Realizing the Electric Vehicle Revolution

Order of authors and affiliations: Martino Tran[a], Justin D.K. Bishop[b], David Banister[c] Malcolm D. McCulloch[d].

[a] School of Geography and Environment and Oxford Martin School, University of Oxford, South Parks Road, Oxford, OX1 3QY, UK. Fax: +44 (0)1865 275 850; Tel: +44 (0)1865 285 039; E-mail: martino.tran@ouce.ox.ac.uk

[b] Department of Engineering Sciences and Oxford Martin School, University of Oxford, Parks Road, Oxford, OX1 3PJ, UK. Tel: +44 (0)1865 273 020; E-mail: justin.bishop@eng.ox.ac.uk

[c] Transport Studies Unit, University of Oxford, South Parks Road, Oxford, OX1 3QY, UK. Tel: +44 (0)1865 285 066; E-mail: david.banister@ouce.ox.ac.uk

[d] Energy Power Group, Department of Engineering Sciences, University of Oxford, Parks Road, Oxford, OX1 3PJ, UK. Tel: +44 (0)1865 283 260; E-mail: malcolm.mcculloch@eng.ox.ac.uk

Corresponding author: Martino Tran

Abstract

Electric vehicle technologies (EVs) have emerged as an important climate mitigation and energy security pathway. Current research demonstrating the potential benefits of EVs has largely hinged on technological and engineering design breakthroughs. However, in order for electric motive systems to scale up to a level necessary to realize such benefits will require crucial shifts in agent behaviour in both supply and demand. We address this gap by assessing both technical and non-technical barriers and opportunities for rapid EV commercialization. We show the importance of considering key interactions between technology performance, infrastructure build, and consumer behaviour across different spatial and temporal scales. Our hope is that a more integrated analysis will better inform planning for the transition towards a future electric transport system, while highlighting the need for bringing together the technical and behavioural sciences to support this endeavour.

Keywords: electric vehicles, technology diffusion, energy demand, grid capacity, consumer behaviour, charging infrastructure, transport and climate change

1. Introduction

Electric vehicle technologies (EVs) have gained much attention in recent years as a key technological pathway to decarbonize the transport sector; although there are important technical and economic differences between electric motive systems, EVs in this analysis broadly refer to the full suite of hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) and full battery electric vehicles (BEV). There has been impressive research showing the potential climate mitigation and energy security benefits of electric vehicle technologies. However, the increasing body of research devoted to quantifying the impacts upon energy supply and related infrastructure from large EV fleets often do not explicitly address the interactions between technology, economics and agent behaviour. We believe there is need to evaluate the viability of EVs from a more integrated perspective, specifically looking at the dynamical interactions between infrastructure build, vehicle technology, and consumer behaviour, thereby giving a more realistic picture of the challenges and opportunities that lay ahead for EV diffusion.

In 2008, global final energy consumption was 8423 million tonne oil equivalent (Mtoe) and is expected to increase on average 1.4% per year reaching 12239 Mtoe in 2035 (Fig. 1). The transport sector accounts for ~27% of global final energy consumption and will nearly double from 2299 Mtoe in 2008 to 3433 Mtoe in 2035 [1].

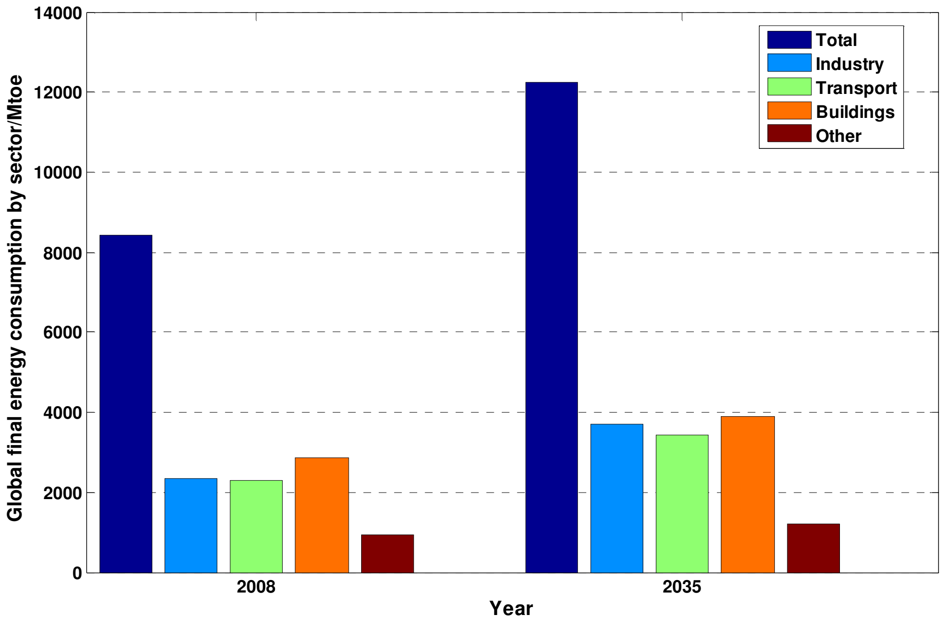

Fig. 1. Change in global final energy consumption by sector. Excludes electricity and heat; Buildings include residential and service sectors; Other includes agriculture and non-energy use. Calculated from data in [1].

Due to ~90% reliance on oil, transport is the second largest source of CO_2 emissions at 6.3 gigatonnes (Gt) in 2008 or 24% of total CO_2 emissions, compared to power generation (40%), industry (16%), buildings (12%) and agriculture and non-energy use (8%) (Fig. 2). Two main factors influence transport CO_2 emissions: change in total volume of travel and fuel efficiency of mode. Between 1990-2004, travel of light-duty vehicles (LDVs) i.e. passenger cars, small vans, and sport utility vehicles (SUVs) in the OECD increased 20%, from 13000 to 15000 kilometres per person per year. Truck travel (tonne kilometres per capita) increased 36% and global air travel increased over 5% per year since 1990 [2]. There is little indication that these trends will reverse. And given the relatively low average rates of vehicle ownership in emerging economies coupled with rising GDP growth rates vehicle travel is expected to increase. The fastest growth in transport is expected from air travel, road freight, and LDVs [2].

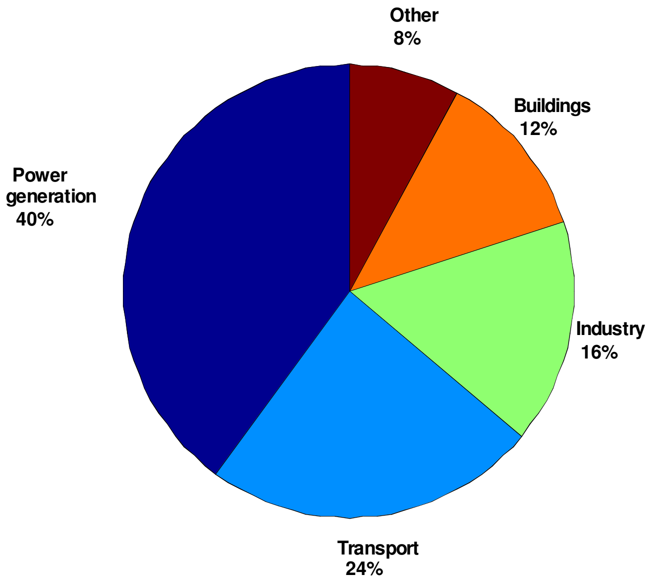

Fig. 2. Global CO_2 emissions by sector in 2008. Buildings include residential and service sectors; Other includes agriculture and non-energy use. Calculated from data in [1].

Across industrialized countries, 60-70% of road transport CO_2 emissions are from LDVs followed by road freight, 20-30% (Fig. 3). Consequently, there has been a central policy focus on the passenger vehicle fleet. Although many uncertainties exist surrounding the scale and timing of EV diffusion, global studies have developed optimistic scenarios ranging from 40-90% market shares by 2030-2050 [2, 3-5]. Although these scenarios are used to explore the potential benefits of rapid EV adoption, the central danger is that EVs may come to be perceived as a technological fix to reduce CO_2 emissions. However, what is clear is that the scale of EV market penetration necessary to decarbonize transport will not be realized without immediate and sustained policy support, industry investment, and fundamental shifts in consumer behaviour.

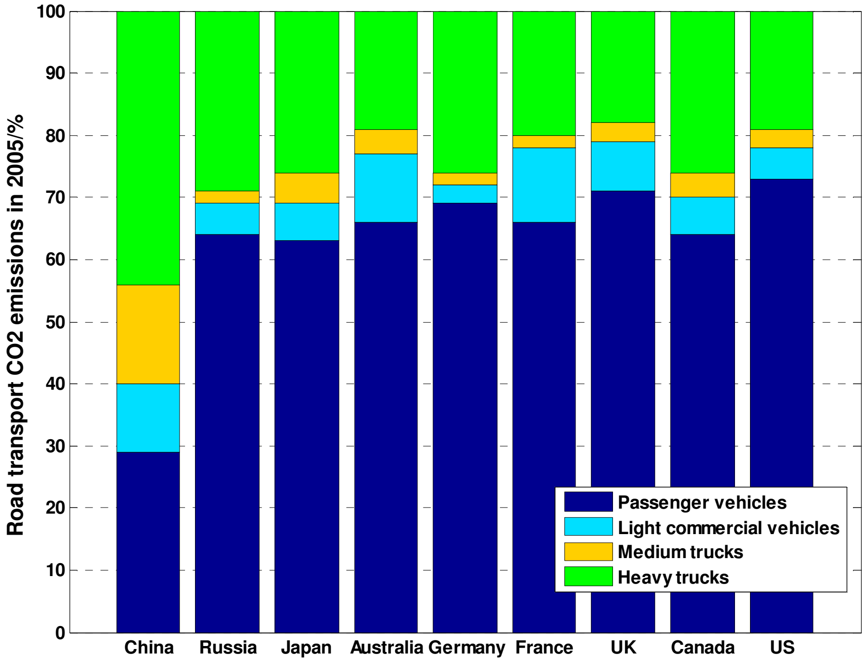

Fig. 3. Breakdown of road transport CO_2 emissions across selected countries in 2005. Data from [6].

2. Electric Vehicle Benefits

Global car manufacturers are now developing a variety of electric motive systems that typically cover three categories: 1) hybrid electric vehicles (HEV) that integrate various configurations of an internal combustion engine (ICE), batteries and/or fuel cells to generate electricity to power an electric drive – an additional variation is a plug-in hybrid vehicle (PHEV) that can recharge a battery from the electric grid by plugging into an electrical outlet, 2) pure battery electric vehicle (BEV), where a battery stores energy taken from the electric grid used to power an electric drive train and, 3) fuel cell powered electric vehicle (FCEV), where electricity is generated on-board by a fuel cell fed with hydrogen from a tank that is produced elsewhere, or onboard by a fuel processor using liquid fuels e.g. gasoline, bio-ethanol [7]. Due to the more near term potential benefits and impacts [8], we focus on the implications surrounding the first and second vehicle categories in our analysis.

In 2008, the transport sector was 94% dependent on oil, consuming 2150 Mtoe and is expected to increase on average 1.4% per year reaching 3102 Mtoe by 2035 (Fig. 4). Based on current trends, electricity and biofuels will increase on average per year 3.1% and 4.8% respectively, reaching 53 Mtoe and 163 Mtoe by 2035, with oil still dominating 90% of total transport fuel end-use. Fig. 4 also shows an alternative scenario developed by the IEA [1] assuming market shares of PHEVs at 24% and

BEVs at 16% of total new passenger car sales in 2035. In this scenario, transport electricity demand increases to 128 Mtoe, with 90% of this due to EVs. Nevertheless, oil remains the dominant fuel at 77% in 2035 down from 94% in 2008. However, most of the oil savings in this scenario occurs in road transport, accounting for more than 80% of all oil savings by 2035. Among road vehicles, LDVs account for more than 75% of oil savings ~560 Mtoe by 2035 while abating ~395 $MtCO_2$ from the transport sector by 2035 [1]. Therefore, electrification of the passenger vehicle fleet has the greatest potential to reduce carbon emissions and save oil.

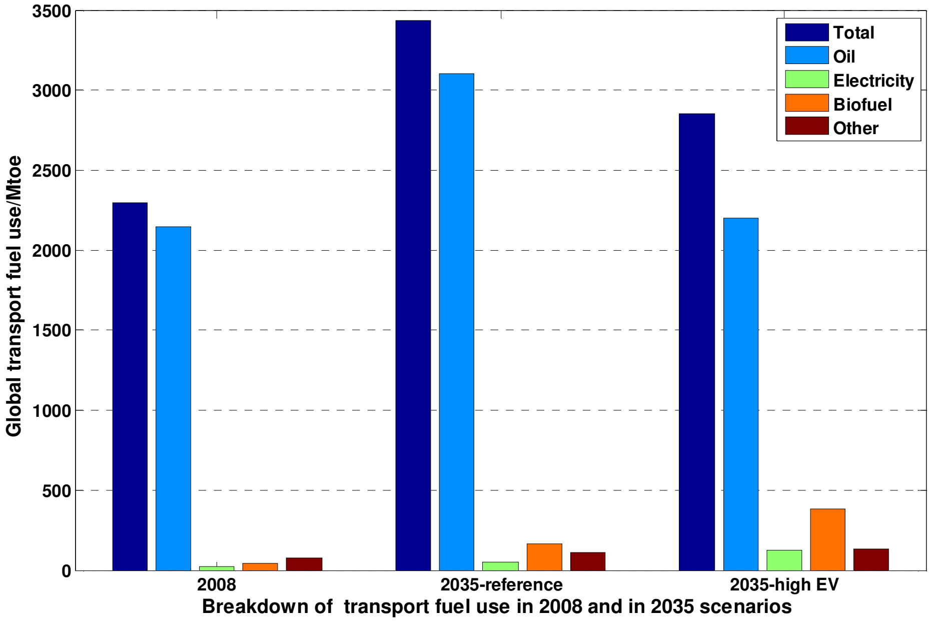

Fig. 4. Comparative breakdown of transport fuel use across different scenarios. Oil includes bunker fuel. Calculated from data in [1].

It is anticipated that the switch to electricity will yield the benefits of higher efficiency energy converters in the form of electric motors, typically three times as efficient as a hybrid combustion engine system [2]. Pure battery electric vehicles for example, are estimated to reduce well-to-wheel emissions 70-85% compared to current ICEs by 2030 with virtually zero tail pipe emissions [5]. Moreover, it is expected that the greenhouse gases (GHGs) currently emitted from mobile fuel converters will be shifted to stationary ones, which can be mitigated more cost-effectively in the near term. Such a scheme would depend on the already existing power system infrastructure i.e. electricity generation, transmission and distribution, upon which a large penetration of EVs will have uncertain impacts. Although BEVs represent the ultimate target, PHEVs may serve as a transition technology, primarily through cost reductions in battery, motor and control systems over the medium term [2, 4].

3. System Demand

The CO_2 benefits from vehicle electrification will not be gained without first decarbonizing electricity generation. Most regions in the world currently do not generate sufficient low CO_2 electricity to enable BEVs and PHEVs to potentially reduce 2-4 Gt CO_2 assuming ~100-200 million EVs are sold in 2050 (Table 1). In the IEA's most optimistic scenario, global EV market share reaches 90% in 2050, electricity demand reaches 580 Mtoe, or 17% of world electricity demand, requiring ~2000 GW of additional capacity [2]. In this scenario, 4 Gt of CO_2 are abated from the transport sector by 2050. The key assumption here is that global average electricity carbon intensity must drop below 100 gCO_2kWh^{-1} by 2050 from an average 460-550 gCO_2kWh^{-1} in 2005 [1, 9].

Table 1. Power generation impacts from electric vehicle technology diffusion scenarios

Scenario	Year[e]	Passenger light-duty vehicle [LDV] market share [%]		Global sales PHEV+BEV [10^6]	Carbon saved[f] [Gt]	Electricity demand[g] [Mtoe]	Global average electricity carbon intensity[h] [gCO_2kWh^{-1}]
		PHEV	BEV				
IEA [2009]							
Blue Map[a]	2050	20	20	100	2	390	<100
Blue Map + Blue Shift[b]	2050	20	20	100	2	330	<100
EV Success[c]	2050	-	90	200	4	580	<100
IEA [2010]							
450 scenario[d]	2035	24	16	84	0.40	142	120-160

Note. All figures are based on author estimates of data and scenario results in [1, 9]
a. Blue Map scenario assumes by 2050 new power train technologies such as EVs penetrate the LDV and truck market (25% of global stock); 30% energy efficiency gains across all modes relative to 2005; 33% final transport end use mainly from 2nd generation biofuels; 40% market share from FCVs.
b. Blue Shift scenario is similar to Blue Map but assumes LDV passenger travel is reduced 25% in 2050 relative to baseline. Ownership and travel per vehicle is reduced hence slightly lower electricity demand despite near same levels of EV stock.
c. EV Success is similar to Blue Map except it assumes that EVs almost completely displace ICE LDVs by 2050 and FCVs do not achieve significant market shares.
d. 450 Scenario assumes implementation of strong policies after 2020, including near-universal removal of fossil-fuel consumption subsidies to limit concentration of GHGs in atmosphere to 450 ppm of CO_2-equivalent and global temperature increase to 2° Celsius.
e. Denotes projection period 2005-2050 for IEA [9] and 2008-2035 for IEA [1]; all other figures in table are for final year of projection 2050 and 2035.
f. Carbon saved from baseline projection; transport CO_2 emissions in 2005 ~6-7 Gt with baseline projection to 2050 ~14 Gt [9] and 2035 ~9.5 Gt [1].
g. Electricity demand primarily for LDV PHEVs and BEVs in each scenario.
h. Assumptions on power generation carbon intensity to achieve stated carbon reductions. Global average electricity carbon intensity in 2005 was 460-550 gCO_2kWh^{-1}.

For many industrialized nations, electrification of the passenger vehicle fleet is a key strategy to achieve deep cuts in CO_2 emissions by 2050 [10-12]. However, increasing EV market shares around the world will be ineffective if it occurs in regions with high carbon electricity. In 2006, average electricity emissions ranged from a low of 190 gCO_2kWh^{-1} in Latin America to a high of 944 gCO_2kWh^{-1} in India. One of the largest potential EV markets is China with a current grid mix of 788 gCO_2kWh^{-1}. In 2005, LDV ownership rates (vehicles per 1000 people) in China were 11 compared to 424 and 559 in OECD Europe and North America respectively. However, between 2000-2005, sales of LDVs in China increased from 700,000 to 3.1 million, a 319% increase, and will continue to rise [9]. Over the same period, North American LDV sales increased 3% from 16.9 to 17.5 million, while OECD European sales decreased 2% from 16.7 to 16.3 million [9]. Fig. 5 shows a comparison of vehicle lifecycle CO_2 emissions as a function of power generation CO_2 intensity in the UK (A) and US (B) across different vehicle technologies. In the UK, a PHEV-20/30 operating on a current grid mix of 450 gCO_2kWh^{-1} emits 110 gCO_2km^{-1} dropping to 85 gCO_2km^{-1} assuming a grid mix of 170 gCO_2kWh^{-1}. The same PHEV in the US would emit 183 gCO_2km^{-1}, 60% more than its' UK counterpart due to a higher current grid mix of 670 gCO_2kWh^{-1} but dropping to 126 gCO_2km^{-1} assuming a 200 gCO_2kWh^{-1} gridmix with high penetrations of renewables and nuclear or coal with carbon capture and sequestration (CCS).

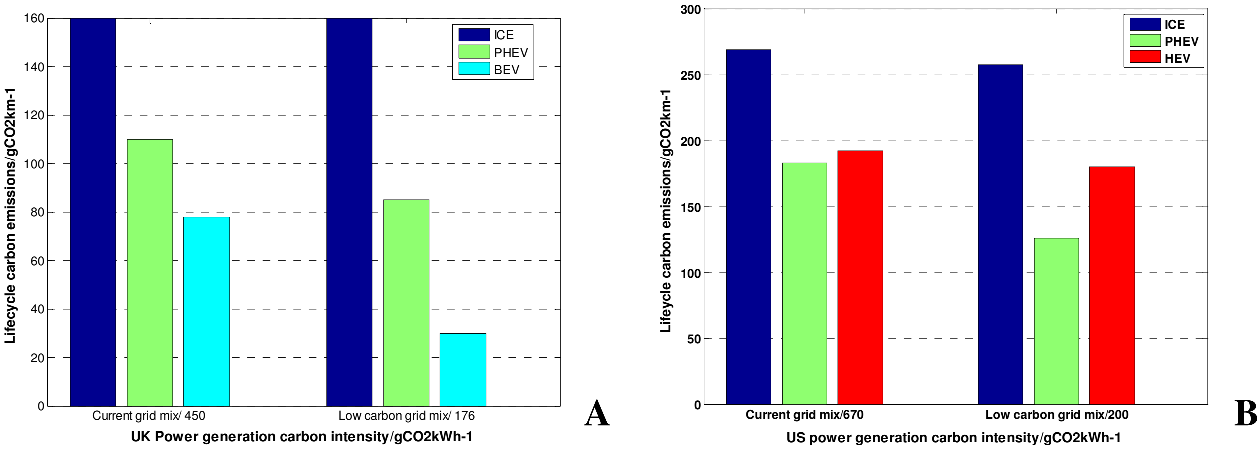

Fig. 5. Comparison of vehicle lifecycle CO_2 emissions as a function of power generation CO_2 intensity in the UK (A) and US (B). Notes for A: Current grid mix in 2007/08; Low carbon grid mix assumes increased renewables/nuclear and use of CCS with coal; ICE is medium size sedan 50:50 petrol/diesel mix; PHEV-20/30 with 50% electricity, 50% liquid fuel; ~85% lifecycle emissions from road use. Further details see [13]. Notes for B: Current grid mix in 2007/08; Low carbon grid mix assumes increased renewables/nuclear and use of CCS with coal; ICE is medium size sedan; PHEV-30 with Li-ion battery (75-250 kg), 50% electricity, 50% liquid fuel; HEV is medium size sedan i.e. Toyota Prius with Li-ion battery 16 kg. Further details see [14].

Another key uncertainty is whether or not high penetrations of EVs will require additional capacity and over what period. Globally, the IEA suggest a range between 142-580 Mtoe increase in electricity demand assuming 40-90% EV market share between 2035-2050 (Table 1). National studies in the UK [15, 16] and US [16] indicate that additional capacity will not be required over the short to medium term (2010-2030). In 2006 for instance, the Pacific Northwest National Laboratory found that the existing grid could charge up to 70% of all cars and light trucks in the US if they were charged overnight when idle generation capacity is available [16]. In the UK, estimates of EV market shares range from 20% in 2030 to nearly 70% by 2050, potentially requiring 2-18 GW of installed capacity [15, 17, 18]. Yet, both the UK Department for Transport (DfT) [17] and the UK Energy Research Centre (UKERC) suggest that additional capacity will not likely be required over the short to medium term [15, 18]. Predicting the need for additional capacity over the long-term (2050) is far less certain and depends on a host of unknown factors, such as future grid mix and interactions with other sectors. Under a carbon constrained scenario with high wind penetrations more installed capacity would be required to meet electricity demand relative to a business-as-usual grid mix reliant on coal or nuclear. Additional capacity would also be required for decarbonization of the building stock, indicating unprecedented interactions between the power, transport and housing sectors. For instance, UKERC has developed a scenario of 80% system wide carbon reductions by 2050 using 60% wind penetration. This would require almost a doubling of electricity generation capacity in 2050 reaching 120-145 GW relative to a 2000 baseline. In this scenario, demand is primarily driven by EVs and residential electrification for boilers and heat pumps [15, 18]. Although it is important to account for system-wide interactions, which most studies do not, predicting future mobility patterns let alone household energy demand poses a significant challenge.

Other studies adopt a more micro view of PHEV penetration as opposed to economy-wide scenarios. These micro level approaches typically follow two methods: in the former, vehicle quantity is stipulated and its impacts on the power system assessed; while in the latter, the existing system capability is used to limit the number of PHEVs which may be supported. In other words, the first method drives system expansion to meet a particular PHEV penetration, while the second constrains penetration to fit within current system capacity. A modification of this approach used by Lemoine et al. [19] where PHEV penetration is taken as the maximum number of vehicles that can be charged in a given hour before the cost per mile travelled on electricity exceeds that of travelling on petrol. The latter approach constitutes a more defensible premise because it does not rely on arbitrary PHEV penetration estimates [20-22]. Regardless of the methodology, there is an underlying assumption that a large proportion of consumers will eventually switch to PHEVs. But since there is no evidence offered about what proportion of the population is most likely to own a low or zero emissions vehicle, based on their needs and where they live and work, findings cannot be refined to offer insight as to where high concentrations of EVs would most likely occur. Consequently, there is insufficient information to inform early planning and investment for local transmission and distribution, and charging infrastructure to support large EV fleets. This may negatively affect chances for large-scale EV adoption since adequate charging infrastructure investment will have to precede vehicle commercialization in order for consumers to have confidence in the utility of the vehicle [17]. Overcoming this barrier will require bringing together conventional power systems analysis with more sophisticated understanding of consumer psychology in terms of purchasing behaviour, economic constraints, and social aspirations.

4. Charging Regimes

Household charging infrastructure will also affect system demand due to interaction between energy end-use behaviour and infrastructure requirements, in turn, potentially impacting local transmission and distribution networks. Oak Ridge National Laboratories in the US have shown that the difference between using a 120V/15A and a 240V/30A charging socket could result in a four-fold increase on system demand from 1.5 GW increasing to 6 GW [23]. Other studies [19, 24] prescribe use of a standard household circuit (120V/15A) that delivers up to 1.4 kW to the PHEV. In Schneider et al. [21] and Parks et al. [25], both standard household circuits, and 240V connections are available. In the latter study, the circuit can deliver 1.8-2.0 kW continuously and a 240V/40A circuit to provide up to 3.2 kW power. The Electric Power Research Institute assume that cars and mid-size SUVs will charge on a household circuit, but a full-size SUV will use a 240V circuit to account for the larger battery pack, the need to have a full pack in the morning and an overnight charging window [26].

Most scenarios assume night time recharging during low demand periods with potentially grid-balancing benefits if PHEVs are used as distributed energy storage. This raises many unanswered questions about when users will actually plug-in, which is likely to be influenced by myriad factors including personal convenience, daily work schedules, leisure activity and household energy behaviour. Other charging regimes which are subject to the same uncertainty in individual consumer behaviour include: 1) grid connection which is coincident with the day time peak, 2) occurrence in the early evening (before 2000h), or 3) uniformly spread across the 24-hour day. Potential grid impacts from PHEVs have been assessed across these three main charging regimes along with various other possibilities by a number of studies [25, 27-29]. Conversely, Sioshani and Denholm [30] assume the vehicle to be charging whenever it is not in motion, while others adopt spare capacity, valley filling algorithms [20, 22, 24, 31-33]. Another approach is to use staggered times for the PHEV fleet to connect to, and disconnect from the grid [21, 34].

Regardless of the charging regime, there is typically an assumption that every driver will subscribe to the same charging behaviour. A more realistic scenario is to assume an unrestricted charging regime [33, 35]. In an effort to create a realistic agent-centred charging profile, Taylor et al. [35] use transport survey data to identify when commuters return home from work. This yields an empirical distribution of likely PHEV connection times and constitutes a defensible charging regime premise. Conversely, Denholm and Short [33] propose removing individual behaviour from the assessment by having the electric power utility exert full control over vehicle charging. This would result in optimal timing, minimum cost charging and introduce top-down control so as to avoid grid overloading. This has important implications for local distribution as the vehicle stock grows, and especially if quick-charging technology emerges, substantial daytime charging could increase peak demand [2]. This could overload local distribution networks that are already near capacity, requiring investment into local infrastructure reinforcement [4, 17]. Refuelling a high range electric vehicle in less than 10 minutes for example, could require up to 0.5 Megawatts (MW) per vehicle. This is a substantial amount of electric power for a standard commercial electricity grid which may require close proximity to a dedicated source of electric power [4].

5. Driver Behaviour

There is also an implicit assumption that consumers will wish to maximize their all electric range (AER), leading to scenarios where all vehicles begin each day with a full battery. The assumption that a vehicle can charge whenever it is not moving depends on sufficient infrastructure for drivers to connect their vehicles to the grid at any location [30]. This assumption would support an unrestricted charging regime; however, it is unreasonable to expect that every car park location will have access to electricity for the purpose of charging. In order to accomplish any of the charging regimes, the presence of smart charging infrastructure or utility control is assumed. Although the technology exists, the integration of components into vehicles, intelligent charging stations, and back to the utility central control faces problems of near-term feasibility and long-term scalability [36]. Moreover, there is often a focus on assessing the commute between home and work but little consideration is given to driving outside of travel to and from work and the resulting system demand. Specifically, the differences in trip frequency and length between the work commute, or other trip journey purposes, and opportunities for drivers to plug in more often during the weekend are typically not considered. For example, car journey distances in the UK increased on average per year ~0.5% from 486,988 million passenger kilometers (pkm) in 1996 to 510,475 million pkm in 2006 [37]. Fig. 6 shows the proportion of pkm travelled as a function of journey purpose in the UK from 1996-2006. Although pkm for commuting to and from work take up the largest share (20-19%), other trip journey purposes such as shopping (13-14%), personal (16-18%), visiting friends (17-15%), and holidays (9-12%) are non-trivial and on the rise. More realistic assumptions behind future trends in driver behaviour will need to be made to inform the development of EV technology AER, charging profiles, and charging infrastructure build as a function of trip journey purpose and distance.

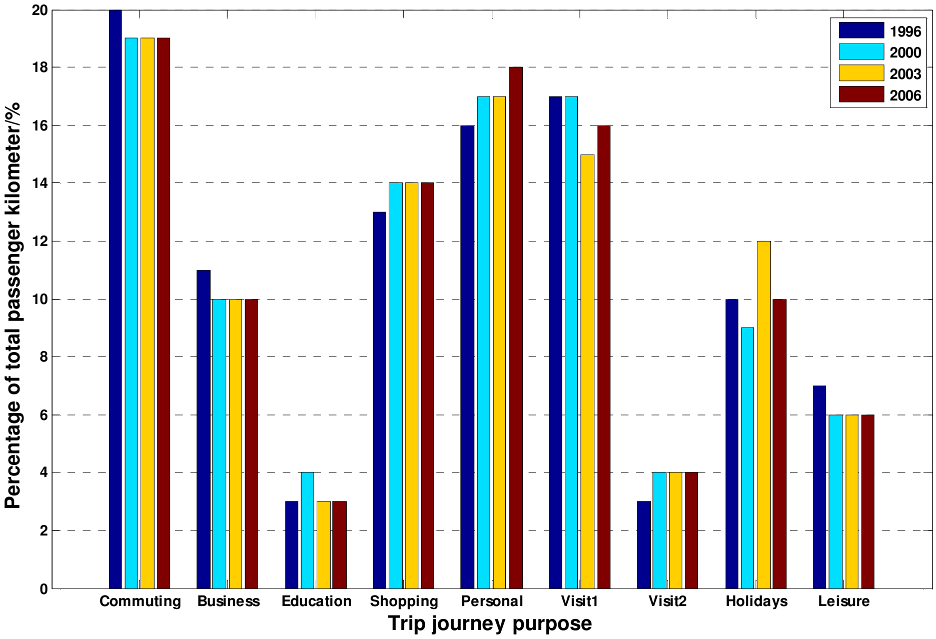

Fig. 6. Passenger distance travelled as a function of household car journey purpose in the UK, 1996-2006. Commuting - trips between home and work; Business - trips during the course of work; Education - trips to educational institutions by students and those escorting students; Shopping - trips between home and shops; Personal - visits to services e.g. laundrettes, banks, doctors and accompanying others on such a trip; Visit1 - visiting friends/relatives at private home; Visit2 - visiting friends/relatives elsewhere; Holidays - trips within UK to and from any holiday (including stays of 4 or more nights with friends or relatives), or trips for pleasure within a single day; Leisure - all types of entertainment, sports, clubs, voluntary work, etc. Data from [37] and based on the UK National Travel Survey (NTS) at the household level. The survey collects data from 8000 households, with 19000 individuals, each year. Information on the household, each individual within the household and any vehicles to which the household has access, is collected via a face to face interview. Each household member records trip details over a 7 day period. The NTS defines a trip as a one way course of travel with a single main purpose. A trip consists of one or more stages, where a new stage is defined when there is a change in the form of transport or a change of vehicle requiring a separate ticket.

Assumptions behind driving behaviour patterns have important implications for EV energy management and therefore CO_2 mitigation. Total UK passenger car CO_2 emissions in 1996 was 57 $MtCO_2$ decreasing to 56 $MtCO_2$ in 2006. Fig. 7 shows the change in proportion of passenger car tailpipe CO_2 emissions as a function of trip journey purpose in the UK. Commuting CO_2 emissions dropped from 27% to 25% between 1996 and 2006, while shopping and personal use each increased by 1% reaching a combined 30% of total passenger car emissions. Although we cannot assume that EV technologies will completely replace current LDV travel patterns, the scale of diffusion required to achieve the carbon savings often assumed by governments requires EVs to far surpass niche markets.

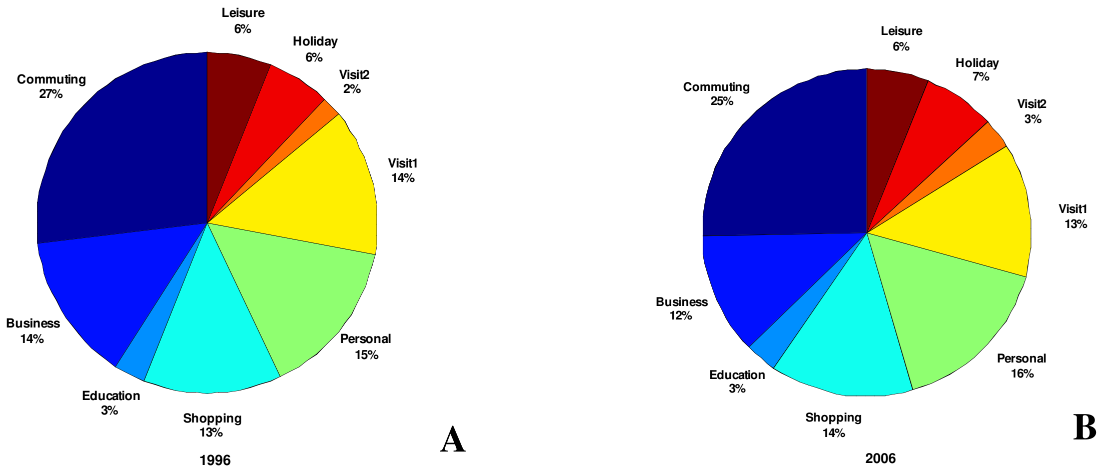

Fig. 7. Change in proportion of passenger car tailpipe CO_2 emissions as a function of trip journey purpose in the UK, 1996 (A) and 2006 (B). Data from [37].

For EV energy management testing (See Section 7 below), driving behaviour is also assumed that may not reflect actual vehicle use. For instance, the Society of Automotive Engineers (SAE) has proposed a standard method (SAE J1711) [38] for testing the fuel consumption of HEVs and PHEVs based on a utility factor (UF) (SAE J2841) [39] calculated as a ratio of the number of miles driven under charge-depleting mode to the total number of miles driven. This in turn, is based on average driving habits derived from US National Household Transportation Surveys [40]. Although the UF may be useful as a standardization tool, the UF implicitly assumes that vehicles charge only once per day, PHEV driving patterns reflect national averages, and PHEV energy consumption mode changes are best characterized by a charge depletion range [41]. Bradley and Quinn [41] demonstrate that the UF is in fact more sensitive to assumptions in consumer charging behaviour rather than vehicle fuel economy, vehicle class and driver characteristics.

6. Consumer Acceptance

Nearly all large-scale EV diffusion scenarios assume increasing performance, lower costs and overall convenience of the vehicle. This in turn depends on key assumptions related to the cost and performance of battery technologies. Although nickel metal-hydride (Ni-MH) batteries were the first to be used on a large scale in HEVs (~600,000 Toyota Prius' have been equipped with this technology as of 2006/07), lithium-ion (Li-ion) batteries are lighter (Li, ρ = 530 kgm^{3-1}; Ni, ρ = 8800 kgm^{3-1}) and have higher energy and power densities (Table 2). However, Li-ion battery cost per kilowatt hour is currently comparable to its' competitors, but its' average annual rate of energy density improvement between 1990-2005 was 7% compared to Ni-MH, 4% and Ni-Cd, 1%. Importantly, Li-ion energy density has continued to improve reaching 450 Whl^{-1} in 2005, whereas Ni-Cd and Ni-MH improvements levelled off at 130 Whl^{-1} and 350 Whl^{-1} respectively since 2005.

Table 2. Comparative overview of key characteristics of energy storage technologies

Energy[a] storage technology	Energy [$Whkg^{-1}$]	Energy [Whl^{-1}]	Power [Wkg^{-1}]	Number of cycles @80% DoD	Efficiency [%]	Temp. range [˚C]	Cost [€kWh^{-1}]	Average annual rate of energy density [Whl^{-1}] improvement[b] 1990-2005 [%]
Ni-Cd								
Power	25-40	130	500	800-1500	70-75	-40-50	400-1000	
Energy	40-50	130	120-350	800-1500	70-75	-40-50	400-1000	1
Ni-MH								
Power	40-55	80-200	500-1400	500-2000	70-80	0-45	400-1000	
Energy	60-80	200-350	200-600	500-2000	70-80	0-45	400-1000	4
Li-Ion								
Power	70-130	150-450	600-3000	800-1500	85-90	-20-60	700-2000	
Energy	110-220	140-450	200-600	800-1500	85-90	-20-60	150-600	7

a. Data from [42] and indicative only.
b. Authors calculations based on data from [42].

Although Li-ion batteries have become the preferred choice due to improved energy and power densities, high efficiency and long life [7, 43] scaling up the technology remains problematic because of high cost, unresolved safety problems such as risk of fumes or flames with deep over-charge (~200%) especially with cobalt-based batteries, wide operational temperature (adversely affected >65°C, or <0°C) and availability of materials [43-46]. Nevertheless, they are considered the best option for widespread commercialization of EVs [47].

One of the key uncertainties is the evolution of battery costs and associated consumer pay-back periods to achieve rapid EV adoption. The durability of batteries is also an important factor, where they must either endure up to 15 years of recharge-discharge cycles or be replaced, potentially doubling the life-cycle cost [19]. Li-ion batteries currently have a cycle life of 800-1500 cycles (Table 2) irrespective of use in either mobile or static applications [2, 17]. Although the IEA suggests that future battery costs will need to drop to around USD 300 kWh^{-1} [2], other estimates are as low as USD 200 kWh^{-1} at high production volumes [4]. Battery performance and lifecycle costs are therefore closely related in terms of achieving commercial success. Table 3 shows PHEV battery storage, cost assumptions, vehicle range, and driver behaviour patterns highlighting the technical and non-technical barriers that need to be overcome. For consumers to increase AER to 60-80% of daily driving, battery storage will need to increase 4 times from 5 kWh to 20 kWh while battery costs will need to drop 70% from USD 1000 kWh^{-1} to 300 kWh^{-1} over the next 10 years [2] representing a major challenge for research and development.

Table 3. Key interactions between battery performance, cost and consumer driving patterns

Plug-in[a] hybrid battery capacity	Vehicle driving range on batteries [km]	Battery storage required [kWh]	Li-ion Battery Cost [USD]		Average daily driving on battery [%]	UK passenger car journey by trip length and related CO_2 emissions [Avg. 2002-06][b]		
			Current [1000kWh^{-1}]	Future [300kWh^{-1}]		Trip length [km]	Proportion of car trips [%]	CO_2 emissions [%]
Low	20	5	5000	1500	20-40	<8	56	20
Medium	50	12.5	12500	3750	40-60	8-40	37	44
High	80	20	20000	6000	60-80	>40	7	36

a. Data from [2]. Notes: Calculations assume a) battery vehicle efficiency of 0.16 $kWhkm^{-1}$, b) battery discharge up to 66% maximum (50% more battery capacity must be supplied than used in plug-in mode), c) percentage of daily driving on batteries based on US driving profiles.
b. Data from [37]. Notes: UK transport CO_2 emissions performance is similar to other developed countries although UK average CO_2 emissions of new cars are slightly higher than EU-15 average.

Although there are technical and economic challenges to increase the overall battery range of PHEVs, Table 3 also shows the potential opportunity for reducing passenger car CO_2 emissions with current PHEV technology and driver behaviour. In the UK, 56% of daily car trips are less than 8 km, well under the current AER of a PHEV-20. If a 50 km medium range PHEV could be successfully scaled up, 44% of passenger car CO_2 emissions could be saved (assuming low to zero carbon grid electricity), which is the largest share of passenger car tail pipe emissions as a function of trip distance (8-40 km) in the UK. Globally, a large share of daily driving could be satisfied by a PHEVs'AER. In Europe, 50% of daily passenger car trips are less than 10 km and 80% are less than 25 km. In the United States, 60% of daily car trips are less than 50 km and 85% are less than 100 km [9].

7. Future Planning and Research

Although industrialized governments and emerging economies have identified EVs as a climate mitigation pathway, uncertainties surrounding the rate and scale of diffusion are set against massive infrastructure requirements to meet future energy demand over the next 20 years. In the IEA's recent high EV penetration scenarios, additional investment of 7.3 trillion USD (2009) is required from 2010-2035 in the transport sector. Passenger cars account for 55% of this investment at 4 trillion with 38% of that investment occuring in OECD countries, mostly for electrification of transport [1]. The same scenario estimates that nearly 180 billion USD (2009) will have to be invested into renewable electricity by 2035 (Fig. 8). In the UK an additional 30-35 GW of new electricity generation capacity will be required over the next 20 years, with 70% of this capacity needed by 2020, largely due to increasing energy demand combined with closures of existing coal and nuclear power stations over the next 10 years [48]. Most industrialized countries are now entering a new investment cycle in power generation representing an opportunity to deploy more clean and efficient generation technologies. This is important because power investment decisions taken over the next 10 years will lock in CO_2 emissions for the next 40-50 years [49]. However, the planning horizon for the vehicle fleet cycle is 12-15 years. Therefore, electricity generation decisions must also be made within the next 10 years if it is to be matched with the next 2-3 vehicle fleet cycles where large-scale commercialization of EVs is expected.

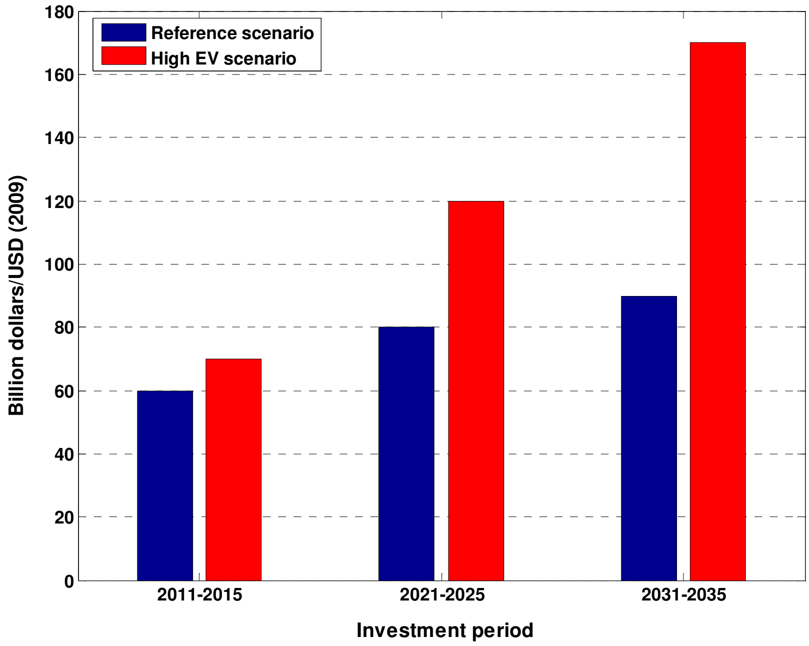

Fig. 8. Average annual investment for renewable electricity in high EV scenario relative to reference. Estimated from data in [1].

There are also a number of uncertainties surrounding the potential system-wide impacts of large-scale EV fleets. One of the key problems in determining these impacts is the differences in methodologies used and their underlying assumptions on supply-side infrastructure, battery cost, and vehicle performance. There is also a fundamental gap in understanding the role of consumer behaviour, how this will influence energy demand and the necessary infrastructure investment to support large EV fleets. There is scope to contribute to the growing body of knowledge by utilizing accurate consumer, social and economic data on the likely/measured behaviour of prospective EV owners to assess proportion of population, car usage and where EV owners may live in order to determine the necessary performance and distribution of vehicles in the electric power system. This load distribution may then be incorporated into existing power generation, transmission and distribution models with an optimal power flow analysis. The specimen PHEV components and performance should be updated to reflect more probable vehicle design, optimized for an AER which meets the needs of the potential customer base using current and new component technologies over standard drive cycles. Finally, the analysis should take the approach of evaluating how many PHEVs the current infrastructure can support under a fully unrestricted charging regime, as a more defensible position than choosing an arbitrary PHEV penetration. The prospect of a large-scale electric vehicle fleet raises many questions concerning interactions between the transport, housing and power sectors. Bringing the technical and behavioural sciences together in a coherent manner will give insight into how consumer markets and energy end-use behaviour will influence, and in-turn be influenced by advancements in vehicle technology and infrastructural build.

Acknowledgements

We acknowledge generous support from the Oxford Martin School for funding this research at the Institute for Carbon and Energy Reduction in Transport (ICERT), University of Oxford, UK.

References

[1] World Energy Outlook, International Energy Agency, Paris, France, 2010.

[2] Energy Technology Perspectives, International Energy Agency, Paris, France, 2008.

[3] Mobility 2030: Meeting the Challenges to Sustainability, World Business Council for Sustainable Development, Geneva, Switzerland, 2004; http://www.wbcsd.org/web/publications/mobility/mobility-full.pdf.

[4] Transport Technologies and Policy Scenarios to 2050, World Energy Council, London, UK, 2007; http://www.worldenergy.org/documents/transportation_study_final_online.pdf).

[5] J. Rosenfeld, et al., Averting the Next Energy Crisis: The Demand Challenge, McKinsey & Co., 2009;http://www.mckinsey.com/mgi/reports/pdfs/next_energy_crisis/MGI_next_energy_crisis_full_report.pdf)

[6] Reducing Transport Greenhouse Gas Emissions: Trends and Data, OECD, Paris, France, 2010.

[7] S. Campanari, G. Manzolini, F. Garcia de la Iglesia, Energy analysis of electric vehicles using batteries or fuel cells through well-to-wheel driving cycle simulations, J. Power Sources 186 (2009) 464–477.

[8] N. Demirdöven, J. Deutch, Hybrid cars now, fuel cell cars later, Science 305 (2004), 974.

[9] Transport, Energy and CO_2: Moving Towards Sustainability, International Energy Agency, Paris,

France, 2009.

[10] Meeting the Energy Challenge: A White Paper on Energy, Department of Trade and Industry London, UK, 2007; http://www.berr.gov.uk/files/file39387.pdf.

[11] Building a low-carbon economy – the UK's contribution to tackling climate change, Climate Change Committee, The Stationary Office, UK, 2008; http://www.theccc.org.uk/reports/building-a-low-carbon-economy.

[12] P. Ekins, G, Anandarajah, N. Hughes, R. Kannan, N. Strachan, Chapter 2: Carbon Reduction Scenarios. Making the transition to a secure and low-carbon energy system: synthesis report. UK Energy Research Centre, 2009.

[13] The King Review of Low Carbon Cars, HM Treasury, London, UK, 2007.

[14] C. Samaras, K. Meisterling, K., Lifecycle assessment of Greenhouse Gas Emissions from Plug-in Hybrid Vehicles: Implications for policy, Environ. Sci. Technol., 42 (2008), 3170-3176.

[15] R. Kannan, Uncertainties in key low carbon power generation technologies – implication for UK decarbonisation targets, App. Energy 86 (2009), 1873–1886.

[16] R.F. Service, Hydrogen cars: fad or the future? Science. 324 (2009), 1257.

[17] Investigation into the Scope for the Transport Sector to Switch to Electric Vehicles and Plug-in Hybrid Vehicles, Department for Transport, UK, 2008; http://www.berr.gov.uk/files/file48653.pdf.

[18] G. Anandarajah, N. Strachan, P. Ekins, R. Kannan, N. Hughes, Pathways to a Low-Carbon Economy: Energy Systems Modelling. UKERC Energy 2050 Research Report 1. UK Energy Research Centre, London, UK, 2009.

[19] D.M. Lemoine, D.M. Kammen, A.E. Farrell, An innovation and policy agenda for commercially competitive plug-in hybrid electric vehicles. Environ. Res. Lett. 3 (2008), 014003.

[20] M. Kintner-Meyer, K. Schneider, R. Pratt, Impacts Assessment of Plug-in Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids - Part 1: Technical Analysis. Technical report, Pacific Northwest National Laboratory, 2007.

[21] K. Schneider, C. Gerkensmeyer, M. Kintner-Meyer, R. Fletcher, Impact assessment of plug-in hybrid vehicles on pacific northwest distribution systems. IEEE PES GM, pages 1–6, July 2008.

[22] C. H. Stephan, J. Sullivan, Environmental and Energy Implications of Plug-In Hybrid-Electric Vehicles, Environ. Sci. Technol., 42 (2008), 1185–1190.

[23] S.W. Hadley, Evaluating the Impact of Plug-in Hybrid Electric Vehicles on Regional Electricity Supplies. 2007 iREP Symposium- Bulk Power System Dynamics and Control - VII, Revitalizing Operational Reliability, August 19-24, 2007, Charleston, SC, USA, 2007.

[24] A. Hajimiragha, C. A. Ca nizares, M. W. Fowler, A. Elkamel, Optimal Transition to Plug-in Hybrid Electric Vehicles in Ontario-Canada Considering the Electricity Grid Limitations, IEEE

Transactions on Industrial Electronics, Forthcoming, 2009.

[25] K. Parks, P. Denholm, T. Markel, Costs and emissions associated with plug-in hybrid electric vehicle charging in the Xcel energy Colorado service territory. Technical Report TP-640-41410, National Renewable Energy Laboratory, 2007.

[26] Environmental Assessment of Plug-In Hybrid Electric Vehicles. Final report, Electric Power Research Institute, 2007.

[27] Y. Li, Scenario-Based Analysis on the Impacts of Plug-In Hybrid Electric Vehicles' (PHEV) Penetration into the Transportation Sector, IEEE International Symposium on Technology and Society, pages 1–6, June 2007.

[28] X. Yu, Impacts assessment of PHEV charge profiles on generation expansion using national energy modeling system, IEEE PES GM, pages 1–5, July 2008.

[29] S. Letendre, R. A. Watts, Effects of Plug-In Hybrid Electric Vehicles on the Vermont Electric Transmission System. In Transportation Research Board Annual Meeting Compendium of Papers, number 09-2542, 2009.

[30] R. Sioshansi, P. Denholm, Emissions impacts and benefits of plug-in hybrid electric vehicles and vehicle-to-grid services, Environ. Sci. Technol, 43 (2009), 1199–1204.

[31] S. Blumsack, C. Samaras, P. Hines, Long-term electric system investments to support Plug-in Hybrid Electric Vehicles, IEEE PES GM, pages 1–6, July, 2008.

[32] R.W. McCarthy, C. Yang, J. Ogden, Impacts of Electric-drive Vehicles on California's Energy System, University of California, Davis UCD-ITS-RP-08-24, 2008.

[33] P. Denholm, W. Short, An Evaluation of Utility System Impacts and Benefits of Optimally Dispatched Plug-In Hybrid Electric Vehicles, Technical Report TP-620-40293, National Renewable Energy Laboratory, 2006.

[34] S. W. Hadley, A. Tsvetkova, Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation, Technical Report TM-2007/150, Oak Ridge National Laboratory, 2008.

[35] J. Taylor, A. Maitra, M. Alexander, D. Brooks, M. Duvall, Evaluation of the Impact of Plug-in Electric Vehicle Loading on Distribution System Operations. IEEE Power & Energy Society, 2009.

[36] C. Quinn, D. Zimmerle, T. H. Bradley, The effect of communication architecture on the availability, reliability, and economics of plug-in hybrid electric vehicle-to-grid ancillary services, J. Power Sources 195 (2010) 1500–1509.

[37] Carbon Pathways Analysis: Informing Development of a Carbon Reduction Strategy for the Transport Sector, Department for Transport, London, UK, July 2008.

[38] Society of Automotive Engineers, Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Hybrid Committee, 1999, J1711.

[39] Society of Automotive Engineers, Utility Factor Definitions for Plug-In Hybrid Electric Vehicles Using 2001 U.S. DOT National Household Travel Survey Data, Hybrid Committee, 2009, J2841.

[40] National Highway Transportation Survey, http://nhts.ornl.gov/.

[41] T. H. Bradley, C. W. Quinn, Analysis of plug-in hybrid electric vehicle utility factors, J. Power Sources, 195 (2010) 5399–5408.

[42] Status Overview of Hybrid and Electric Vehicle technology: Final report Phase III, Annex VII, IAHEV, International Energy Agency, Paris, France, 2007.

[43] B. Scrosati, J. Garche, Lithium batteries: Status, prospects and future, J. Power Sources 195 (2010) 2419–2430.

[44] S. Al-Hallaj, J. Prakash, J.R. Selman, Characterization of commercial Li-ion batteries using electrochemical–calorimetric measurements, J. Power Sources 87 (2000).

[45] J.R. Selman, S. Al-Hallaj, I. Uchida, Y. Hirano, Cooperative research on safety fundamentals of lithium batteries, J. Power Sources (2001), 186-194.

[46] S. Al-Hallaj, J.R. Selman, Thermal modeling of secondary lithium batteries for electric vehicle/hybrid electric vehicle applications, J. Power Sources 110 (2002) 341–348.

[47] E. Karden, S. Ploumen, B. Fricke, T. Miller, K. Snyder, Energy storage devices for future hybrid electric vehicles, J. Power Sources 168 (2007), 2-11.

[48] Energy Markets Outlook, Department for Business Enterprise and Regulatory Reform, London, UK, October 2007.

[49] Tackling Investment Challenges in Power Generation, International Energy Agency, Paris, France, 2007.