Electric Vehicles: A Synthesis of the Current Literature with a Focus on Economic and Environmental Viability

Technical Paper

Authors:

Mr. Marcello Contestabile[1]

Dr Gregory Offer[2]

Dr Robin North[3]

Reviewers:

Mr Mark Akhurst [4]

Dr. Jeremy Woods[5]

June 2012

[1] Research Associate at Imperial College London
[2] EPSRC Career Acceleration Fellow at Imperial College London
[3] Lecturer in Transport and Environmental Planning, at Imperial College London
[4] Honorary Research Fellow at Imperial College London
[5] Senior Lecturer at Imperial College London

Executive summary

LCAworks has carried out a study to evaluate the technological progress and economic viability of electric vehicles (EVs) as an alternative to conventional internal combustion engine vehicles (ICEVs) using traditional fuels (including blends with biofuels). The study assesses the feasibility and cost effectiveness of EVs, to enable decarbonisation of road transportation, taking into account, where possible: lifecycle greenhouse gas (GHG) emissions and the potential of EVs to be deployed at scale, including pure battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).

Based on the evidence we have reviewed, we conclude that the future level of uptake of EVs will depend heavily on progress in battery technology, to bring down costs and increase energy density, and on the provision of a suitable recharging infrastructure. Currently, and for the foreseeable future, BEVs will be characterised by higher purchase price and lower utility than ICEVs, which will affect their future market uptake unless breakthroughs in battery technology occur. We have explored a number of EV uptake scenarios based on the economic and technical evidence. From these, we conclude that the role of BEVs in the passenger car market is likely to be limited to smaller vehicle segments such as mini and super-mini, whereas in larger vehicle segments ICE PHEVs running on biofuels or hydrogen fuel cell PHEVs might be more suitable.

Based on the literature we have reviewed, it appears that EVs have the *potential* to deliver significant GHG emission savings in road transport in a cost-effective way, particularly after 2030, provided that a number of measures are successfully implemented to: drive down GHG emissions associated with battery manufacture and disposal (including recycling of raw materials); significantly reduce the GHG intensity of grid electricity; and target recharging to times of day which will maximise utilisation of low GHG generating capacity (smart charging). Although EVs have higher GHG emissions associated with their manufacture and disposal than ICEVs, in future, given the conditions described above, this should be more than compensated by the lower in-use well-to-wheel (WtW) emissions. However, more work is needed in the area of life cycle assessment (LCA) of EVs, in particular, more accurately to assess GHGs associated with manufacture and disposal, and compare these with the manufacture and disposal emissions of ICEVs, which currently do not feature in most ICEV LCAs published in the literature and are not a part of EU government targets for vehicle GHG emissions. Also, currently, the GHGs associated with provision of recharging infrastructure and end of life disposal do not appear to be included in most LCA studies. In addition, other environmental impacts of battery manufacture, use and disposal, such as acidification, ozone depletion, photochemical smog and eutrophication will be important and need to be addressed fully. In the current study we do not address these impacts directly, although the level of GHG emissions associated with any given product is often a useful proxy for other environmental impacts.

The evidence we have reviewed strongly suggests that, even if the development of battery technology matches the optimistic scenarios described in the literature, EVs are unlikely to ever provide a complete solution to road transport decarbonisation. In fact, due to the very nature of batteries, pure BEVs are likely only to be competitive on a cost and performance basis in smaller vehicle segments such as mini and super-mini. As an additional decarbonisation option for road transport, biofuels will therefore have an important role to play in the larger vehicles segments, possibly used in ICE PHEVs with different degrees of electrification dictated by the size of the vehicle, its intended use and the cost and performance of the batteries. Even in the case of breakthroughs in battery technology, the degree of electrification of PHEVs will still be significantly limited by diminishing returns as the battery size increases, to the extent that future PHEVs will probably use biofuels for 60-80% of their total mileage. Based on this level of electricity utilisation by PHEVs, our analysis shows that, per kWh of battery deployment, PHEVs have a slightly greater potential to reduce GHG emissions than BEVs.

In conclusion, biofuels and batteries are likely to be complementary rather than competing technologies in the timescale to 2030 – 2050. In terms of decarbonisation potential, it appears likely that biofuels contribution (and therefore its share of the passenger car market) will be limited by constraints in the supply of sustainable biofuels rather than by the competition with electricity, at least well beyond 2030 if not beyond 2050 as well.

Synthesis of recent relevant literature on battery electric vehicles.

1. Aim and scope of work

The aim of the study is to provide a synthesis of the most recent, most relevant literature relating to the technological progress and economic viability of electric vehicles (EVs) as an alternative to conventional internal combustion engine vehicles using traditional fuels (including blends with biofuels).

The study assesses the feasibility of EVs to enable decarbonisation of road transportation, taking into account, where possible, lifecycle greenhouse gas emissions and the potential of EVs to be deployed at scale. The study also addresses the cost effectiveness of EVs as a decarbonisation option for road transport. Types of EVs considered in the study are pure battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).

2. Synthesis of literature on BEVs and PHEVs

A synthesis of the most recent, most relevant literature on BEVs and PHEVs is provided in this section. The key themes of battery technology, recharging infrastructure, comparison with internal combustion engine vehicles (ICEVs) and biofuels, market potential and lifecycle greenhouse gas (GHG) emissions of BEVs and PHEVs are discussed in turn in the sub-sections below. Key conclusions are then drawn based on the literature reviewed; these are presented in the concluding Section 3.

2.1. Battery technology

Li-ion batteries are the technology of choice for all new BEV and PHEV models currently being commercialised. This is because of their high gravimetric energy and power densities compared to other battery chemistries, thus allowing EVs to achieve acceptable ranges without imposing an unacceptable weight penalty on the vehicle. Therefore, in this section we discuss the fundamental characteristics of Li-ion batteries, the current state of this technology and future expected developments, also including possible alternatives to Li-ion chemistries. The discussion is based on key review papers that can be found in the peer-reviewed scientific literature [1-3]. Current and projected cost and performance of Li-ion batteries are then briefly discussed, mainly based on the IEA technology roadmap for electric and plug-in hybrid vehicles [4] and on a report by Element Energy for the Committee on Climate Change which has just been released [5].

The first Li-ion batteries were commercialised by Sony in 1991, and rapidly established themselves as the standard for portable electronics [2]. These were based on a carbon anode, a $LiCoO_2$ cathode and an organic solvent containing a Li salt as electrolyte [6]. Despite many new Li-ion battery concepts such as the plastic battery [7] and advances in nano-materials [1], the composition of commercial Li-ion cells for the portable electronics market has not deviated much from the original Sony battery [2]. However, the conventional $C/LiCoO_2$ chemistry is not considered adequate for EV use mainly due to safety concerns [2], and therefore new anode and cathode materials are now being used in commercial Li-ion batteries for EVs in order to improve safety, reduce costs and/or achieve higher power density. Examples of new materials are the $LiFePO_4$ cathode and the $Li_4Ti_5O_{12}$ anode [2]. Meanwhile, research is focusing on advanced materials that can significantly improve the energy density of Li-ion batteries by increasing the specific capacity, such as composites and alloys, or the operating voltage, such as high voltage cathodes. Significant challenges remain though and, even if successfully developed, these materials are not expected to be used in commercial EV batteries before 2020 [5].

New chemistries, such as Li-sulphur (Li-S) and Li-air which could deliver step-change improvements in performance, particularly energy density, are also being developed. Neither is new, but recent advances in materials science, nano-materials in particular, mean the main barriers that have so far prevented these systems from being used practically are now somewhat closer to being overcome. Encouraging results have recently been obtained in the lab for Li-S batteries in particular, whereas the Li-air batteries appear more uncertain [3]. It is impossible to predict with confidence if and when these batteries will become commercially available for use on EVs; however, it is reasonable to assume that Li-air batteries will not be available at scale before 2030 [5]. Therefore, until then, BEVs and PHEVs may have to rely solely on advances in Li-ion batteries to improve their performance.

Non-lithium chemistries are also being researched which may, if successful, offer favourable characteristics compared to Li-ion cells. These include magnesium/sulphur and aluminium/graphite fluoride. However, the practical viability of these systems remains to be demonstrated and their future use in EVs depends on the occurrence of major breakthroughs [1]. Metal air chemistries such as Na/air and Zn/air are also being considered as possible alternatives to Li/air. Na/air batteries in particular have the potential to mitigate some of the problems of Li/air technology but significant breakthroughs are still needed before this technology may be considered for practical applications [8].

Current costs per kWh of Li-ion batteries vary depending upon chemistry, size and power density. However, the typical cost of cells for BEVs manufactured at scale is currently in the order of 400 $/kWh [5]. Cells for PHEVs are reported to cost 1.3 to 1.5 times as much, due to the need to achieve higher power density [4]. However, battery systems for EVs also include electronics and thermal management components, which increase the cost of the battery system by a factor 2 compared to the cells alone, giving a total system cost today, including cell, electronics and thermal management, of $800/kWh. The cost of EV batteries is expected to decrease substantially if advanced Li-ion systems are successfully developed, with Li-S and Li-air systems potentially yielding further savings thanks to the high energy density and relatively low cost of the materials involved [5].

Below is a summary of anticipated developments in batteries for BEVs, based on [5].

Year practical use on EVs	Now	2020	2020-2030	2030+
Battery chemistry	Current Li-ion chemistries (e.g.: C/$LiFePO_4$)	Advanced Li-ion with high-capacity electrodes/ high-voltage cathodes	Li-S	Li-air
Practical energy density (Wh/kg)	100-180	300	300-800	700-1,000
System cost ($/kWh)	≈800	≈400	<400	≈240

To put these figures in context, the energy density of petrol is in the order of 12,000 Wh/kg.

2.1.1 Cycle life and shelf life of batteries

It is important to note that the studies cited in the following Sections 2.3, 2.4 and 2.5 and analysing the techno-economic, market and GHG emission reduction potential of EVs all assume that batteries will last as long as the vehicle itself. If batteries had to be replaced during the lifetime of the vehicle, not only would this result in higher GHG emissions, owing to the manufacturing of the replacement batteries, but most importantly it would significantly affect the economics of EVs and hence drastically reduce their market potential; for more on this see [9], where a discussion of the second hand market for EVs is also provided. It is therefore reasonable to expect that EV batteries will have to meet minimum performance requirements in terms of cycle life and shelf life, such as those set by the US Advanced Battery Consortium. Based on the fact that some OEMs are currently leasing the batteries of the EVs they sell, it appears that there is uncertainty as to whether conventional Li-ion batteries today are already able to meet these requirements. However, this very much depends on how the cells are managed, and understanding degradation and failure of the current generation of commercially available cells is a very active research area, so it is expected that as the electric vehicle industry matures this uncertainty will almost certainly reduce.

As for advanced lithium battery chemistries, much of the ongoing research actually focuses on improving cycle life, which so far has proved unsatisfactory, especially for Li-S and even more so for Li-air systems [3]. In the remainder of the study we will therefore assume that batteries will have met the minimum requirements in terms of cycle life and shelf life and we will not consider scenarios where this is not the case, as these will almost invariably result in little or no market uptake of EVs.

2.1.2 Manufacturing emissions of batteries

The primary literature on lifecycle assessment (LCA) for batteries is very limited and the field should be considered as work in progress [10-15]. Although comprehensive, the report by ARUP commissioned by the DfT and BERR in 2008 [10] did not present in sufficient detail the raw data or underlying assumptions used to calculate the manufacturing emissions of a typical battery; hence the study is not discussed further here. As for the other studies reviewed, there is little consistency between approaches and this makes it difficult to compare them meaningfully. Considerable effort must be made to normalise various assumptions, and in some cases infer implicit assumptions and then try to convert the information into a common metric for comparison. In addition, only greenhouse gas equivalent (GHG) emissions are used in all studies, and only occasionally are other impacts such as acidification, ozone depletion, photochemical smog and eutrophication considered [15]. A significant spread in the values for GHG emissions from the manufacturing of Li-ion batteries has been found depending upon battery chemistry, manufacturing process, and the boundary conditions and assumptions of the lifecycle analysis itself. Only Li-ion batteries with either a mixed metal (nickel & cobalt) oxide (NCM) or iron phosphate (LFP) cathode are discussed here, and results have been normalised to include the emissions only from manufacturing and not from losses during use (which are more accurately included in the in-use vehicle lifecycle studies). Results from the primary literature shown in the table below are normalised per kWh of battery capacity.

Tonnes CO_2/kWh	[11]	[14] based upon GREET 1.7 [16]	[12]	[13] based upon GREET 1.7 [16]	[15]
NCM	0.07	0.12	0.20	0.29	
LFP	0.11-0.23		0.24		0.34-0.44
Comments	Cells only; variability due to manufacturing methods and materials	Cells only; based upon Saft Li-ion VL50E cell and production in the US	Battery system; European electricity mix	Battery system; some untested assumptions; US electricity mix applied to manufacturing in China	Battery system; EU electricity mix; most comprehensive of studies, particularly assembly phase

Based on the approximate midpoint of these results, for a battery manufacturing GHG emission of 0.2 tonnes CO_2/kWh, and for current technology, with a BEV of 100 miles range, requiring a 30 kWh battery (based on the current Nissan Leaf and the consensus of many studies indicating 0.2 kWh/km), we can see that the battery manufacturing emissions alone would amount to 6 tonnes of CO_2 per vehicle. For a vehicle with a 150,000 km lifetime, this would equate to approximately 40gCO_2/km. It is therefore clear that based on the studies cited above, the CO_2 emissions resulting from the manufacture of the battery are very significant, although scope exists, primarily through materials recycling (see below) to reduce this by 50%, to less than 20 gCO_2/km.

For PHEVs, the optimum battery size appears to be 5 – 10 kWh (see Figure 1). Based on 0.2 tonnes CO_2/kWh for battery manufacturing GHG emissions, the PHEV battery manufacturing emissions would therefore be 1 – 2 tonnes CO_2, equivalent to 6.5 – 13 g/km over a 150,000 km vehicle life, but this may be reduced to below 0.5 – 1.0 tonnesCO2/kWh in future, primarily through material recycling.

In conclusion, the high sensitivity of the environmental impacts of battery production to particular manufacturing processes and to the energy mix prevalent in the geographic location of production, coupled with the limited number of studies available, means that it is not possible at this stage to say with any confidence what the range of environmental impacts of battery production are. It is likely that battery manufacturers would have a better idea, but this information is not readily available. However, considering the link between energy use, emissions and cost, it is probably fair to assume that as costs are driven down, less energy intensive materials and processes will be favoured by the market, and as energy supplies are decarbonised, the emissions associated with battery manufacturing should also decrease accordingly.

2.1.3 Recycling and lithium availability

A case study of a NCM battery production chain [17] concluded that recycling of batteries reduced resource consumption by over 50%, not just by decreasing mineral ore dependency but also reducing energy consumption. The study only considered the recycling of nickel and cobalt, and not manganese or lithium, which are typically not currently recovered, and therefore further reductions were possible. Another study [18] commented that current recycling revenues are driven by cobalt recovery, and therefore chemistries which use cheaper starting materials may be recycled less, and therefore may require strong legislation.

Recycling is also important to mitigate concerns over the availability of the key materials required. Significant controversy has emerged recently over concerns that there will not be enough lithium to meet future demand driven by electric vehicles. A forthcoming UKERC working paper [19], which reviewed the recent literature on lithium availability and production estimates, concluded that if the market for these technologies grows as substantially as suggested by the IEA Blue Map scenario then lithium production would have to grow by up to 2900% by 2050 relative to 2011. However, although challenging, there was no evidence to suggest that lithium production could become a bottleneck, even ignoring recycling, until at least 2050. Identified lithium resources, including seawater, are substantial, although it is unclear what price will make more diffuse resources and lithium recycling viable [19].

In conclusion, recycling could be important in terms of minimising the lifecycle impact of plug-in vehicles, but price alone may not prove a strong enough driver and hence regulation may be required. Lithium availability appears to be a red herring, as with current prices resources appear to be healthy compared to projected demand, and lithium is one of the cheaper components of most batteries.

2.2 Battery recharging infrastructure

Aside from suitable batteries, the other main pre-requisite for the large scale adoption of BEVs is the availability of an extensive battery recharging infrastructure. Despite its importance, to date there is limited peer-reviewed scientific literature specifically assessing the techno-economics of battery recharging infrastructure [20]. However, we have identified a number of recent reports, commissioned by governments, industry or NGOs. Based on their findings, in this section we briefly discuss the following topics in turn: techno-economics of battery recharging infrastructure, the impact of the uptake of BEVs and PHEVs on the electricity grid, the well-to-wheel CO_2 emissions of BEVs and PHEVs relative to ICEVs as a function of the GHG intensity of grid electricity, and finally the potential for BEVs and PHEVs to provide grid balancing services (“vehicle to grid” – V2G). As far as we could find there is no primary literature or reports discussing the GHG emissions associated with the provision of battery recharging infrastructure, although this would have to be considered when comparing lifecycle emissions of BEVs and PHEVs with those from ICEVs using gasoline and/or biofuels. To facilitate this, the lifecycle GHG emissions associated with the provision and renewal of the conventional gasoline/diesel refuelling infrastructure would also need to be established. To date, there is very little peer reviewed literature on this topic.

2.2.1 Capital costs of recharging point

The capital costs of recharging points are relatively well defined and there is general agreement in the reports we have reviewed [21-27], despite the fact that they don’t use a consistent nomenclature to indicate the different types of charging points. Costs range from £0.5-1k for an open access 3kW facility, suitable for private parking spaces, to £2.5-9k for restricted access, up to £50-100k for a 60kW “fast” charging point [27]; clustering could reduce costs, as 50% of costs are associated with installation. The lifetime of charging points is generally thought to be in the order of that of the vehicle. Hence, the total cost of the recharging infrastructure per vehicle can be estimated from the average number and type of charging points required and their respective utilisation rates. It is however on this point that the studies reviewed diverge quite significantly. [21] for example assumes that BEVs will mostly be adopted by users that have access to a private parking space. However [24] assumes that BEVs will also be adopted by users who mainly park in public places; hence the infrastructure cost per car they arrive at is significantly higher. On top of this we have to add the cost of secondary charging points, the need for which will vary based on several factors, such as the driving patterns of the BEV users in the area considered; fast charging in particular may stimulate demand for BEVs by easing range anxiety, however their economics is very uncertain and likely to significantly drive up overall infrastructure costs [20]. It is likely that PHEVs will result in lower infrastructure costs than BEVs due to fewer secondary charging points being required. In conclusion, estimating the typical cost of battery charging infrastructure per vehicle is somewhat arbitrary, but this can vary between £ 1k and £ 6-7k depending on the assumptions made. Finally, an alternative to battery charging could be battery swapping, as in the business model proposed by Better Place, but the capital cost involved would be significantly higher than the figures reported here for battery charging infrastructure [28], hence in the present study we do not discuss this option any further.

2.2.2 Impacts on electricity supply and the grid

The impact that high levels of penetration of BEVs and PHEVs may have on the electricity grid and the potential need for grid reinforcement must also be considered. Since there is broad agreement between the studies addressing this aspect, for simplicity here we only refer to [27]. The study finds that the impact of high levels of penetration of BEVs and PHEVs on the electricity grid would mainly be on the low voltage (LV) distribution grid, and would depend on the technical characteristics of the particular LV grid considered, as well as on the timing, location and rate of battery recharging required. In particular, the main technical constraint to the uptake of BEVs and PHEVs from the point of view of LV distribution networks would be the possible thermal overload of transformers, particularly in heavily loaded urban or sub-urban networks. The total cost of replacing a typical distribution transformer is in the order of £20-30k; assuming that around 30% of the distribution transformers on the UK grid required upgrading, the total cost would be in the order of £2.6-3.9bn. However, demand-side management measures shifting battery charging to off-peak times have the potential to significantly reduce the need for grid reinforcement and the costs associated with it. Effective demand-side management would require the roll-out of smart metering systems and variable electricity tariffs [10, 27].

High levels of penetration of BEVs and PHEVs may require additional generation capacity to be installed. Similarly to the case of grid reinforcement, the extent to which additional capacity is required will significantly depend on the time of day when recharging occurs. If battery recharging occurs mainly at peak times, such as around 6pm when people come home from work, then an increase in power generation capacity will be required. The additional demand could be in the order of 1 to 8% of the UK's national electricity production in 2030 [10]. If however battery recharging can be controlled to occur at times of low demand (e.g. at night) when there is surplus capacity, then the need for increasing the total power generation installed capacity becomes minimal; moreover, this could also increase the utilisation factor of existing low-GHG power generation assets such as nuclear plants and wind farms, thus improving their economics [10].

The timing of recharging of BEV and PHEV batteries has very important implications also on the well-to-wheel (WtW) CO_2 emissions of these vehicles. If recharging occurs at times of low electricity demand, it is possible that the marginal generator will be low or zero carbon (e.g.: coal with CCS or even excess wind power). If however recharging occurs at peak times, then the marginal generator is more likely to be high carbon (e.g.: open-cycle gas turbine). [27] estimates that if in 2030 the average GHG intensity of grid electricity has reduced to 140 gCO_2/kWh, then the WtW emissions of a BEV would range between 30-80 gCO_2/km, depending whether the time of battery recharging is effectively managed or not. However, considering that by 2030 the fleet average tailpipe emissions for ICEVs will probably have been reduced below 100 gCO_2/km, the WtW CO_2 savings associated with high levels of penetration of BEVs and PHEVs will only be realised if smart charging occurs. The savings could be relatively modest though if BEVs are at least partly recharged using high carbon marginal electricity and ICEVs use advanced biofuels instead of fossil fuels, although as natural gas and wind powered generation replaced legacy generating capacity the likelihood of high carbon electricity in the charging mix will lessen. It should be pointed out that these figures are indicative only of [27]. Besides, WtW analysis does not address all GHG emissions associated with the manufacture of the vehicles and supporting infrastructures, which would also need to be considered in order to compare EVs and ICEVs on an equivalent basis. Here, the issues of battery manufacture and recycling discussed in Section 2.1 are relevant and this issue is further discussed in Section 2.5.

Finally, it has often been argued that BEVs and PHEVs could provide significant benefits to the electricity system, in the form of vehicle-to-grid (V2G) services. In particular, the total amount of energy stored in the batteries of large fleets of BEV and PHEV would be such that it could potentially satisfy the UK's total demand for electricity for a few hours [27], and in the case of a PHEV the engine could even be considered as back-up generating capacity. However, the usable energy storage capacity is rather difficult to estimate with confidence, and the impact on battery lifetime and warranty is unknown. Therefore using EV batteries to provide grid frequency and voltage regulation services may be a more realistic starting proposition. In all cases, though, harnessing this potential largely relies on the development of smart grids, which raises questions as to if and when this option will become practically feasible.

2.3 Techno-economic comparison between BEVs and ICEVs running on biofuels

A number of recent, high-profile studies have compared from a techno-economic and environmental point of view BEVs and PHEVs with ICEVs, conventional and advanced and/or running on biofuels, and other options such as hydrogen fuel cell vehicles (FCVs) [21, 29-31]. For a concise critical review of these studies see also [32]. In addition, a comparative study has been carried out by Element Energy for the LowCVP [9] which is not included in [32] and which is widely cited, at least in the UK; this study is referred to as appropriate in this section.

These studies have generated a tremendous amount of knowledge, however they also differ in scope, data used and methods; hence their results are not directly comparable. Despite these differences, though, a high-level story emerges when the studies are considered in a chronological order. In particular, it appears that many assume there is a 30% maximum potential for increasing the efficiency of conventional ICEVs, by means of turbocharging and downsizing the ICE, hybridising the powertrain and reducing the vehicle's energy consumption by using lightweight materials and other energy-saving technologies. These improvements, though important in the short to medium term, will not be sufficient to achieve the ultimate policy goals set for road transport. Hence, all studies agree that BEVs, PHEVs, biofuels and FCVs all potentially have a role to play. The studies however do not agree on exactly what role each one of these technologies should play. In general though it is suggested that the use of PHEVs in the long run may be constrained by the availability of sustainable biofuels, hence BEVs and FCVs would also have to play a role. [21, 30] also suggest that in the long run (i.e. after 2030) the total cost of ownership (TCO) of all these three options will converge; the analysis leading to this finding is mostly based on a typical vehicle, with a typical usage pattern, and assumes that all technologies considered are successfully developed (which also involves breakthroughs in battery technology; see Section 2.1).

[32] points at key limitations of the studies above and presents additional analysis aimed at addressing these limitations. In particular, with the sole exception of the complexity of the passenger car market, characterised as it is by many different segments, is not accounted for. The paper demonstrates analytically that, if different segments are considered, then differences in TCO across different technologies start to emerge even when these are fully developed, and that the role of batteries is likely to be more significant in smaller vehicles driven over shorter distances and on lower energy drive cycles (see Figure 1 below). In particular, only if batteries become extremely inexpensive (i.e. 100 $/kWh for the battery system) could BEVs achieve a significant penetration of the medium to large segments of the passenger cars market; this is consistent with the findings in

[9]. Instead, PHEVs running on biofuels or petrol would be cost-competitive even with higher battery costs (i.e. 250 $/kWh), and a PHEV with a downsized engine could be an even cheaper option. However, it is clear from Figure 1 that, above a certain size, PHEV batteries show diminishing returns; hence PHEVs with relatively small batteries (4-14kWh) show minimum TCO. This result is also broadly in line with [9], which however only considers a 10% penetration of biofuels in liquid fuels by 2030, hence arguably underestimates their role.

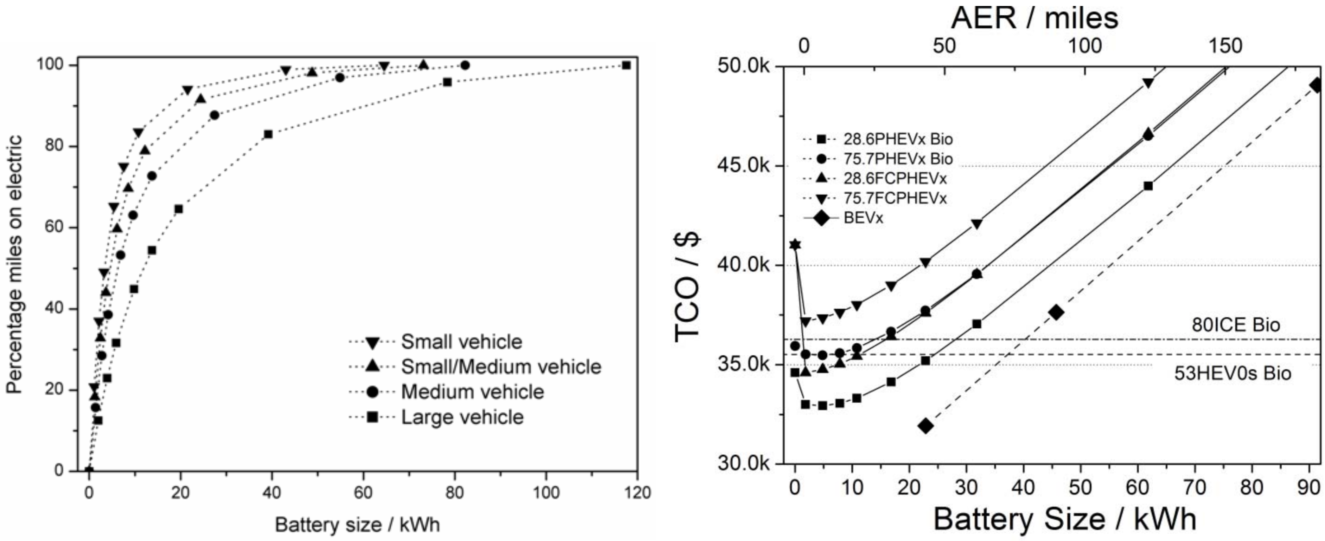

Figure 1: The diagram on the left shows the percentage of electric only operation as a function of battery size for PHEVs of different segments based upon average UK behaviour. The diagram on the right shows the total cost of ownership (TCO) of different powertrain types, as a function of battery size, for a passenger car in the executive segment. The numeric prefix indicates the nominal power of the ICE or FC in kW; the suffix bio stands for biofuel (E100). Sources: [33] and [32]

Additionally it is important to note that cost is only one of the limiting factors for batteries, and that volumetric and gravimetric energy densities are also important. [34] for example clearly demonstrates that, beyond a certain size, batteries become impractical because the additional weight they introduce requires the vehicle chassis to be strengthened, which further increases the vehicle's weight and decreases its energy efficiency, thus requiring even larger batteries, which leads to a vicious circle.

It can therefore be concluded, based on the economic and technical evidence above, that in a future, sustainable road transport system the role of BEVs in the passenger car market could be limited to smaller vehicle segments such as mini and super-mini, whereas in larger vehicle segments ICE PHEVs running on biofuels or hydrogen fuel cell PHEVs might be more suitable. Moreover, batteries and biofuels should not be seen as antagonistic options, because they can coexist well in PHEVs, with different degrees of electrification dictated by the size of the vehicle, its intended use and the cost and performance of the batteries. For example, from Figure 1, we can infer that, for a passenger car in the executive segment, a PHEV running on biofuels has minimum TCO with a battery size of 5-10kWh, which would allow roughly 20-40% of the total lifetime miles to be driven on electricity, whereas the remaining 60-80% would be driven on blends of fossil and biofuels.

It must also be mentioned that the comparative analysis in [32] is based on the TCO metric which, although insightful, does not reflect the criteria on which car users base their adoption decisions today [9]. In fact there is general agreement in the literature that capital cost is the single most important economic parameter in adoption decisions, while possible fuel cost savings are heavily discounted by the potential adopters. This clearly puts BEVs and PHEVs at a disadvantage over conventional ICEVs. The implications of this on adoption of BEVs are further discussed in the following section.

Finally, there is increasing concern about material scarcity, especially metals and rare earths, and the impact this may have on the cost of EVs. In Section 2.1.3 we have already discussed the issue of lithium availability for batteries. The UKERC working paper previously cited [19] has also assessed the case of neodymium, a key material in permanent magnets for electric motors, showing that meeting future demand may be challenging but could be done by increasing both production and recycling rates. The paper however also highlights significant uncertainties and the need for further research on future availability of this as well as other critical materials for EVs.

2.4 Future market uptake of EVs

BEVs and, to an extent, PHEVs have different attributes compared to conventional ICEVs and this raises questions as regards the extent of their future market uptake. In particular, BEVs are zero emission vehicles at point of use and evidence suggests that potential early adopters are prepared to pay a premium, albeit small, for this attribute [27]. However, BEVs are also characterised by higher purchase price and lower utility than ICEVs, which will affect their future market uptake unless breakthroughs in battery technology occur. Due to the fact that new generation BEVs and PHEVs equipped with Li-ion batteries have only recently been commercialised, inferring future market shares of these vehicles based on available market data is not possible. In the absence of this data, surveys of potential adopters based on choice experiments have been performed which have shed some light on their response to EVs [35], but much uncertainty remains and nothing conclusive can be said on adopters' willingness to pay a premium for EVs and willingness to accept reduced utility, other than both are likely to be limited. Instead, several uptake scenarios for BEVs and PHEVs have been developed by consultancies and research institutes, based either on key supply/demand constraints or on GHG emission reduction targets. These scenarios implicitly assume that adoption is not significantly affected by reduced utility, as a result of both positive response of passenger car users to EVs and breakthroughs in battery technology.

A particularly relevant example is a report by McKinsey [36], which considers three uptake scenarios for BEVs and PHEVs based on different possible development paths for the automotive industry: the "Optimised ICE" scenario where ICE manufacturers improve the emissions and fuel efficiency of these vehicles, and they maintain a dominant share of the market (99% in 2030); a "Mixed Technology" scenario, where all vehicle technologies improve over time and increase their market share, with ICEs maintaining a 58% share in 2030; and a "Hybrid and Electric" scenario, described as relatively aggressive, with hybrid and electric vehicles rapidly gaining market share (29% in 2030). In the latter group, of particular importance is the Blue Map scenario developed by the IEA (see Figure 2) and used as a basis for various key reports [4, 30, 37]. Unlike the McKinsey scenarios, the Blue Map scenario of the IEA is driven by the IPCC's 2050 GHG emission reduction targets, effectively modelling demand based upon what is necessary rather than on vehicle supply, and is slightly more aggressive than even the most optimistic of the McKinsey scenarios. The IEA considers this scenario challenging but feasible, provided breakthroughs in battery technology occur following the trajectory indicated in Section 2.1 and strong government support is available in form of targeted policies and coordination activities [4]. The relevance of the Blue Map scenario to the development of the market for BEVs and PHEVs is confirmed by the fact that it is in line with the targets set by various key national governments for the uptake of these vehicles technologies [4].

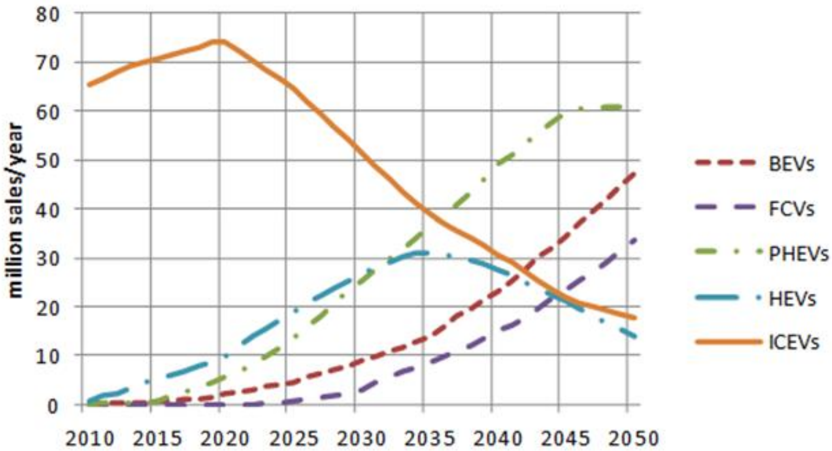

Figure 2: Illustration of IEA Blue Map scenario. Source: adapted from [30].

However, the challenging nature of the scenario is also clear, based on the fact that current BEV and PHEV production ramp-up plans of major automotive OEMs fall significantly short of the national targets previously mentioned (about 1.4 million units per year by 2020, as opposed to the 7 million of the national targets) [4]. Hence, government support would be needed in order to rapidly develop extensive battery recharging infrastructures and further stimulate demand for BEVs and PHEVs by providing prospective adopters with adequate incentives. Moreover, as the literature on adoption of alternatively fuelled vehicles (AFVs) shows, achieving widespread adoption of new technology such as BEVs and PHEVs requires policy support to be both targeted and strong enough, and also sustained for long enough to overcome key barriers and tipping points, falling short of which leads to market stagnation or collapse [38, 39].

In conclusion, it is reasonable to say that the IEA Blue Map scenario can be regarded as a best case scenario for the future adoption of BEVs and PHEVs. Achieving it requires that all the necessary conditions occur for a rapid uptake of BEVs and PHEVs to take place. At the other extreme, no significant uptake of BEVs and PHEVs until 2050 is also rather unlikely, due to the presence of strong drivers behind electrification of road transport. So, any scenario in between these two extremes could be regarded as possible, with the "Mixed Technology" scenario by McKinsey a potentially plausible one. A summary of these scenarios to 2030 is provided below.

		Global vehicle sales (millions per year) – 2015 to 2030		
		2015	2020	2030
IEA Blue map scenario	PHEVs	0.7	4.9	24.6
	BEVs	0.3	2.0	8.7
McKinsey "Mixed Technology" scenario	PHEVs	-	5	16
	BEVs	-	1	3

2.5 Lifecycle GHG emissions and cost effectiveness of EVs as a decarbonisation option

Analysis of lifecycle GHG emissions of EVs in the peer-reviewed scientific literature is rather incomplete and affected by significant uncertainty. Life Cycle Inventories (LCI) databases exist, some of which are in the public domain, but issues remain concerning both consistency of the data and standardisation of the LCA method for EVs. Overcoming these issues will require, *inter alia*, strong support from automotive OEMs and suppliers. Despite all these limitations, a high-level assessment performed by Ricardo Plc. for the LowCVP [40] provides useful indications on GHG emissions associated with the manufacture and disposal of EVs. An overview of the state of the art of LCA of EVs is provided below, followed by brief discussions of issues with current regulation on GHG emissions from vehicles and of the cost effectiveness of EVs as an option for road transport decarbonisation.

In published life cycle assessment (LCA) studies, well to wheel (WtW) emissions refer to the actual emissions resulting from the manufacture of the fuel and its use in the vehicle. The WtW emissions are broken down into well-to-tank (WTT) and tank-to-wheels (TTW) emissions. In the case of conventional ICEVs, the majority of the WtW emissions (80 – 90%) occur in the TTW part of the chain, during the combustion of the fuel in the vehicle. However, for EVs, all the actual emissions occur in the WTT phase due to generation of the electricity, since the vehicle (TTW phase) is zero emission. Most published work on vehicle WtW emissions refers to ICEVs, using a range of different fuels including: gasoline, diesel, compressed natural gas, liquefied petroleum gas, and hydrogen (which can also be used in a fuel cell). Most of these studies does not include any of the emissions associated with manufacture and disposal of the vehicles themselves, nor the infrastructure needed for fuel manufacture, distribution and marketing. In addition, the relevant European Directive (EC 443/2009) applies only to WtW emissions and takes no account of GHG emissions associated with vehicle and infrastructure manufacture and disposal. This approach is based on the assumptions that: these "embedded" emissions are small in comparison with the WtW emissions, and that they are broadly similar for any vehicle of a given size (43). However, for BEVs, (and to a lesser extent for PHEVs) these assumptions do not hold true, and so GHG emissions associated with manufacture and disposal of the batteries should be included in WtW studies, because it is so much more significant than the vehicle manufacturing and infrastructure emissions of ICEVs. In some cases, studies refer to the emissions associated with vehicle manufacture and provision of infrastructure as "embedded" emissions; however, in this study we maintain reference to "vehicle manufacturing and infrastructure emissions" for clarity.

The tank-to-wheel (TtW) or in-use phase has been extensively studied [5, 10, 13, 14, 21, 30-34, 41] but uncertainty remains: pure BEVs have zero TtW emissions but their energy efficiency is somewhat influenced by the weight of the battery [34]; PHEVs present the additional complexity that TtW GHG emissions are ultimately determined by their utility factor (i.e.: the fraction of the mileage driven on electricity) which, as we have seen from Figure 1, is a function of battery size, vehicle segment and driving patterns [33]. As for well-to-tank (WtT) GHG emissions, in EVs these largely depend on the GHG intensity of the electricity used. As we have seen in Section 2.2.2, this varies greatly depending on whether the time of battery charging is or is not managed. In the latter case, using the average grid GHG intensity based on official figures as is generally the case is likely to lead to significant underestimation of the actual WtW GHG intensity of the electricity emissions of EVs [42]; improving on this assumption however requires rather complex analysis.

As for GHG emissions associated with the manufacture and disposal of vehicles and infrastructure, there is significant uncertainty with respect to battery manufacturing, as we have seen in Section 2.1.1, and additional complexity arises from the fact that battery materials will change as the technology evolves. However, based on the figures provided in Section 2.1.1 and assuming a BEV emitting an average of 30gCO_2eq/km WtW (hence using very low GHG electricity), the GHG emissions from manufacturing a 30kWh battery would be in same order of magnitude as the total WtW emissions over a lifetime of 150,000km. This is in good agreement with the results of the study by Ricardo Plc; although based on a number of assumptions, the study clearly indicates that BEVs and PHEVs can achieve lower lifecycle GHG emissions than ICEVs, thanks to the smaller contribution of in-use WtW emissions to total GHG emissions; however due to the additional GHG emissions associated with manufacture and disposal of components such as batteries, electric motors and power electronics, the GHG emissions associated with the manufacture and disposal of an EV powertrain would be somewhat higher than those of an ICE powertrain. Hence, as both electricity and liquid fuels are gradually decarbonised, GHG emissions associated with manufacture and disposal of powertrains become more important and should be taken into account. No estimates of GHG emissions associated with the provision of battery charging infrastructure were found in the literature, although these should also be accounted for; the materials used are known, but the main uncertainty relates to the number and type of charging points required per vehicle; as seen in Section 2.2.1 the cost of the infrastructure can vary up to a factor of 7 depending on its configuration, so it is reasonable to assume that associated GHG emissions will show a similar range of variability. Finally, end-of-life and recycling GHG emissions of BEVs and PHEVs are poorly understood and need attention, as also pointed out in [40].

In summary, by 2030, fleet average tailpipe emissions for ICE vehicles will have reduced to well below 100 gCO_2/km, with lower emissions for smaller vehicles such as mini and super mini (the relevant EC directive (443/2009) mandates a fleet average of 95gCO_2/km to be achieved by 2020. Already in 2012 there are 12 ICEVs with GHG emissions below 100gCO_2/km and biofuels are not considered within these figures, so actual emission are likely to be even lower for these vehicles. In the period 2020 – 2030 a number of advanced biofuels are likely to be commercialised. Emissions savings performance of biofuels in this period should greatly exceed the emissions savings performance and sustainability of current biofuels. Thus, as vehicle emission standards continue to push down emissions and more advanced biofuels are blended with transport fuels in greater quantities, the actual well-to-wheel GHG emissions of mini and super-mini vehicles by 2030 is likely to be significantly below 100gCO_2/km. The impact of increased amounts of biofuels in fuel blends is likely to reduce this further. For mini and super mini BEVs, by 2030, with smart charging, WtW emissions could be as low as 30 gCO_2/km, and GHGs associated with battery manufacture and disposal could be as low as 20 gCO_2/km, assuming extensive recycling of raw materials (see section 2.1.1), giving an overall GHG emission of 50 gCO_2/km for BEVs, excluding other vehicle manufacturing emissions (which are also excluded from the ICE WtW figure of <100 gCO_2/km), and emissions associated with the provision of charging infrastructure.

Summary of GHG emissions for ICEVs and BEVs

By 2030 (g/km)	ICEV	BEV
Well-to-Wheel emissions	<100 and <<100 for mini and super mini and lower due to biofuels	as low as 30
GHG emissions associated with battery manufacture and disposal	0	as low as 20
Lifecycle GHG emissions (excluding vehicle manufacture and disposal, infrastructure)	<100 and << 100 for mini/super-mini with biofuels	as low as 50

This analysis suggests that BEVs could therefore offer a GHG saving of up to 50%, however this is likely to be eroded by a combination of: mini and super mini ICEVs having lower GHG emissions than the 100gCO_2/km fleet average; biofuels reducing the effective fleet average emissions; GHG emissions associated with the provision of EV recharging infrastructure being excluded, and also end-of-life and disposal emissions being excluded altogether from the analysis.

For PHEVs, the analysis in section 2.3 (Figure 1) suggests that battery sizes between 5 – 10 kWh would be most effective (in terms of TCO) and would offer the potential to allow 20 – 40% of total lifetime miles to be driven on electricity. Our analysis in section 2.1.1 suggests this would entail 1 – 2 tonnes CO_2 emissions per vehicle relating to the battery manufacture. With extensive material recycling, this could be reduced to 0.5 – 1.0 tonnes per vehicle. For a PHEV driving 20 – 40% of its lifetime miles on electricity, equating to 30,000 – 60,000 km, then GHG emissions associated with battery manufacture and disposal would represent 17 gCO_2/km for the fraction of driving using electricity. In addition, WtW emissions of 30 gCO_2/km (relating mainly to the generation of the electricity), would result in overall emissions of 47 gCO_2/km, which is very significantly lower than the projected fleet average GHG emission in 2030 of 100 gCO_2/km, for the 20 – 40% of driving using electricity as the fuel and slightly lower than the emissions from BEVs as described above.

Despite the clear importance of GHG emissions associated with the manufacture and disposal of vehicles (including powertrains and batteries) and infrastructure, these are currently not addressed by the main EC directives on GHG emissions from road vehicles and fuels. Directive 443/2009 mandating fleet average CO_2 emission targets only addresses tailpipe or TtW emissions, which is relatively satisfactory for today's ICEVs running on conventional fuels but not for future electrified powertrains including BEVs and PHEVs. Fuel cycle or WtT CO_2 emissions of conventional fuels and biofuels are covered by the Renewable Energy (28/2009) and Fuel Quality (30/2009) directives, whereas decarbonisation of electricity is addressed by the EU Emissions Trading Scheme (29/2009). Harmonising this regulation in order to create a level playing field for low-GHG vehicles and fuels is part of the strategy of the EC, as stated in the 2011 Transport White Paper. However, for GHG emissions associated with vehicle manufacture and infrastructure to be included in the relevant EC directives, more work is required in standardising the LCA method and input data, including LCIs and vehicle usage assumptions.

As for the potential of EVs to offer a cost-effective option for decarbonising road transport, this largely depends on the GHG content of the electricity used relative to liquid fuels. We have already seen in Section 2.3 that BEVs can be competitive with ICEVs on a TCO basis in the smaller vehicle segments, and that PHEVs can successfully compete in larger vehicle segments. So if the electricity they use emits less GHGs on a WtW basis than the liquid fuels considered, then BEVs and PHEVs become a cost-effective means of reducing GHG emissions from road transport. As for the effect of GHG emissions from vehicle and infrastructure manufacture, despite it will certainly not be negligible, once accounted for it should not change the picture entirely either. This is because electric powertrains and particularly batteries not only have higher GHG emissions associated with vehicle (and battery) manufacture than ICE powertrains, but they also have higher capital costs; therefore electric powertrains are only cost competitive on a TCO basis if a high utilisation can be guaranteed [32, 41], in which case the impact of the higher GHG emissions associated with battery manufacture and disposal over the lifecycle of the vehicles reduces relative to that of WtW emissions. A similar argument can be made for GHG emissions associated with the provision of the recharging infrastructure, given that this too can become rather expensive if its level of utilisation is low. Therefore, increased utilisation needs to accrue over time from real competitiveness of the EVs with ICEVs and not rely solely on subsidies; otherwise GHG emissions will not be reduced. Subsidies may be necessary in the early years to help establish and support the initial roll out of the EV technology but must be tapered down in the medium to longer term.

3. Conclusions and Recommendations for Further Study

Based on the literature we have reviewed, it appears that EVs have the potential to deliver significant GHG emission savings in road transport in a cost-effective way, particularly after 2030. EVs have higher GHG emissions associated with the manufacture and disposal of the vehicle (mainly the battery) than ICEVs, which however should be more than compensated by the lower in-use WtW emissions; but more work is still needed in the area of LCA of EVs. The deployment of EVs at scale however crucially relies on breakthroughs to be achieved in battery technology, without which EVs could remain a niche technology. Moreover, an extensive battery charging infrastructure and smart grids that allow managing demand as appropriate are important enablers for EVs, the development of which may somewhat delay their uptake although it should not prove a limiting factor in the long term.

It is clear though that, even if the development of battery technology matches the optimistic scenario previously outlined, EVs will never provide a complete solution to road transport decarbonisation. In fact, due to the very nature of batteries, pure BEVs will probably only be competitive on a cost and performance basis in smaller vehicle segments such as mini and super-mini. Biofuels will therefore have an important role to play in the larger vehicles segments, possibly used in ICE PHEVs with different degrees of electrification dictated by the size of the vehicle, its intended use and the cost and performance of the batteries. And even in the case of breakthroughs in battery technology, the degree of electrification of PHEVs will still be significantly limited by diminishing returns as the battery size increases, to the extent that future PHEVs will probably use biofuels for 60-80% of their total mileage. In conclusion, biofuels and batteries should be seen as complementary rather than competing technologies. It is also likely that the biofuels share of the passenger car market will be limited by constraints in the supply of sustainable biofuels rather than by the competition with electricity, at least well beyond 2030 if not beyond 2050 as well.

Throughout the report, we have highlighted several areas of significant uncertainty, and a number of data gaps, which together combine to limit the certainty with which we can forecast the most likely outcomes in terms of EV uptake and impacts. These uncertainties include:

- Assessment of lifecycle GHG emissions of EVs in the peer-reviewed scientific literature is rather incomplete and affected by significant uncertainty.
- There is significant uncertainty with respect to the GHG emission and other environmental impacts of battery manufacturing
- GHG and other environmental impacts of providing battery charging infrastructure is unknown, and there is little work published on the GHG and other impacts of building and renewing existing infrastructure for conventional (gasoline/diesel) refuelling

- For ICEVs, the most widely cited studies tend to focus upon the WtW emissions only, and do not consider in any detail the GHG emission and other environmental impacts of manufacture and disposal of the vehicles.

We recommend that each of these areas be addressed separately and in more detail. A practical approach would be to break down the value chain for each vehicle category (BEV, PHEV. ICEV etc) into manageable segments (e.g., fuel manufacture, vehicle manufacture, infrastructure provision, end of life disposal etc) and create a set of detailed LCA guidance for each, which would identify all impacts which need to be included within the LCA boundary and make recommendations on consistent assumptions and input data. Application of the LCA guidance in future LCA studies would help to ensure consistency and therefore facilitate more meaningful comparisons of results.

References

1. Armand, M. and J.M. Tarascon, *Building better batteries.* Nature, 2008. **451**(7179): p. 652-657.
2. Scrosati, B. and J. Garche, *Lithium batteries: Status, prospects and future.* Journal of Power Sources, 2010. **195**(9): p. 2419-2430.
3. Scrosati, B., J. Hassoun, and Y.-K. Sun, *Lithium-ion batteries. A look into the future.* Energy & Environmental Science, 2011. **4**(9): p. 3287-3295.
4. IEA, *Technology Roadmap. Electric and plug-in hybrid electric vehicles - Updated June 2011*, 2011, International Energy Agency: 9 rue de la Fédération 75739 Paris Cedex 15, France.
5. Element Energy, *Cost and performance of EV batteries. Final report for The Committee on Climate Change*, 2012, Element Energy Limited: 20 Station Road, Cambridge CB1 2JD.
6. Ozawa, K., *Lithium-ion rechargeable batteries with* $LiCoO_2$ *and carbon electrodes - The* $LiCoO_2/C$ *system.* Solid State Ionics, 1994. **69**(3-4): p. 212-221.
7. Tarascon, J.M. and M. Armand, *Issues and challenges facing rechargeable lithium batteries.* Nature, 2001. **414**(6861): p. 359-367.
8. Peled, E., et al., *Parameter analysis of a practical lithium- and sodium-air electric vehicle battery.* Journal of Power Sources, 2011. **196**(16): p. 6835-6840.
9. Element Energy, *Influences on the Low Carbon Car Market from 2020-2030 - Final report for the Low Carbon Vehicle Partnership*, 2011, Element Energy Limited: 20 Station Road, Cambridge CB1 2JD.
10. Arup & Cenex, *Investigation into the Scope for the Transport Sector to Switch to Electric Vehicles and Plugin Hybrid Vehicles*, 2008, Department for Business Enterprise and Regulatory Reform (BERR) and Department for Transport (DfT).
11. Kushnir, D. and B.A. Sanden, *Multi-level energy analysis of emerging technologies: a case study in new materials for lithium ion batteries.* Journal of Cleaner Production, 2011. **19**(13): p. 1405-1416.
12. Majeau-Bettez, G., T.R. Hawkins, and A.H. Stromman, *Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles.* Environmental Science & Technology, 2011. **45**(10): p. 4548-4554.
13. Ou, X., X. Yan, and X. Zhang, *Using coal for transportation in China: Life cycle GHG of coal-based fuel and electric vehicle, and policy implications.* International Journal of Greenhouse Gas Control, 2010. **4**(5): p. 878-887.

14. Samaras, C. and K. Meisterling, *Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: Implications for policy.* Environmental Science & Technology, 2008. **42**(9): p. 3170-3176.
15. Zackrisson, M., L. Avellan, and J. Orlenius, *Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles - Critical issues.* Journal of Cleaner Production, 2010. **18**(15): p. 1519-1529.
16. Ni, M., *Current status of fuel cell technologies.* Energy Exploration & Exploitation, 2005. **23**(3): p. 207-214.
17. Dewulf, J., et al., *Recycling rechargeable lithium ion batteries: Critical analysis of natural resource savings.* Resources Conservation and Recycling, 2010. **54**(4): p. 229-234.
18. Gaines, L., et al., *Life-Cycle Analysis of Production and Recycling of Lithium Ion Batteries.* Transportation Research Record, 2011(2252): p. 57-65.
19. Speirs, J., et al., *Materials Availability: Potential constraints to the future low-carbon economy. Working Paper II: Batteries, Magnets and Materials*, 2012, Commissioned by UKERC from Centre for Energy Policy and Technology (ICEPT), Imperial College.
20. Schroeder, A. and T. Traber, *The economics of fast charging infrastructure for electric vehicles.* Energy Policy, 2012. **43**(0): p. 136-144.
21. McKinsey & Co. / EU powertrain coalition, *A portfolio of power-trains for Europe: A fact-based analysis. The role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles*, 2010.
22. MIT Energy Initiative, *Electrification of the Transportation System - An MIT Energy Initiative Symposium*, 2010, Massachusetts Institute of Technology.
23. Morrow, K., D. Karner, and J. Francfort, *Plug-in Hybrid Electric Vehicle Charging Infrastructure Review*, in *U.S. Department of Energy Vehicle Technologies Program - Advanced Vehicle Testing Activity*2008.
24. Nègre, L., *Green Book on publicly accessible charging infrastructures for "low-carbon" vehicles*, 2011, French Government.
25. Transport for London, *Guidance for implementation of electric vehicle charging infrastructure*, 2010.
26. Wiederer, A. and R. Philip, *Policy options for electric vehicle charging infrastructure in C40 cities - Report for the Clinton Climate Initiative*, 2010, Kennedy School, Harvard.
27. Element Energy, *Strategies for the uptake of electric vehicles and associated infrastructure. Implications for The Committee on Climate Change. Final Report October 2009*, 2009, Element Energy Ltd: Cambridge, UK.
28. Kemp, R., *Electric Vehicles: charged with potential*, 2010, The Royal Academy of Engineering.
29. Bandivadekar, A., et al., *On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions*, 2008, Massachusetts Institute of Technology (MIT): Boston, MA.
30. IEA, *"Transport, Energy and* CO_2 *- Moving Towards Sustainability"*, 2009, International Energy Agency (IEA), 9 rue de la Federation, 75739 Paris Cedex 15, France.
31. NHA, *The Energy Evolution: An Analysis of Alternative Vehicles and Fuels to 2100*, 2009, National Hydrogen Association (NHA): 1133 19th Street NW, #947, Washington, DC 20036.
32. Contestabile, M., et al., *Battery electric vehicles, hydrogen fuel cells and biofuels. Which will be the winner?* Energy & Environmental Science, 2011. **4**(10): p. 3754-3772.

33. Offer, G.J., et al., *Techno-economic and behavioural analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system in the UK.* Energy Policy, 2011. **39**(4): p. 1939-1950.
34. Thomas, C.E., *Fuel cell and battery electric vehicles compared.* International Journal of Hydrogen Energy, 2009. **34**(15): p. 6005-6020.
35. Energy Technology Institute, *Plug-in Vehicle Economics and Infrastructure Project*, 2011.
36. McKinsey & Co., *Roads toward a low-carbon future: Reducing CO_2 emissions from passenger vehicles in the global road transportation system.*, 2009: New York.
37. IEA, *Energy Technology Perspectives 2010 - Scenarios and Strategies to 2050*, 2010, International Energy Agency (IEA): 9 rue de la Fédération, 75739 Paris Cedex 15, France.
38. Struben, J. and J.D. Sterman, *Transition challenges for alternative fuel vehicle and transportation systems.* Environment and Planning B-Planning & Design, 2008. **35**(6): p. 1070-1097.
39. Yeh, S., *An empirical analysis on the adoption of alternative fuel vehicles: The case of natural gas vehicles.* Energy Policy, 2007. **35**(11): p. 5865-5875.
40. Patterson, J., M. Alexander, and A. Gurr, *Preparing for a Life Cycle CO_2 Measure - A report to inform the debate by identifying and establishing the viability of assessing a vehicle ‟s life cycle CO_2e footprint*, 2011, Ricardo.
41. Michalek, J.J., et al., *Valuation of plug-in vehicle life-cycle air emissions and oil displacement benefits.* Proceedings of the National Academy of Sciences of the United States of America, 2011. **108**(40): p. 16554-16558.
42. Hawkes, A.D., *Estimating marginal CO_2 emissions rates for national electricity systems.* Energy Policy, 2010. **38**(10): p. 5977-5987.
43. Edwards, R., Larive, J-L., Beziat., J-C. Well to wheels Analysis of Future Automotive Fuels and Powertrains in the European Context, July 2011, available at http://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu.about-jec/files/documents/wtw3_wtt_report_eurformat.pdf