Rover), Peugeot and Renault are introducing prototype fleets of electric cars. However, with the exception of a few expensive vehicles, almost all are designed for limited mileage urban use such as the school run, commuting and shopping.

In addition to these smaller family cars, there are many specialist commuter cars, such as the G-Wiz (figure 13).

Present expectations in European countries for introducing electric vehicles by 2020 range from 40,000 cars in Sweden to 2,000,000 in France. But for EVs and plug-in hybrids to make a significant difference to energy use and CO_2 emissions, total market penetration will have to be measured not in tens or even hundreds or thousands of vehicles, but in many millions.

The message from manufacturers would appear to be that it is technically possible to manufacture millions of EVs but, with the cost of current battery technology, they do not see the market developing much beyond the second car in environmentally conscious and affluent households – as in market development scenario 2 outlined in section 4.

6.2 Production facilities

Most of the EVs available in the UK are still made in small numbers and there will be challenges to building up production volumes. Although cell production is automated, assembling cells into a battery and integrating that with the battery management system is a major task that is not yet automated. New factories, of the scale of the £200m battery plant announced by Nissan in Sunderland, will be needed to mass-produce motors and power semi conductor assemblies.

Several researchers have commented on fundamental problems over supplies of rare earth materials for the magnets needed for high-performance motors. However, if these are not available, there are fallback solutions made of common materials – iron and aluminium – that would reduce performance or efficiency by only a few per cent. Similar issues have been raised over the supply of lithium for batteries. Although lithium is the currently preferred material for battery chemistry, the next section of this report will show that it is not the only option that can produce a viable battery.

7 Storage technology

7.1 Recent battery developments

Over the last 20 years, a wide variety of battery types has been developed that could be used in EVs. Much of this development has been driven by the needs of laptop computers, mobile phones and cordless power tools. Current EV and PHEV battery types are most commonly grouped around lithium-ion (Li-ion) based products with various additional cathode additives to improve attributes such as energy density, power density and safety. Other alternatives such as nickel metal hydride and sodium nickel chloride are already commercially available, with lithium-air, lithium-sulphur, zinc-air and bi-polar lead-acid providing cheaper long-term solutions.

As an example of this variety, Modec, a company in the West Midlands making electrically-powered light commercial vehicles with a practical range of 160km, has used sodium nickel chloride batteries (ZEBRA batteries) which operate at 300°C using molten sodium chloroaluminate ($NaAlCl_4$) as the electrolyte. The ZEBRA battery has a specific energy of around 90Wh/kg and specific power of 150W/kg. Modec's recent production has used lithium iron phosphate ($LiFePO_4$) batteries, which achieve an energy density of around 90Wh/kg. For the near future, Modec are considering lithium sulphide batteries. These have the benefits of being low-cost, biodegradable and abuse tolerant and are expected to produce 500Wh/kg.

At the smaller end of the scale, the *Smart Move* cars involved in the trials in the North East also used sodium nickel chloride batteries, but with a capacity of 15kWh, although future vehicles are planned to use other chemistry.

TATA, the parent company of Jaguar Land Rover, has developed a range of small four-seat cars with a performance, in urban situations, equivalent to a petrol vehicle. They use Li-ion batteries which have a capacity of 26kWh and mass of 160kg, a specific energy density of 165kWh/tonne, including local support structure and connections.

The Tesla Roadster, a sports car designed by Lotus and produced by the American firm Tesla Motors, uses lithium-ion cells with lithium cobalt oxide (LiCo) chemistry, similar to laptop batteries. The 185kW output gives 0–60 mph time of 3.9 seconds. The 375V, 53kWh battery pack has a specific energy of 120kWh/tonne and can be recharged, using a 70A 240V supply, in 3½ hours.

Much of the expertise in using modern batteries is in the charge and heat management of the complete battery pack. Most high-performance Li-ion batteries have an active cooling system, Tesla's being active whenever the battery is charged, not just when in use. Cells are discharged in groups to ensure that they share the total load and to avoid excessive heat build-up in some areas of the pack. In some current applications, up to 50% of the energy storage device costs, and up to 35% of the total energy storage systems mass is due to packing, mechanical and electrical protection, voltage and temperature management and ancillary cooling equipment.

For the EV industry, energy density, that is how many kWh can be stored in a tonne of battery, is the key factor that determines range; for hybrids, however, power density is more important. These factors determine that batteries are likely to evolve in two distinctly separate ways. We already see cell suppliers who are concentrating primarily on power density (Hitachi) and others who are concentrating primarily on energy density (Electrovaya, EiG).

7.2 Comparative battery performance

Table 1[26] below lists some battery types that are under development for electric vehicles:

Cell chemistry	Specific Energy kWh/tonne	Specific Power kW/tonne	Charge-discharge efficiency	Cycle life
Lead acid (for reference)	35	40	90%	1000
Li-ion	110-190	1150		2000
NiMH	<80	200	91%	3000
NaS	90	90-150	85%	5200
Bi-polar Pb/SO_4	50	500	91%	
Li-ion phosphate	95-155	1060		1000-5000
Li-ion titanate (nano)	74-83			15,000
Lithium sulphide	500			1000
Zinc-air	470	100	57%	
Zinc bromine	70	100		
Super capacitor	15	4000	98%	500,000

Table 1 : Options for battery chemistry

7.3 Availability of battery materials

Table 1 (above) demonstrates the wide variety of batteries being developed for possible use in EVs. Many are based on lithium and there has been some concern over the long-term availability of this material. Data from the 2009 US Geological Survey[27] and Meridian International Research[28] provide the figures in the following table:

	2008 Production tonnes	Reserves t x 1000	Reserve base t x 1000
Argentina	3,200	1,000	2,000
Australia	6,900	170	220
Bolivia	NA	2,700	5,400
Brazil	180	190	910
Canada	710	180	360
Chile	12,000	3,000	3,000
China	3,500	540	2,700
Portugal	570	NA	NA
United States (2005 data)	1,700	38	410
Zimbabwe	300	23	27
Total	c. 30,000	c. 7,000	c. 15,000

Table 2 : Availability of lithium

Worldwide lithium resources are estimated as some 15 million tonnes. In addition there is an estimated 230 billion tons of lithium in seawater, but the concentration is low (0.1-0.2 ppm). If the mass of lithium metal in an EV battery is 10% of the total pack, then the total lithium requirement of a whole vehicle is about 15kg. The reserve base thus represents sufficient lithium for a billion EV batteries, meaning that lithium shortages do not appear imminent.

The diversity of possible battery chemistries suggests that a shortage of battery materials is unlikely to put a brake on EV development in the UK in the foreseeable future.

7.4 Optimum battery size

Researchers at Imperial College[29] have used data from the National Travel survey to assess the proportion of journeys that can be made by an EV with different battery capacities.

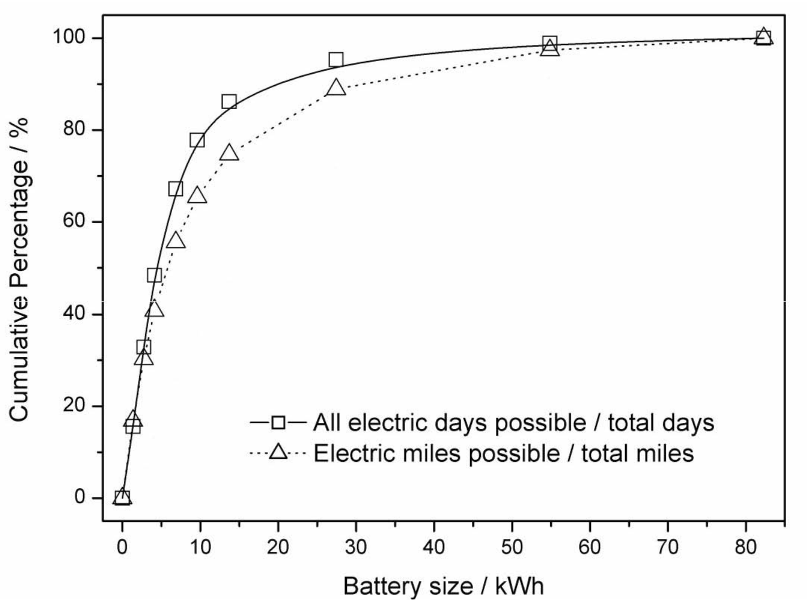

Figure 14 : Proportion of trips possible from batteries of different capacities

Thirty years ago a similar study was undertaken by David Bayliss (Imperial College) of traffic in London.[30] This calculated the percentage of users who would be satisfied by vehicles with a particular range using two different criteria. With energy use of 200Wh/km (typical of small EVs in city use) the upper curve implies a battery capacity of 20kWh would satisfy 86% of daily journeys, a figure very similar to the Imperial College figures.

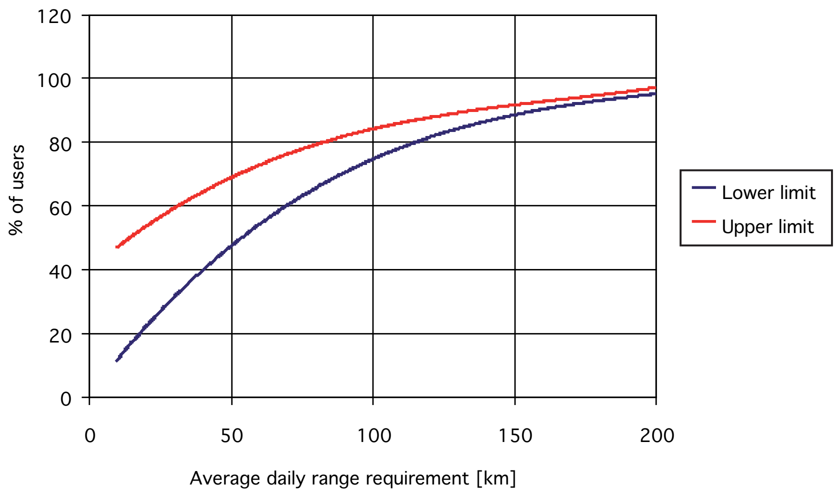

Figure 15 : Average daily range requirement for personal vehicles

These studies suggest that, with a battery capacity of around 20kWh, on nine out of 10 days, the vehicle could be operated entirely by electric power. To increase this to 19 out of 20 days would require a further 20kWh, adding perhaps £10,000 to the battery cost and 100kg to the battery weight.

The conundrum is that satisfying nine out of 10 of daily journeys may sound positive but the other side of the coin is that, roughly once a week, the average EV user would want to undertake a trip for which a 20kWh EV would not be suitable. The extra cost (potentially up to £10,000) of a battery sized to enable owners to reduce the number of trips they cannot undertake from once a week to once a fortnight would probably not be seen as good value for money. In either case, drivers would be reticent to run their vehicles to the limit of the theoretical range to avoid the risk of being stranded with a flat battery. With the battery chemistries and costs presently foreseeable, electric vehicles are unlikely be economically attractive other than for predictable low-mileage uses, such as the second car in a multi-car household.

There are three possible solutions to this problem – one would involve changing the ownership model so more vehicles are leased or shared and a user could select either an EV or an internal combustion engine car depending on the plans for that day – if they are known sufficiently well in advance. The alternatives are rapid recharging and/or battery exchange schemes, discussed in section 8, or the adoption of plug-in hybrid electric vehicles (PHEVs) that would allow most daily mileage to be electric but with the back-up of a small engine for longer trips. Figure 14 suggests that, with a battery capacity as low as 10kWh, the average driver would use the hybrid engine only once a week. And, because the cost of a small internal combustion engine drivetrain is less than a 10kWh battery, a PHEV with a 10kW battery is expected to cost less than an EV with a 20kWh battery.

7.5 Safety risk

Although storing energy in a battery is intrinsically less risky than as a highly inflammable liquid, there are certain failure modes that have been identified, such as an internal short circuit causing a fire or a failure of the charging system resulting in the emission of explosive gases. A number of new safety issues need to be considered such as how visually impaired people can recognise the approach of a vehicle not producing engine noise or how emergency services should tackle a crashed EV.

7.6 Options for battery charging during the day

If the option of installing a very large battery has disadvantages, there are two alternative possibilities – either changing the ownership model so drivers have the use of a hybrid or internal combustion engine car on those days it is necessary to make a longer trip or finding some means of recharging the EV battery at points on the journey. Four possibilities have been described for the latter option:

- Fast charge stations, equivalent to petrol/diesel outlets.
- Battery exchange stations, where a discharged battery can be swapped for a fresh one.
- Series hybridisation where a small diesel/petrol engine or fuel cell provides the average energy needed for the trip.
- Recharging at the destination and perhaps intermediate destinations.

These are discussed further in the section 8.

8 En-route charging

8.1 Fast charge stations

There are three possible impediments to fast charge stations: the ability of the battery to absorb charge in a short time, the ability of the local supply system to cope with the high instantaneous loads and the difficulty of ensuring an efficient and "user-friendly" connection between the grid and the battery.

The Li-ion battery has a maximum charge rate of 1C – meaning that it takes an hour to charge the battery, even in optimum conditions. Li-ion phosphate and Li-ion titanate batteries can be charged at much higher rates; however cell interconnections and cell heating then become the limiting factors. If a 500V 25 kWh battery could be recharged in three minutes at a rate of 20C, the current into the cells would be (25,000/500) x 20 = 1000A. To carry 1000A, even for a short time, requires heavy electrical conductors both within the cells and between cells. Another consideration is that of the Butler-Volmer equation, which relates the current to the overpotential (the additional voltage required in charging a battery, which is not recovered on discharge, to force the chemical reactions inside). It suggests that a higher current would require the application of a higher overpotential (leading to higher losses), which in turn would affect the charge/discharge efficiency, thus the CO_2 per kilometre performance would be worse.

A typical suburban filling station has a dozen pumps to deliver fuel. If converted to fast recharge points for EV batteries, of the rating discussed above, the load could be 5MW. Bearing in mind the peaky" nature of the load and the likely harmonic content, such a facility would probably need to be fed at 11kV from the HV supply, the level usually reserved for large commercial or industrial premises.

The third difficult area is the interface between the power supply and the battery. To avoid carrying around heavy charging equipment, most fast chargers carry out the isolation and rectification processes 'on shore', rather than on the vehicle. This raises the need for international standardisation of the charging interface – not only the heavy duty power connectors but also the control signals to ensure the battery is charged at the appropriate rate for the appropriate time. Charging a traction battery can be a hazardous operation and the charging regime has to be tailored to the battery and its condition. This is several orders of magnitude more complicated than standardising petrol and diesel nozzles in filling stations.

8.2 Battery exchange stations

Several proposals have been made for battery exchange stations. The principle is straightforward – a vehicle is positioned over a pit with a servo controlled lift, the battery is dropped down to below road level, replaced by another fully charged battery and conveyed to an adjoining warehouse to be recharged. In practice, the engineering would be more complicated as the system would have to cope with different sizes of battery for different vehicle types. The capital expenditure on facilities to give good coverage, even limited to main roads and motorways, would be considerable and it is highly unlikely that a battery exchange infrastructure could be available nationwide.

A difficult area would be the commercial arrangement for ownership and safety assurance of the batteries. In other sectors where empty energy containers are exchanged for full ones, such as *Camping Gaz*™, the container itself is cheap, reliable, easy to inspect and does not degrade so there is little penalty in trading in a new container for an older one. But a battery's capacity can reduce by 30% or

Figure 16 Charging point in Central London

more during its lifetime and a five year old EV battery will have a very different residual value from a new battery.

If by 2050 there are 30 million electric vehicles in the UK and an EV battery has come down in cost to £5,000, the first cost of the batteries in use would be £150 billion. Allowing for other batteries in the supply, charging and recycling chain and the total asset value could be £200 billion. Battery leasing has been suggested as a way to allow regular battery swapping but the scale of the operation (roughly 100 times greater than the asset value of the UK railway rolling stock leasing business) would be challenging to implement, particularly on a Europe-wide scale.

8.3 Recharging at destination

Some local authorities are experimenting with city recharging stations where a motorist driving an EV can recharge in a parking bay. It is technically feasible that this scheme, which so far has covered only a few dozen charging points, could be extended to cover larger car parks and out-of-town venues. However, there is no obvious source of funding for such infrastructure. Present costs of installing a charging point are estimated at £5,000, including a card reader and data connection. Installation of a few dozen stations might be funded by a local authority to promote electric vehicles; but meeting the cost of providing the thousands that could be needed in, say, Manchester's 50 car parks and multitude of on-street parking spaces would be a major issue.

The widespread adoption of charging at the destination would make it difficult to ensure that the electrical load was taken at a time to fit with the availability of surplus low-carbon electricity. Fans parking in Manchester United's 5000-vehicle capacity car parks during an evening football match might put their cars on charge at 17:00 and expect them to be recharged by 20:00 – the peak load period for the grid.

8.4 Plug-in hybrid electric vehicles (PHEVs)

Figure 17 (below) shows, in simplified form, two main types of hybrid vehicles. On the left is the battery vehicle. Energy comes from the charging socket, is stored in the battery and can be transmitted by the controller to the motor and thus to the wheels. During braking, energy is taken from the wheels through the motor and back into the battery.

The centre diagram is a series hybrid. It is basically an electric vehicle but with an on-board supply of electricity from a small internal combustion engine, sometimes referred to as a range extender. Under normal day-to-day running, the engine is not used but it can be started during a long journey to maintain the battery state of charge.

The right-hand diagram shows a parallel hybrid. In this case the engine can drive the wheels directly via a mixing gearbox of some sort. In parallel hybrids, the electric drive system is often sized to be adequate only for low speed running and the engine is started whenever the car speed exceeds a certain value. A parallel hybrid can have a charging socket or, like the current models of the Toyota Prius, could take all its energy from the petrol and recharge the electric drive system from braking or via the mechanical drive system, when the full power of the petrol engine is not needed.

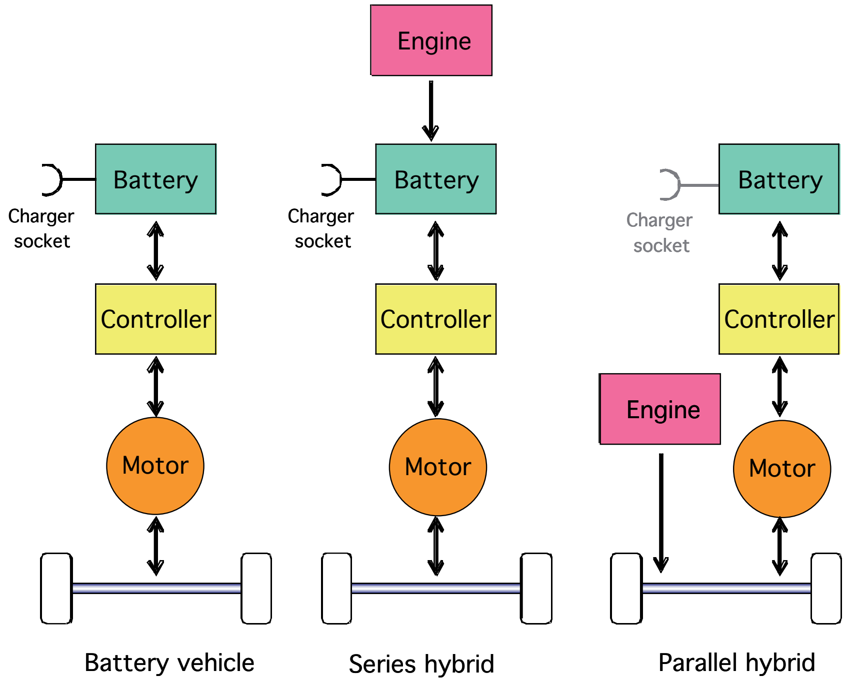

Figure 17 : Alternative hybrid configurations

There is likely to be a wide variety of different types of electric and hybrid vehicle meeting different market sectors. Some manufacturers may offer alternative levels of hybridisation for a basic vehicle, much as they offer different engine options at present. A hybrid could become an attractive option for the uses described as market development scenario 1, where vehicles offering immunity from fuel shortages satisfy the luxury end of the market. But relying on this scenario would not achieve sufficient market penetration to effect a significant reduction in CO_2 emissions.

If adequate supplies of low-carbon electricity are available, the series hybrid is likely to give better overall emissions than a parallel configuration, but much depends on the rating of the various components and the control strategy. Several researchers have put forward schemes for series hybrids where the 'top-up' power is derived from fuel cells, rather than diesel or petrol engines[31]. Others have suggested that the power supply module, rather than being permanently installed in a vehicle, could be rented for longer trips.

Because the engine in a PHEV is required to provide only average vehicle power rather than to power acceleration or hill-climbing, it can be smaller than a conventional engine – less than 25kW for a family car, compared with 75kW for a conventional drive train – and thus would be lighter and cheaper. Figure 14 showed that, with only 10kWh of on-board storage, an EV would allow average motorists to transfer 70% of their energy use to the electrical supply; if the energy provided by petrol or diesel is used with the efficiency of a non-plug-in hybrid, such as the Prius, the overall reduction in liquid fuel use would be approaching 80%. Whether or not this would result in an adequate reduction in CO_2 emissions depends crucially on the decarbonisation of the electricity supply. This is conditional on a vehicle being able to upload most of its energy from the grid at off-peak hours – which, for most people, means charging at home and this is the subject of the next section.

Figure 18 : A standard European charging connector?

9 Charging at home and away

9.1 On-street parking

Images of electric vehicles often include a car being charged in a spacious car park in an up-market business district or on the user's driveway in a leafy suburb. Under such circumstances, it is easy to see how plugging in the EV would be no more onerous than putting out the milk bottles used to be seen. The reality for many people is somewhat different as in the UK, a large proportion of vehicles are parked on public roads, often some distance from the owners' homes. In London, two thirds of homes do not have off-street parking.

It is not easy to see how to arrange reliable on-street charging for so many vehicles, most parked in ill-defined spaces, rather than delineated parking bays. Greater regimentation of on-street parking would inevitably reduce the number of spaces and could result in opposition from residents.

Assuming on-street residential parking can be divided into marked bays, the next challenge would be to install suitable charging points. Each would have to incorporate a smart-card reader, socket outlet with electrical protection and a data link back to some central system capable of validating the smart card and then switching on the power.

In principle, an EV charging point is not very different from the electricity supply points that exist on family camp sites throughout Europe. However, even the complexity of the smart card interface would be dominated by the different social environment. Some unscrupulous car users might be tempted to transfer a car that is on charge to a dead socket and plug-in their own vehicle to the paid-for supply. Youths might find it amusing to push aluminium foil between the pins of plugs and watch the reaction of the drivers next morning when they realise they will not be able to get to work. And there are simpler issues such as cable theft, crash damage and driving away with the cable connected.

Because of these considerations, the cost of a vandal-resistant charging point is unlikely to be less than £1,000 even in large numbers (current costs are five times this) and the costs of providing the underground distribution infrastructure will add to the cost. Providing hook-up points for on-street parking in a major city could, therefore, cost many millions of pounds. It is not obvious which body would carry the costs of such infrastructure.

9.2 Charging at work

For people living in a detached or semi-detached house who keep their car in a garage or on the drive at night, charging at home offers no problems and, for a proportion of the population, this is the likely way in which an EV would be charged.

For many millions of others living in flats, terraces or other accommodation without a dedicated parking space, charging at home would be likely to be complicated, time consuming and expensive. For some, the alternative would be to charge in a car park during the day. From the point of view of the user, this would be convenient – many people park in the same multi-storey car park each day or have access to an employer's car park. However, this would impose a very different load pattern on the grid – discussed in following chapter.

The same constraints might not apply evenly across Europe. One could imagine a factory in, say, Spain with a roof consisting of photo-electric cells that charge employees' cars during the daytime.

10 Interface with electricity grid

10.1 Generation capacity

There are two distinct issues that have to be addressed when considering generation capacity – the ability to provide adequate low-carbon energy over a 24-hour period and the ability to provide the peak power when vehicles are being recharged.

Figure 19[32] shows daily demand profiles for the days of maximum and minimum demand on the GB transmission system in 2008/09 and for days of typical winter and summer weekday demand.

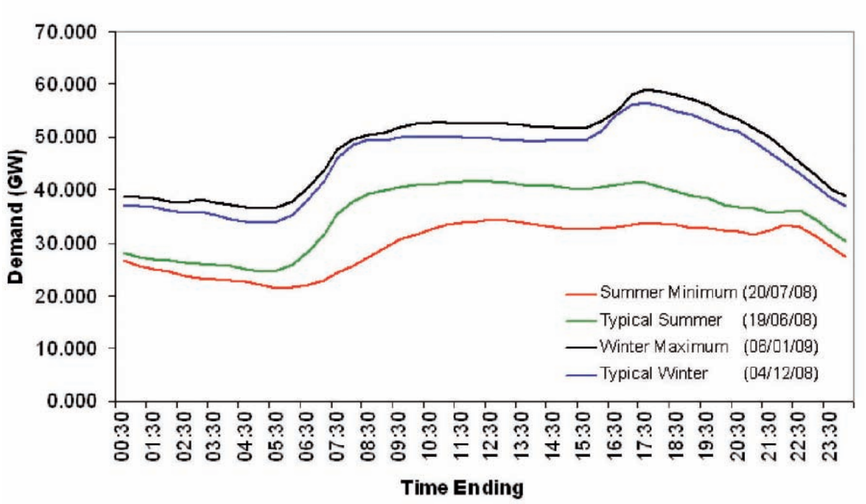

Figure 19 : Electricity demand on the UK grid

The maximum daily electricity demand is about 1000GWh. By comparison, 20 million EVs averaging 40km/day (equivalent to 15,000 km p.a.) and consuming 200Wh/km represents electricity use of 160GWh, an increase of 16% on the winter load in 2008/09. If the charging of the EVs were arranged to mirror the other loads on the network, they would fill the gap between 22:00 and 06:30 allowing 20 million vehicles to be charged with negligible additional generating capacity needed.

Unfortunately, this ideal is far from being practical. The previous chapter has discussed how en-route charging is likely to produce electrical demand during the day, rather than in the early hours of the morning. Participation in evening events (such as sports, shopping or theatre) would cause an early evening peak as drivers plugged in their cars ready for the return trip. Widespread adoption of 'at work' rather than 'at home' charging would further reduce the ability to tailor demand for capacity. And the daily charging load would be unlikely to be distributed evenly throughout the year, as implied by the above calculation. Travel patterns vary during the week and the season, with surges during holiday periods.

A more fundamental issue is that the National Grid report is based on an energy generation mix that is very different from what might be expected when EVs are the usual means of transport. Figure 20 shows the assumptions for 2006/07 through to 2012/13.[33]

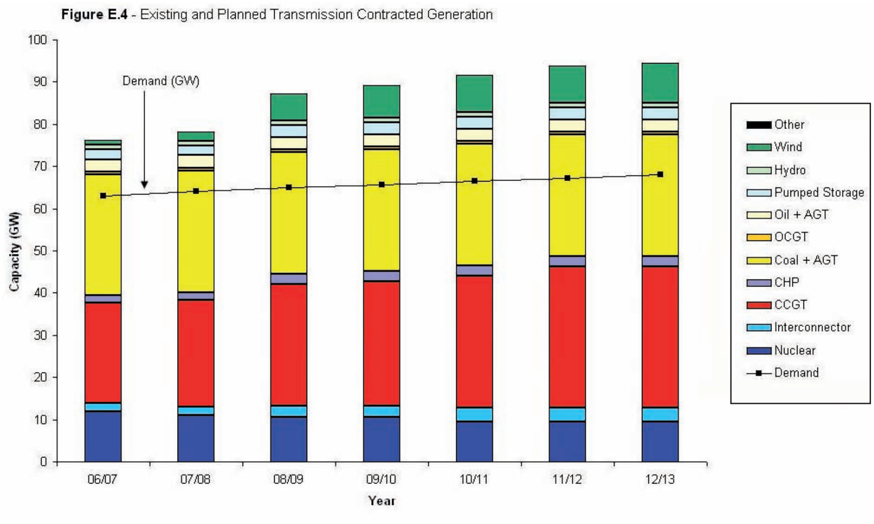

Figure 20 : Energy mix for generation

For this period, nuclear and combined-cycle gas turbine (CCGT) provide a base load with open cycle gas turbine and coal used for peak lopping. During the winter of 2009/10, when there was a prolonged anticyclone over Europe, coal and gas were used to provide the peak demand with wind often contributing less than 1% to the total supply.[34]

Overall, the contribution of low carbon sources such as renewables and nuclear to the UK's electricity mix is one of the lowest in Europe, as shown in Figure 21 below[35].

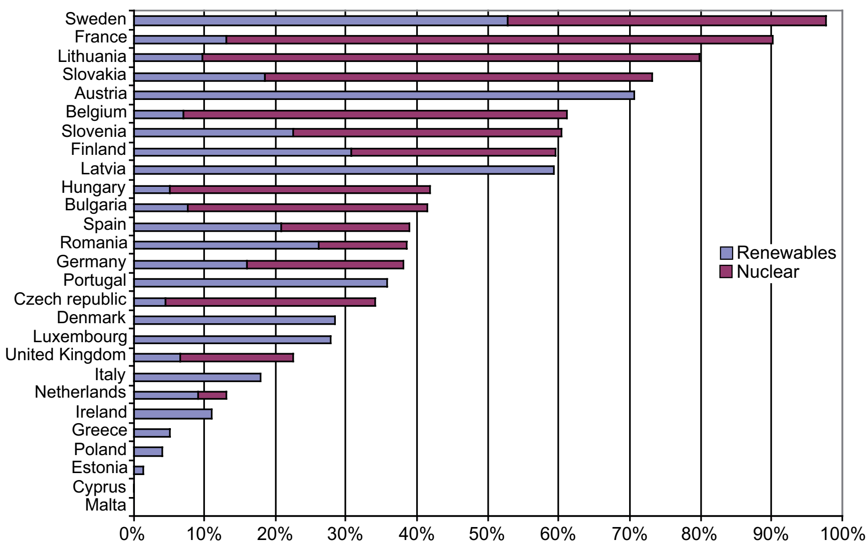

Figure 21 : Proportion of low carbon electricity in European countries

This demonstrates the fundamental issue is that the UK's current generator portfolio is far from carbon neutral. Figure 22, below[36] indicates the installed capacity of renewable generators in the UK in 2006 and the predictions for 2020. Given the UK's current total installed capacity of approximate 90 GW, this demonstrates the challenge discussed in section 5.4 above.

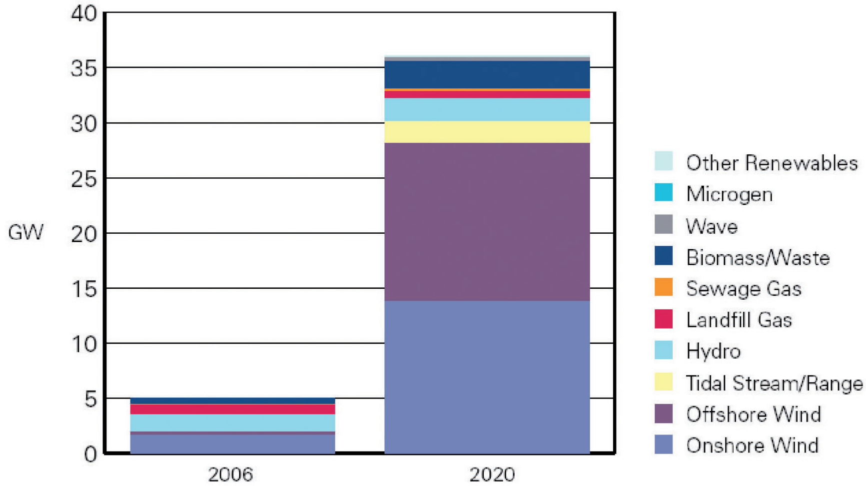

Figure 22 : UK renewable energy mix 2006 and 2020 (predicted)

It is clear that, if the UK is to meet its renewable energy targets, all possible sources will be needed: on-shore and off-shore wind, tidal barrages and tidal stream and photovoltaic energy are likely to find their way into the grid. These are not readily controllable – if the sun shines, PV systems will generate more electricity than when there is heavy cloud cover; wind turbines generate little during an anticyclone and the output of a Severn barrage would be determined by the phases of the moon, not the clock.

The challenge for those involved in supplying energy for a fleet of EVs is thus to match their varying demand to a fluctuating and unpredictable supply. In terms of annual energy consumption, the additional load caused by the mass take-up of EVs would be entirely manageable: in terms of peak power demand from the supply system, the picture would look very different. This is not determined entirely by technical factors: most of the peaks will be determined by how people use their electric cars and the patterns of charging they adopt. If EVs develop according to market development scenario 1, as luxury family cars with reserved off-street parking, the load is likely to be reasonably predictable and controllable; if they widely adopted, as in scenario 3, it will be much more difficult to manage demand to match the available generation.

10.2 The national transmission network

It is helpful to consider separately the 132/400kV grid and the local distribution networks in urban and rural areas, as they would be affected differently by a large number of EVs. The previous section showed that EVs might increase total power demand by about 16%. This is less than the likely increase that will be caused by the domestic sector switching from gas-fired central heating to electrically-powered heat pumps – likely to be necessary to reduce residential emissions by 80%. With or without EVs, the HV grid will need radical changes to cope with the planned increase in renewable generation and the different geographic location of supplies and loads. In addition, there may need to be some reinforcement specifically to cope with EVs, particularly under Scenario 3, but as they will be spread evenly across populated areas, the widespread use of EVs is unlikely to require major changes.

10.3 Local distribution networks

More serious problems arise with the local MV and LV distribution networks. If, under scenario 3, 'at destination' charging is widely adopted, there could be very large variable loads at car parks, shopping centres, sports venues and sites such as the National Exhibition Centre (29,000 parking places). Because of the short time vehicles will be parked, the opportunity for load spreading by a smart grid are likely to be limited and peak loads will necessitate electricity supplies at 11kV or above to quite modest shopping centre car parks.

Charging EVs at home will also produce heavy loads in residential areas. Current practice is to calculate a maximum load and then reduce this by an assumed diversity factor. This method predicts the maximum likely voltage drop, accounting for diversity. For sizing underground cables or naturally-ventilated distribution transformers, which have a thermal time constant of several hours, this method is satisfactory but some researchers[37] have suggested that it underestimates the variations that are likely to be seen in practice.

These variations are likely to be increased if EVs with high-capacity batteries are charged. As an example, Strathclyde University[38] has produced graphs showing the effect of charging a Tesla electric car on the electricity demand of a private house, assuming it is put on charge when the driver gets home from work at 18:00 hours. Figures 23 and 24 shows the assumed load at present and figure 25 the assumed load with the additional EV charging load.

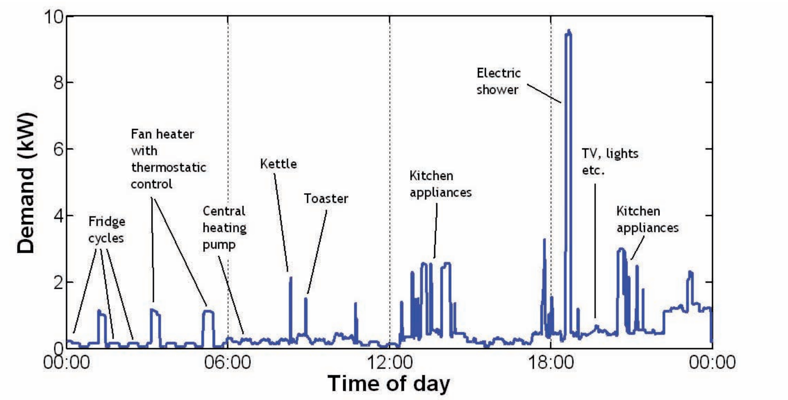

Figure 23 : Power demand (without EV)

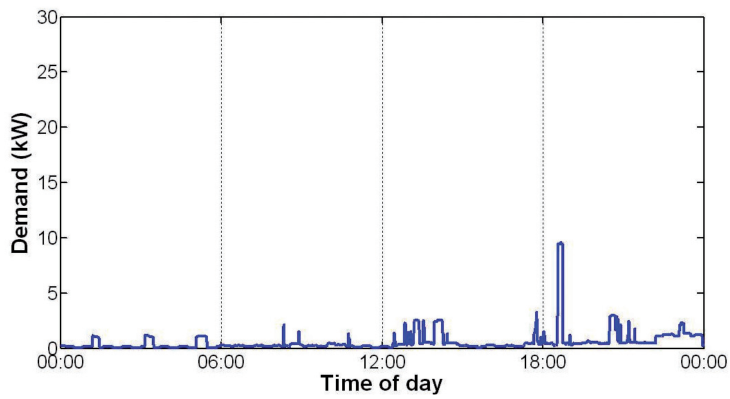

Figure 24 : Power demand (without EV) – rescaled to 30kW

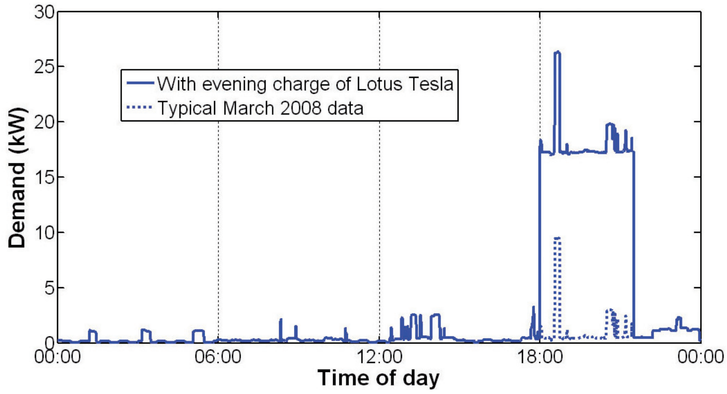

Figure 25 : Power demand (with EV) – scaled to 30kW

While a local system managing a battery charger to eliminate the short term peaks could be envisaged, it can be seen that the EV charging load swamps the general load in the home. This is obviously an extreme case as the Tesla is the electric car with the highest battery capacity being sold at present. But, in the future, it may not be out of the ordinary. If lithium sulphide batteries with an energy density of 500Wh/kg became widely adopted, it could be normal for an EV to have a 100kg battery capable of storing 50kWh, which would give the vehicle a range of 200km. To give users fast recharge times, the industry is already talking about chargers with an output of 50kW or more. Even under scenario 1, a small up-market housing development could host a dozen families with high-performance EVs, which would add more than 0.5MW to the demand on the local distribution transformer, potentially overloading local circuits as all EVs in the estate are put on to charge at the same time.

The above example demonstrates one of the problems that will need to be addressed by the designers of a smart grid that could tackle these issues. Apart from equalising the load on the generating capacity, it might also have to apply intelligent control to charging loads in a residential area. If the switch-on time for all battery chargers in a street were controlled by a regionally-generated price signal, determined by the availability of generation capacity, it is likely that they would switch on at much the same time so peak currents would be additive, leading to potential overload on the distribution network. Unless there were to be a wholesale upgrading of the local distribution system, the widespread adoption of EVs would require a smart grid that not only matched electricity use to generation but also managed charging loads in a street. These issues are discussed in the next chapter.

11 The 'smarter grid'

11.1 Why is a smarter grid important to EVs?

The widespread adoption of electric vehicles is an important step towards meeting the obligations of the 2008 Climate Change Act. However, previous sections have identified that an electric vehicle is only as "green" as the electricity that charges its battery. Following new regulations in 2005,[39] electricity generators are required to publish the CO_2 intensity of the electricity they generate (ignoring the emissions released in manufacturing the generating plant and the transmissions and distribution losses – typically 9%). The BIS website[40] presents a snapshot of the carbon intensity of different types of generation on a particular day (2 October 2009):

Energy Source	g/kWh
Coal	910
Natural Gas	360
Nuclear	0
Renewables	0
Other	610
Overall average	480

Table 3 : CO_2 intensity of different types of generation

An independent website[41] has used data released under these regulations to calculate the maximum and minimum emissions produced over the year 2009, shown below.

	Week	Weekend
Max g/kWh	607	584
Mean g/kWh	445	387
Min g/kWh	234	227

Table 4 : CO_2 intensity of UK generation 2009

It can be seen that EV users who charged their vehicles at the peak times during the week would be responsible for more than twice the CO_2 emissions than those who charged vehicles at the quieter time over the weekends. That would mean that a typical electric car with an energy use of 200Wh/km, if charged at peak weekday times with electricity of the above carbon intensity, creates emissions of 120g/km, no better than a petrol or diesel car.

With the commissioning of more renewable electricity generation, the difference between high and low carbon intensity will become even more marked, particularly if one looks at the incremental generation – that which would have to be brought on line to meet a new demand for energy. It is likely that there will be periods of several hours on most days when the whole electricity demand can be provided by nuclear or renewable energy; at the other extreme, there are likely to be times (such as in the morning and evening peaks during cold winter conditions) when the additional load provided by recharging EVs could only be met by coal-fired plant.

For EVs to achieve their potential contribution in reducing CO_2 emissions, it will be necessary to schedule their charging to match the availability of low-carbon electricity. The times when low-carbon electricity is available will vary – if the Severn barrage is built, carbon intensity of the supply could depend on the phases of the moon. As discussed in the previous section, it may also be necessary to control the charging of EVs in a street to avoid overloading the distribution network.

11.2 Smart meters and smarter grids

The terms 'smart meters' and 'smart grids' are often used interchangeably, which can be confusing. Although no legal definitions exist, the term 'smart meter' is usually reserved for a system that provides real-time information to consumers on energy use, enables supply contracts where consumers are charged different prices for electricity consumed at off-peak and peak times, allows remote meter reading and limited remote control (such as disconnection of the supply) and that can transmit price signals to consumers indicating when the cheaper tariff is available, thus allowing the cost-effective scheduling of non-time-critical loads. Although decisions have not been taken, it is likely that these functions could be carried out by a self-contained communications system that has no interfaces with the electrical distribution system other than in the meter itself.

The term 'smart grid' has been used for aspects of control of the extra high voltage (EHV) 'super grid' in the UK but, in the context of this report, refers to intelligence that might be embedded in the local electricity distribution network. This could be designed to share the available supply capacity between a number of high-power chargers connected in the same street, to control the generation of small-scale renewables, such as solar panels or micro-wind turbines or to control vehicle to grid (V2G) regeneration (see below) and to interface with smart meters.

11.3 UK plans for smart meters

In July 2009, the Government published the UK Low Carbon Transition Plan (LCTP), including a commitment that every home in the UK would be fitted with 'smart meters' by the end of 2020. Smart meters are seen as necessary for the proposed 'smarter grid', described by DECC in these terms:

> *Building a 'smarter grid' is an incremental process of applying information and communications technologies to the electricity system, enabling more dynamic 'real-time' flows of information on the network and greater interactivity between suppliers and consumers. These technologies help deliver electricity more efficiently and reliably from a more complex network of generation sources than it does today.*

The smart metering implementation programme is led jointly by DECC and OFGEM, and it has been described by DECC[42] as *"arguably the biggest energy industry change programme since the changeover to North Sea Gas, with ambitious policy goals, complex policy and operational issues for Government and Industry, links to other policy areas, a wide range of stakeholder interests, a range of risks to be managed, and the need to visit every home in the country, and affect the lives of millions"*. DECC forecast that 47 million smart meters must be installed by 2020.

At present, the priority of those managing the smart meter programme is to install meters with a limited functionality described above. The programme does not include developing a system architecture that allows for the real-time control of embedded generation or EV charging. How the system fits with the

widespread introduction of EVs and how it will eventually migrate towards a smarter grid is still undecided. Ofgem has launched a £500m Low Carbon Networks Fund to help industry address questions such as these by supporting research and pilot studies.[43]

11.4 Introducing smart meters

The introduction of smart meters represents a large-scale change programme with a major computing and telecommunications component. Smart meters contain computer systems and meeting the programme's objectives will require millions of meters to be read regularly. There are major challenges to be overcome before the programme can meet its objectives, not all of them specifically technical:

- **Security:** *"Smart Meters are computer-based systems utilising as yet undefined means of remote access. As such these systems are potentially vulnerable to attacks including the propagation of viruses and mal-ware and the possibility of user generated attacks into the metering infrastructure."*[44] Such attacks have already been implemented and demonstrated for one model of smart meter.[45] Hacking into a smart meter could reduce a consumer's electricity bill by hundreds of pounds per year, so there is an important incentive for this type of illegal activity.
- **Privacy:** a Privacy Impact Assessment by the US Department of Commerce concluded that *"distributed energy resources and smart meters will reveal information about residential consumers and activities within the house. Roaming Smart Grid devices, such as electric vehicles recharging at a friend's house, could create additional personal information.*[46]
- **Safety:** a smart meter may have the capability of disconnecting supplies to the premises or to specific (smart) equipment. This introduces additional hazards, as some equipment may have safety implications if it is turned off – or on – without the owner's knowledge and control (for example, heating and cooling systems in extreme weather conditions, medical systems or cooking equipment).

11.5 A smarter grid

Implementing a smarter grid that interfaces with EV chargers and renewable generation and is integrated with an existing smart meter infrastructure will be a major feat of project engineering and management as it will bring together power generation and distribution companies, IT companies, local authorities and car park operators with the manufacturers of cars, battery chargers, renewable generation a wide range of white goods and domestic heating and air-conditioning systems.

The DECC definition of a smarter grid, quoted above, makes the assumption that smart meters installed over the next decade will be compatible with a future smarter grid. Unless the systems architecture of the future smart grid is determined in parallel with defining the functionality of the meters, this is far from certain: some of the issues are discussed in subsequent paragraphs.

The widespread adoption of EVs controlled by a smarter grid also introduces new commercial issues into the energy market. Most debates on the smarter grid assume that electricity-consumers' commercial relationships will continue to be with competing private-sector electricity retailers (part of the justification for smart metering was to make it easier for consumers to switch suppliers). However, as discussed earlier, it is likely that many EV battery charging loads will have to be controlled to limit currents in the final 415V distribution circuit, rather than by price signals emanating from a national electricity reseller or the grid control centre. It is not clear how a competitive retail market would work if a distribution company (by necessity, a local monopoly) has control of the times when EV charging may take place.

11.6 EVs as embedded generation?

The problems of charging and possibly discharging of EVs on a distribution network has many similarities with those of embedded generation, where small scale electricity generators are connected to the distribution system locally rather than directly to the grid as a large central generator would be. The connection of small-scale generation into a distribution network designed for the one-way power flows from central power stations consumers will require a rethink of protection systems. Within a building, there are few problems. The electrical standards for electrical equipment of buildings[47] specify that solar panels (and, by implication, other sources of generation) should feed into the supply "upstream" of the final circuit fuses. This means that there is no possibility of the renewable generation feeding potentially hazardous voltages into a nominally "dead" electrical system.

At present, the amount of energy generated by solar panels, wind turbines and other renewables in residential areas is well below the local electrical load. If the 415V in the street is lost as a result of a blown fuse at the 11kV/415V substation, the rest of the connected load acts as a short circuit on the line, which reduces the voltage to a level where the inverters connecting solar panels to the grid would stop operating and everything would shut down.[48]

The situation could be rather different in an estate of new houses, each fitted with several square metres of solar panel. At certain times of the day, the houses might be net generators of electricity and, if there are any induction machines on the network, such as for air-conditioning units, CHP boilers or heat pumps, one could envisage a self-sustaining power system, even if the 11kV/415V substation were off line. This would be a potentially hazardous situation as the inverters would not be able to detect the loss of grid connection and there would be no effective protection on the 415V network, which could run at an indeterminate frequency and voltage. If embedded generation becomes widespread, it would be possible to envisage a substantial area becoming an electrical 'island' operating independently from the main 50Hz grid.

The control of this sort of situation would be quite new for distribution companies. A traditional way of dealing with it would be to run a pilot wire to all houses with renewable generation, interlocked with the substation so that, in the event of it tripping, the embedded generation in all the houses could be isolated so the 415V lines in the street would be dead. An alternative might be to send a message through a smart grid instructing the renewable generation to disconnect from the mains supply. An even more radical approach would be to use the smart grid to modulate the power being provided to maintain frequency and phase synchronised with the rest of the UK grid. If the smarter grid were to used in these ways, it would become part of the electrical protection system, so a much faster response time and a greater level of system integrity would be required that if it merely performed a commercial function. At present, this issue is not included in Ofgem's brief to enable smart meters and there appears little likelihood of a smart grid with this level of functionality in the next 20 years.

The idea of using a distributed fleet of EVs as "hot standby" for renewable energy supplies has been proposed by David Mackay, Chief Scientific Adviser to DECC.[49]

The concept has been given the acronym V2G (vehicle to grid). In the event of a major reduction in the supply (for example caused by the failure of the cable from an offshore array of wind turbines) the smarter grid would send a message to all EVs on charge in a particular region asking that the chargers be 'put into reverse' taking energy from the battery to support the grid. Conceptually, it is a brilliant idea: practically, by the time one analyses possible effects on the 415V protection system and thus the necessary safety integrity level (SIL) of the software, the commercial implications on battery life and other aspects, the true challenge becomes clear. If the smarter grid is to fulfil all these demands, as well as allowing EV users to have international 'roaming' contracts with a supplier, it will need to be a very different creation to that envisaged by the businesses leading the introduction of smart meters.

11.7 Systems Engineering

A recent paper produced by the IET[50] stresses that, in the development of the smarter grid, "a Systems Engineering approach is needed. The silo based activity which has been conducted up to now - regarding this as the application of an ICT solution to an energy business problem - will not deliver the flexible systems approach needed for the future. What is needed is a complete collaboration of Power and ICT engineering expertise to design the intelligent grid that will be essential for energy security in the coming decades."

One of the first actions of a systems engineer is to attempt to 'nail down' the specification of what the 'system' is intended to do. To date, it is not clear what functionality of the smarter grid is envisaged: the overall architecture is up in the air; there is no lead player and the relationship of the multitude of players is ambiguous. However key components – smart meters and the associated communications network – will be committed well before the functionality of the ultimate smart grid is agreed. A project could hardly be launched in a less propitious manner.

12 A strategy for the electrification of road transport

12.1 The scenarios

In section 4, we identified three scenarios under which EVs might be introduced:

- **Scenario 1: Competition**
  Small numbers of up-market vehicles with extended range, mainly charged at home or at work.
- **Scenario 2: Complementarity**
  EVs adopted as second cars in 2-car households used for short urban trips.
- **Scenario 3: Substitution**
  Fully fledged EV system seen as smarter, quicker and more reliable that gradually replaces ICE vehicles.

Already two of these scenarios are being followed by commercial organisations. The Tesla Roadster Sport is in the first of these categories. It has a top speed limited to 125 mph, can accelerate from 0 to 60 mph in 3.7 seconds, has a 230 mile range and sells for $130,000. At the other end of the scale, publicity for the Tata Indica EV talks about a day involving the school run, a trip to the gym, taking children to football and city shopping, putting it firmly in Scenario 2.

Neither of these scenarios would result in the switch to EVs that would be achieve the CO_2 reductions necessary. That would require greater penetration of the family car and company car markets which, in turn, would require either PHEVs or the infrastructure for recharging away from home, to permit longer trips than can be achieved using an affordable battery.

12.2 Battery capacity

Previous sections have identified some of the factors that influence the choice of battery capacity. No feasible EV battery and recharging system would give a car the flexibility to run 1,000km between refuelling stops and refuel in five minutes from a low-capital cost infrastructure, which is what drivers obtain from their petrol or diesel cars today.

Figure 26 shows some of the trade-offs that have to be considered when considering battery capacity. The situation has been simplified with two alternative battery types – one high capacity (50kWh or more) and the other low capacity (20kWh or less) but, in reality, there would be many more shades of grey.

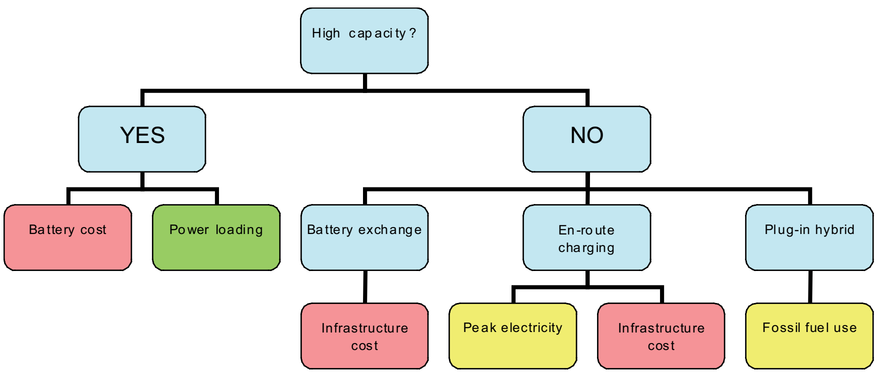

Figure 26 : Choice of battery capacity

If a high capacity battery is selected, the cost would be significantly higher and the impact on the local electricity distribution network would be greater. There would be knock-on effects in that the higher-capacity battery would be larger and heavier, so the car would have to be heavier and would use more energy. The higher charging load might require a reinforced power supply to the owner's house and, if many people in a street adopted similar technology, the cables in the road would have to be upgraded.

If low-capacity batteries became the norm, the range of EVs would be reduced but there are three possible ways in which this could be mitigated: either battery exchange stations could be introduced or there could be an intensive network of on-street charging points or a high proportion of EVs would be sold as plug-in hybrid electric vehicles with small internal combustion engines acting as range extenders.

Battery exchange stations would be much more expensive than conventional petrol stations. They would take up more space, they would have to stock a wide range of battery types and they would need a high-power electricity supply. They would appear far more like a workshop than a retail outlet. Although one can envisage a number of battery exchange stations stocking a wide range of battery types on a corridor like London to Brighton, it is more difficult to imagine a similar level of infrastructure investment on a road like that between Fort William and the Kyle of Lochalsh where the lower volumes of traffic would not justify the capital investment needed in such exchange stations.

The implications of *en-route* or at *destinatio*n battery charging have been discussed in sections 8 and 9. For EVs to be acceptable as family or company cars, there would need to be widespread investment in charging points, for example in company car parks, at entertainment venues or in shopping centres, as well as at motorway rest areas, restaurant car parks and other places where cars could be recharged during a long trip. Charging at such destinations would carry the disadvantage that the load on the grid could not be timed to match the availability of low-carbon electricity and might be provided by open-cycle, peak-lopping gas turbines, with obvious implications on CO_2 emissions.

PHEVs have the benefit that they do not need an extensive network of charging stations for them to achieve acceptance by the mass market. Although PHEVs use diesel or petrol as an energy source, they may not be less "green" than a vehicle using *at destination* charging. Figure 14 shows that, using a 20kWh battery, 80% of daily mileage could be electrically powered. If that is provided at night by renewable energy, the overall emissions could be less than an EV with a similar size battery that is regularly recharged during the day "to be on the safe side".

12.3 Barriers to EV use

There are strategic benefits in encouraging commuter cars or the second car in two-car households to be electric. It would result in a small benefit to emissions, improve the environment in city centres and kick-start the provision of a charging infrastructure. However that would not lead to a situation which achieves the CO_2 reduction necessary and there are barriers to the widespread use of EVs as commuter or second cars. One could be the lack of charging facilities at home or at work. Current planning policies often limit the number of off-street parking places and, in many rented properties, installing charging sockets could be complicated.

Converting the mainstream car market to electric propulsion would necessitate the establishment of a national recharging infrastructure and there is the familiar 'chicken and egg' situation – there is no financial incentive to install charging points until there is a large fleet of EVs waiting to be charged but no-one will buy EVs until there are charging points available.

The PHEV conveniently sidesteps this barrier. If charging points exist, they could be used, if none are available, the car can run on liquid fuel. If most family or company cars were to be PHEVs, businesses and local authorities would be able, over time, to introduce charging points that would be self-financing. Gradually a charging infrastructure would become established that would allow EVs to take over from PHEVs for more and more applications.

13 Resourcing the dream

Earlier sections of this report have discussed various engineering developments, such as wiring the streets to accommodate on-street charging, decarbonising the electricity supply with renewable energy and nuclear power, renewing the HV grid, reinforcing the local distribution networks, introducing a smarter grid and implementing road user pricing to replace fuel tax. Providing the human resources needed by these various programmes will be a major challenge. In particular, the supply of engineering professionals is unlikely to keep up with the need, unless there is a new urgency to the education and training of engineers and technicians.

If these were the only major engineering projects in Britain over the next 30 years, the challenge of providing the human and financial resources would be difficult, but manageable. However, the country is also faced with the need to replace or reinforce much of the water supply, flood protection and drainage infrastructure. There is a major programme of rail electrification, new lines in London and the possibility of new high-speed lines. To meet the CO_2 emission targets from buildings there will have to be a huge programme to replace gas boilers by heat pumps, which can only add to the challenge of decarbonising the electricity supply. The armed forces have major re-equipment contracts and thousands of people are involved in the clean-up of the nuclear legacy. On top of these, several government departments have large IT projects, all of which will absorb both qualified personnel and finance.

Climate scientists have argued that, to have any hope of maintaining the level of CO_2 in the atmosphere to 550 ppm, emissions must peak in the next 10 years and then start to reduce. This means that there is no possibility of delay. Over the past two years, Britain has seen the deepest recession for several generations. Finance, whether for private or publically funded projects, is likely to be in short supply over the critical period. This report is not the place to analyse the conflicting demands all these projects but it is unlikely that the implementation of the EV dream could be fully funded by private capital. It will require significant public investment and new forms of regulation.

14 The international dimension

Motor manufacture is a global business and at present the UK is a niche player concentrating on components such as engines. Of the two million new cars sold in the UK each year, all but a small minority were imported from mainland Europe or the Far East. No mass manufacturers are headquartered in the UK and the luxury brands thought of as quintessentially British are all owned by overseas companies. The motor industry is an international market regulated largely by international rules and complying to international standards.

Each year six million[51] British motorists take their cars to mainland Europe or Ireland and, at any one time, there may be 140,000[52] overseas-registered vehicles in use in the UK.

The IET report (op cit) notes that the ICT industry has learned that universal - generally meaning worldwide - standards are vital for the interfaces between communicating devices or modules. This applies particularly to smart grids, and especially to those that reach into a user environment. These now involve not just the external communications discussed above but the communications between the smart meter and domestic equipment, meaning computers and smartphones[53] for consumer analysis and also home networks and consumer equipment that may in future be remotely adjusted to enable load balancing in the local network and, of course, electric cars. This requires that the smart meter be able to communicate reliably with such equipment, which might be manufactured anywhere. It is also desirable that smart meter and smart grid infrastructure is freely procurable on the international market. Hence the need for standard communications technologies and standardised control interfaces, and for standard means of ensuring security.

The widespread introduction of EVs would require an unprecedented degree of international coordination. At its most basic, this would include the international harmonisation of safety standards and the standardisation of charging connectors. Beyond this there would be a need for interoperability of smart cards – possibly with the equivalent of roaming contracts. If fast-charging or battery exchange facilities are anticipated, the level of international technical and commercial coordination would have to increase yet again. And, if fuel duties were no longer levied, European governments would need to decide how to recoup the costs of their road network both from residents and from international visitors.

15 Conclusions and recommendations

This study has shown that EVs could provide a major contribution to meeting the target of an 80% reduction in greenhouse gas emissions by 2050. A positive factor that came to light in preparing this report is the readiness of the motor industry to switch to EVs and the effort that is going in to designing and testing prototypes. Developing a range of EVs and changing the support infrastructure in garages and service stations is within the capabilities of industry and they have started work.

But EVs will be built in mass-production numbers only when there is a sustainable social and business model for their use, allowing manufacturers to plan for a long-term market and when they have a carbon efficiency benefit over and above the latest internal combustion technology. To date, those conditions are many years into the future in the UK and sustained Government support will be needed. There are solutions to allow EVs and plug-in hybrids to take over the majority of the present applications of petrol and diesel vehicles but these are unlikely to develop without encouragement and financial incentives from policy makers.

EVs are not a direct 'transparent' replacement for petrol and diesel cars. Their introduction would change how people use personal transport and they would be likely to be part of a raft of new technologies and ways of working – greater communication between infrastructure and vehicles, auto-drive systems, hybrids, hydrogen storage, new liquid fuels, road pricing, teleconferencing as well as mainstream acceptance of shared vehicle use as a solution to personal mobility. Apart from new social models for personal transport, the introduction of large numbers of EVs would be likely to go hand-in-hand with new ownership models, whether by short-term vehicle leasing, "power by the hour" contracts for batteries or other arrangements is not clear but is unlikely to follow the ownership model of the last half century.

Devising a suitable charging infrastructure to allow widespread adoption of the technology, including on-street and off-street charging and the necessary 'smart' control infrastructure is going to be challenging. This is particularly so as it will bring together companies, local governments, NGOs and regulators from sectors that, to date, have not been involved in transport or energy. There is evidence that the present efforts to define the requirements of 'smart grids' and 'smart meters' are faltering because they have not taken a co-ordinated systems engineering approach that takes into account all energy users and providers. Without an efficient and optimised smart grid, there will be only a poor environmental case for the development of EVs.

There have been transport modal shifts in the past that were implemented by the private sector – the canal network, the railways, development of motor vehicles, low-cost airlines. In each case, entrepreneurs became involved because they hoped to make a quick return on investment. The development of EVs in our complex 21st century societies is not something that could be implemented by private investors alone. At the very least, national and local government action and money would be required to kick-start the enabling infrastructure necessary for EVs to develop.

An alternative model to the widespread adoption of EVs with their infrastructure requirement would be the plug-in hybrid electric vehicle (PHEV). While this type of vehicle has most of the environmental benefits of an EV, it does not rely on a comprehensive network of recharging points at possible destinations. This means that it could be adopted quickly as a family car or executive car, leaving EVs to achieve initial market penetration as second cars, covering low mileages and thus having little impact on CO_2 emissions.

Plug-in hybrids, as their name suggests, still need some where to plug in. The 'early adopters' could be to users with off-street parking but, to meet the 80% target, a solution would have to be found for the millions of motorists who park on-street at nights.

Recommendations

Electric vehicles and plug-in hybrid electric vehicles stand at a crossroads in terms of becoming viable, mass market options for the UK to radically reduce CO_2 emissions from transport. Technical development is proceeding, driven by an industry that sees their potential as the future of personal transport. However, their success will rely on a number of infrastructural improvements and early agreement on standards and protocols. Development of the technologies ahead of these decisions could reduce public acceptance of EVs if different charging solutions are being offered and ultimately require increased future investment in infrastructure to accommodate multiple standards.

1. Government needs to outline its long-term policy direction for EVs in order to provide the right incentives for early adopters as well as providing a stable policy environment for the EV market to develop over time. This policy needs to extend into strategies for the timely investment in the required infrastructure, the ownership of that infrastructure and the timescales over which it must be implemented so as not to delay the development of EVs and PHEVs as mass market solutions. Government also needs to map out intentions for the funding of road networks in the medium term as tax revenues from conventional road fuels reduces.

2. The introduction of electric vehicles on a large scale can only have a beneficial effect on CO_2 emissions if low carbon energy, universal broadband provision and smart grids can be delivered. There is an opportunity to integrate these policy areas and adopt a fully systems-based approach to ensure that that all work together and the critical links between them are explicitly recognised.

3. The automotive industry, with the support of other interested parties, including UK and European governments, must proactively develop international standards for charging EVs and billing protocols.

4. The Government, Ofgem and the UK electricity industry must develop protocols to integrate the long term needs of EV charging into current plans to roll out smart meters and smart grid technologies country wide. Not doing so will risk either stifling growth in the EV market or being faced with early obsolescence of the first generation of domestic smart meters.

5. Further research and development of EV batteries, energy management systems and fast charging is needed to maintain and increase the carbon advantage that EVs currently enjoy and to reduce costs of the battery and EV drive train relative to internal combustion engine vehicles. This needs to be achieved in parallel with continued decarbonisation of the UK electricity system.

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This uses the following definitions:

Reserves. – *That part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials; thus, terms such as "extractable reserves" and "recoverable reserves" are redundant and are not a part of this classification system.*

Reserve Base. – *That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the inplace demonstrated (measured plus indicated) resource from which reserves are estimated. It may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base* *includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently subeconomic (subeconomic resources). The term "geologic reserve" has been applied by others generally to the reserve-base category, but it also may include the inferred-reserve-base category; it is not a part of this classification system.*

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Appendix A – Steering committee

The following people were members of the steering committee responsible for this report:

Professor Roger Kemp FREng, Lancaster University (Chair)
Professor Phil Blythe, Newcastle University
Dr Chris Brace, Bath University
Pete James, Prodrive
Richard Parry-Jones FREng, RPJ Consulting
Davy Thielens, KEMA Consulting
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Supported by

Richard Płoszek, Senior Policy Advisor, The Royal Academy of Engineering
Jenny Roberts, Project Researcher, Sprocket Design Consultancy

Appendix B – Submissions from the call for evidence

The following organisations are thanked for their substantial input into this study:

The Energy Institute
The Institute of Engineering and Technology
The Institution of Chemical Engineers
The Institution of Civil Engineers
The Institution of Mechanical Engineers
The Royal Academy of Engineering

Cambridge University
Imperial College London
Strathclyde University

Ford Powertrain Engineering
BMW
Lotus Engineering
Modec
TATA Motors
Scottish & Southern Energy
Arthur D Little
The Department for Transport
Pitchill Consulting
Mott MacDonald
Ofgem

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