REVIEW ARTICLE
PUBLISHED ONLINE: XX MAY 2012 | DOI: 10.1038/NCLIMATE1429

nature climate change

Realizing the electric-vehicle revolution

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Full battery electric vehicles (BEVs) have become an important policy option to mitigate climate change, but there are major uncertainties in the scale and timing of market diffusion. Although there has been substantial work showing the potential energy and climate benefits of BEVs, demand-side factors, such as consumer behaviour, are less recognized in the debate. We show the importance of assessing BEV diffusion from an integrated perspective, focusing on key interactions between technology and behaviour across different scales, including power-system demand, charging infrastructure, vehicle performance, driving patterns and individual adoption behaviour.

Transport is a major source of unsustainable energy use owing to a nearly complete dependence on liquid fossil fuels. Advancements in battery technology have made electric vehicles a potentially important strategy to decarbonize transport[1–13]. Here we review the literature on electric vehicles, focusing on the market diffusion of full battery electric vehicles (BEVs). We examine their potential from an integrated perspective, looking at interactions between technology and behaviour, and how that can influence diffusion. We draw mostly on evidence from Western Europe and North America, but the energy implications of the analysis are global.

At present, the transport sector accounts for 27% of global final energy consumption and is expected to increase 50% by 2035 (ref. 1). Owing to 94% reliance on oil, transport is the second largest source of CO_2 emissions at 6.3 Gt or 24% of the total, compared with power generation (40%), industry (16%), buildings (12%) and agriculture and non-energy use (8%)[1]. Two main factors influence transport CO_2 emissions: the change in total volume of travel and the fuel efficiency of the mode of travel. From 1990 to 2004, travel by light-duty vehicles (LDVs), including passenger cars, small vans and sport utility vehicles, in the Organisation for Economic Co-operation and Development (OECD) countries increased 15% (13,000 to 15,000 km per person per year). Truck travel (tonne-km per capita) increased 36% and global air travel has increased 90% since 1990 (ref. 2). The fastest growth in transport is expected from air travel, road freight and LDVs[2]. Although high-impact events such as peak oil or major economic downturns could influence these trends, based on current knowledge there is little indication that these trends will reverse. Furthermore, given the relatively low average rates of vehicle ownership in emerging economies coupled with rising gross domestic product growth rates, aggregate vehicle travel is expected to increase.

Figure 1a shows that 60–70% of road transport CO_2 emissions are from passenger vehicles, prompting energy policy to focus on the passenger vehicle fleet. BEVs are estimated to reduce well-to-wheel emissions by 70–85% by 2030 with virtually zero tailpipe emissions, compared with current internal-combustion-engine (ICE) vehicles[5]. However, these CO_2 benefits will depend on sufficient low-carbon electricity, indicating that BEVs have important interactions with the domestic and power sectors as discussed below.

Figure 1b shows a global policy scenario assuming 16% of total new passenger car sales are BEVs by 2035. In that scenario, transport electricity demand reaches 128 million tonnes of oil equivalent (Mtoe) with 90% for BEVs. Most of the oil savings are from road transport, which accounts for >80% of total oil savings. Among road vehicles, LDVs account for >75% of oil savings, abating 395 Mt of CO_2 by 2035 (ref. 1). Such scenarios have brought attention to the potential of electrifying the LDV fleet to mitigate carbon emissions and save oil. Yet even under such highly optimistic BEV penetration rates, oil still dominates transport at 77%. Figure 1b also shows that biofuels and other advanced fuels could play an important role in future transport. The rise of BEVs in developed markets could be threatened by the emergence of alternative-fuel technologies. If industry research and development efforts are able to increase the total energy efficiency of advanced fuel and biofuel engines, adoption of BEVs may be delayed because of consumer acceptance of existing technology. Recent studies indicate that advanced ICE vehicles could achieve 13–30% efficiency gains over the next 8–10 years[13,14]. Although BEVs have an important role to play, they will face increasing market competition from advanced-fuel vehicles and should not necessarily be viewed as a panacea to decarbonize transport.

Major uncertainties exist in the scale and timing of market diffusion. Although the energy saving potential of BEVs has been shown[1–5], the technological and behavioural dynamics of diffusion have not been fully explored in the literature (Box 1). Our Review assesses key interactions between technology and behaviour across different scales, including system-level implications between large BEV fleets and power-system demand, local-level interactions between charging infrastructure and driving patterns, individual adoption behaviour, and policy and planning implications.

System-level implications

Decarbonizing the grid. Although electrification of LDVs could achieve deep cuts in CO_2 emissions[10–12], BEV diffusion will be ineffective if it occurs in regions with high-carbon electricity. Optimistic scenarios[1,9] show global BEV shares reaching 90% by 2050, abating 4 Gt of CO_2. These scenarios assume that global average electricity CO_2 intensity must drop below 100 g CO_2 kWh^{-1} by 2050 from a current average of ~500 g CO_2 kWh^{-1}. That is a fivefold decrease within 40 years. Most industrialized countries are now entering a new power-generation investment cycle that represents an opportunity to deploy clean and efficient power-generation technologies. This is important, because power-generation investment decisions taken over the next 10 years will lock-in CO_2 emissions for the next 40–50 years[15]. The planning horizon for the vehicle-fleet cycle is 12–15 years. Electricity generation decisions must therefore be made within the next 10 years if it is to be aligned with the next two to three vehicle-fleet cycles where large-scale commercialization of BEVs is expected.

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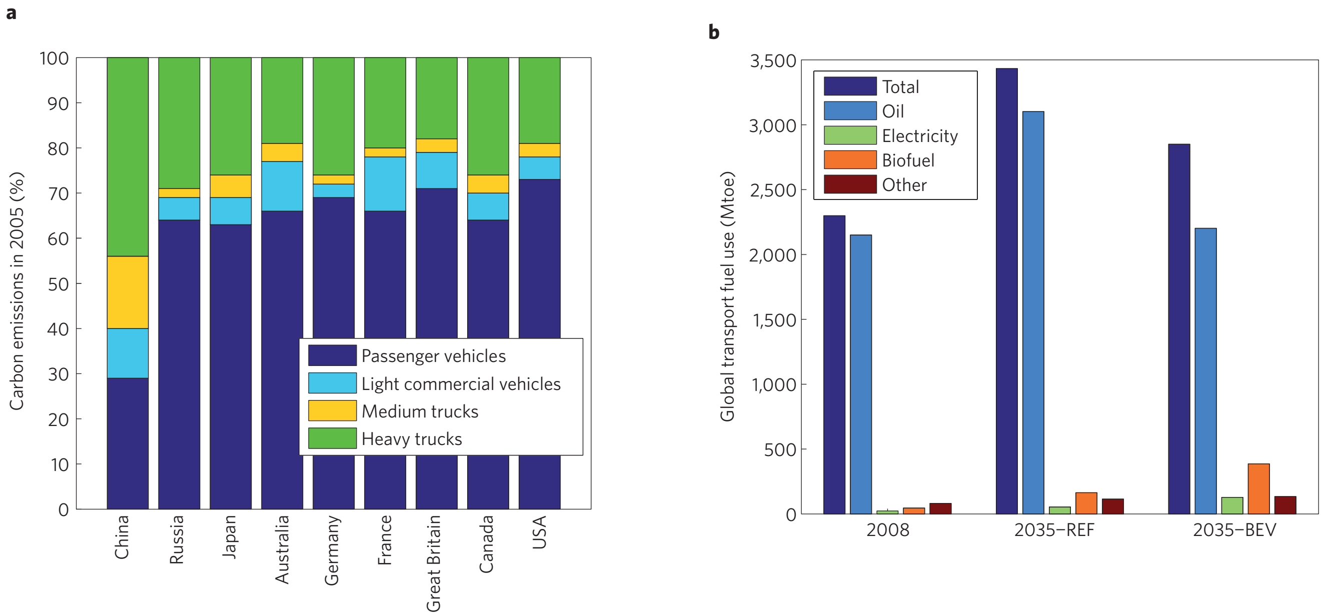

Figure 1 | Global transport carbon emissions and energy use. a, Road transport CO_2 emissions across selected countries in 2005. Data taken from ref. 6. **b**, Breakdown of global transport fuel use for two different scenarios, compared with 2008. 2035-REF and 2035-BEV correspond to current policy and 450 scenarios from ref. 1, respectively. Oil includes bunker fuel. Other covers the range of advanced alternative fuels. Data taken from ref. 1.

The scale of that challenge has not been fully appreciated in the policy discussion. Consider the current regional differences in electricity CO_2 intensity coupled with the rise of LDV ownership in emerging economies. In 2006, average electricity emissions ranged from 190 g CO_2 kWh^{-1} in Latin America to 944 g CO_2 kWh^{-1} in India. In 2005, LDV ownership rates (vehicles per 1,000 people) in China were 11, compared with 424 and 559 in OECD Europe and North America, respectively. During 2000–2005, LDV sales in China increased 340% (700,000 to 3.1 million), and will continue to rise[9]. Meanwhile, North American LDV sales increased 3% while OECD European sales decreased 2% (ref. 9). The largest potential BEV market is China, which at present has the world's second-highest grid CO_2 intensity (868 g CO_2 kWh^{-1}). These differences have a massive impact on the potential CO_2 savings of BEVs. The on-road CO_2 emissions from a BEV in France is ~10 g CO_2 km^{-1} owing to a low grid CO_2 intensity of 86 g CO_2 kWh^{-1} derived from 80% nuclear generation, whereas the same vehicle in China would emit ~110 g CO_2 km^{-1} because of a greater reliance on coal-based generation[16]. But there is opportunity in countries, such as China, with low levels of ICE vehicles to move to a new technology ('leapfrogging'), as far less capital has been sunk into supporting infrastructure (second-hand markets, maintenance, repairs, refuelling).

Also, BEV benefits are often calculated based on the average emissions factor, which is the average grid CO_2 intensity, rather than the marginal emissions factor, which calculates the change in grid CO_2 intensity from an increase in power production to meet rising electricity demand. During 2002–2009, the UK's marginal emissions factor was 690 g CO_2 kWh^{-1} compared with an average emissions factor of 510 g CO_2 kWh^{-1} (ref. 17). Not using the marginal emissions factor could underestimate CO_2 emissions from increasing BEV electricity demand, if grids meet that additional demand by ramping up production from fossil-fuel thermal plants[16,17]. Integrated power-system planning will need to ensure any additional BEV demand is met with low-carbon electricity.

Additional generation capacity. There is uncertainty whether high BEV penetrations will require additional electricity generation capacity and over what period. If BEVs can capture 40–90% of the market share from 2035 to 2050, global electricity demand could increase by 142–580 Mtoe (refs 1,9). Over the short to medium term (2010–2030), national studies in the UK[18] and the United States[19] indicate that additional capacity will not be required. The current US grid could charge 70% of all cars and light trucks if they were charged overnight when idle generation capacity is available[19]. In the UK, estimates of BEV market shares range from 20 to 70% from 2030 to 2050, potentially requiring 2–18 GW of installed capacity[18,20,21]. However, predicting the need for additional capacity over the long term (until 2050 and beyond) is far less certain and will depend on the future grid mix and the degree of interaction with other sectors. Under a carbon-constrained scenario with high wind-power 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 will also be required to decarbonize the building stock, indicating new interactions and uncertainties between the power, transport and housing sectors. The UK has developed an 80% system-wide carbon-reduction scenario by 2050 using 60% wind-power penetration, which could double generation capacity to 120–145 GW relative to a 2000 baseline. In that scenario, demand is primarily driven by BEVs and residential electrification for boilers and heat pumps[18,21]. Households will also have widely differing patterns of energy consumption influenced by income, household composition, tenure and location[22]. Many of the challenges for rapid diffusion relate to uncertain feedback effects of how local-level behaviour might impact on the larger technological system.

Local-level interactions

Charging regimes. Household charging will affect system demand through interactions between energy end-use, charging infrastructure, and local transmission and distribution networks[23–26]. These factors in turn will influence the rate of adoption. In the United States, 63% of respondents expressed concern over the reliability of local utilities to support vehicle charging[27]. Night-time charging during low-demand periods could have grid-balancing benefits if BEVs are used as distributed energy storage. This scenario coincides with consumer expectations — in a survey of US vehicle owners, 81% of respondents preferred home charging over work charging[27]. But this raises unanswered questions about when users will actually plug-in, which is influenced by many factors (convenience, work, leisure, tariff structures). Many charging regimes have been assessed, including: daytime peak, early evening (before 2000 hours), uniformly spread over 24 hours, charging when the vehicle is not in motion, spare capacity valley-filling algorithms, staggered fleet connection times and agent-based profiles derived from survey data[24–26,28–36].

Most approaches assume that drivers will subscribe to the same charging behaviour, and therefore do not account for consumer heterogeneity. Recent advances in remote-controlled timers that can be pre-programmed to recharge batteries during off-peak rates could capture a wider range of behaviour. But the effectiveness of such technologies to mitigate system impacts will not be proven until tested by large vehicle fleets. Conversely, removing individual behaviour by having the electric power utility exert full control over vehicle charging has also been proposed[34]. This could result in optimal timing and minimum cost charging, and introduce top-down control to avoid grid overloading, but would depend on further technological advancements and consumer acceptance of smart-charging infrastructure and utility control to optimize vehicle-to-grid interactions. Although the technology exists, the integration of components into vehicles, intelligent charging stations and returning control back to the utility faces problems of near-term feasibility and long-term scalability[37].

Trip journey purpose. There is also often a focus on work commuting with less attention on other trip journeys and potential system demand. Differences in trip frequency and length are also not typically considered. From 1996 to 2006, UK passenger kilometres for work commuting were ~20% of the total. But other trip journey purposes, including shopping (13–14%), personal (16–18%), visiting friends (15–17%) and holidays (9–12%) were non-trivial and on the rise[38]. Assumptions behind driving patterns have important implications for BEV energy management and CO_2 mitigation. Figure 2 shows that the proportion of UK passenger-car tailpipe CO_2 emissions as a function of trip journey purpose remained relatively stable from 1996 to 2006. Although commuting made up the single largest share of CO_2 emissions, the combined effects of all other trip journeys was ~75%.

A central focus on work commuting can overlook the carbon emissions from other trip destinations. More realistic assumptions behind trends in driver behaviour will need to be made to inform development of an all-electric range, consumer charging profiles and infrastructure build. It will also be important to consider how trip destinations may change over time — which is influenced by demographics, socio-economics and lifestyle trends — and what implications this has for mitigating CO_2 emissions.

Range anxiety. Across the European Union, 74% of consumers expected a range of 480 km before having to recharge. Yet the typical distance driven by that group is 80 km per day[39]. This shows that there is an important disconnect between perceived utility and the actual performance of the vehicle. Determining the number of charging points necessary to trigger adoption may not mean having a high density of charging points within a given area, but just enough to reduce driver range anxiety as a function of trip destination. Other possibilities to mitigate range anxiety would be adoption of longer-range plug-in hybrid cars, or households opting for a multi-car solution where shorter-range BEVs are used for daily city driving, with longer-distance trips left for a second vehicle. Recent empirical work in the UK indicates that some hybrids were purchased as a second household car[40].

Recharging convenience will also be important for adoption, which could be met through quick-charging technology. However, as the vehicle stock grows, considerable daytime charging could increase peak demand[2], overload local distribution networks already near capacity and require local infrastructure reinforcement[4,20]. Refuelling a long-range (80 km) BEV in <10 minutes could require up to 0.5 MW per vehicle and close proximity to a dedicated source of electric power[4]. Some consumers are willing to invest in community charging infrastructure ranging from a high of 65% in China to a low of 23% in Japan, reflecting the relative difference in interest for BEVs between these countries. In the European Union, 24–39% of respondents were willing to invest in neighbourhood charging infrastructure[41]. Although this sounds promising, we discuss below the inconsistencies between stated consumer preferences and willingness to pay.

Box 1 | Technological and behavioural dynamics of diffusion.

Innovation diffusion is influenced by behavioural and technological factors. Innovations spread through social networks, and technologies improve over time. Individuals learn of innovations from previous adopters, which can positively influence further adoption[55]. Improved technological performance can increase returns to adoption and accelerate diffusion[76]. Energy-technology diffusion is typically assessed with learning curves, which is the relationship between cost, c, and the cumulative growth in stock, y, empirically observed to be a power law of the form $c(y) \propto y^{-\alpha}$ where the exponent, α is the rate of improvement called the progress ratio, $2^{-\alpha}$, which is the factor by which costs decrease with each doubling of cumulative production. That relationship has been observed for different energy technologies (ethanol fuels, installed wind capacity, photovoltaic cells)[77]. The learning curve reduces the diffusion process to cumulative stock and price effects. Although this is appropriate for supply-side technology[78], growth in demand-side technology (BEVs) will also be influenced by behavioural factors (preferences, attitudes, lifestyles and social norms). These factors are not typically accounted for in the analysis of energy-technology diffusion[79]. There is a need to better understand the feedbacks between how behaviour can influence technological diffusion and how technology improvements can in turn influence adoption.

Battery performance and acceptance. Rapid consumer adoption is contingent on increasing vehicle performance and lowering the cost, which depends on advancements in battery technology. Although nickel-metal hydride (Ni-MH) batteries were the first to be used on a large scale in hybrids, lithium-ion (Li-ion) batteries are lighter (Li density = 530 kg m^{-3}; Ni density = 8,800 kg m^{-3}) and have higher energy and power densities[42]. From 1990 to 2005, the average annual rate of Li-ion energy-density improvement was 7% compared with Ni-MH (4%) and Ni-Cd (1%). Importantly, Li-ion energy density has continued to improve, reaching 450 Wh l^{-1} in 2005, whereas Ni-Cd and Ni-MH have levelled off at 130 Wh l^{-1} and 350 Wh l^{-1}, respectively, since 2005 (ref. 42). Although Li-ion batteries have become the preferred choice owing to high efficiency and long life[7,43], scaling up the technology remains problematic because of high cost, potential safety problems such as risk of fumes or flames with deep over-charge (~200%) especially with cobalt-based batteries, narrow operational temperatures (adversely affected >65 °C or <0 °C) and availability of materials[43–46] such as rare-earth minerals. But recent research shows that Li-Fe phosphate ($LiFePO_4$) batteries perform better and degrade less quickly under real-world driving conditions than previously thought[47]. Furthermore, battery technology will continue to improve with advancements in nanomaterials, where gains in capacity, power, cost and materials sustainability are far from being fully exploited[48].

Mass diffusion will ultimately depend on consumer's acceptance and use of battery technology — an area of great uncertainty. Consumers often expect unrealistic short payback periods for any innovation (~18 months)[13]. This relates to the vehicle and battery, and means that the costs, the residual value and the perceived benefits are all key decision criteria for drivers. Battery performance

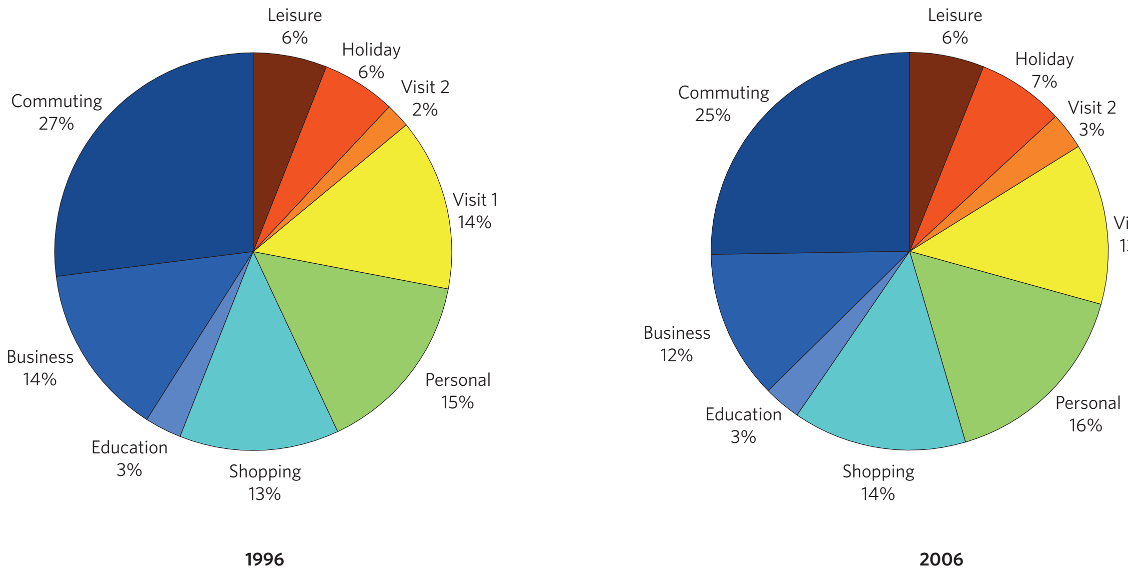

Figure 2 | Proportion of passenger-car tailpipe CO_2 emissions as a function of trip journey purpose in the UK for 1996 and 2006. Visit 1 includes visiting friends/relatives at private homes; Visit 2 is visiting them elsewhere. Data taken from ref. 38.

and the related life-cycle costs will be influenced by how consumers use the technology. Batteries will need to endure up to 15 years of recharge–discharge cycles or be replaced, potentially doubling the life-cycle cost[23]. To trigger widespread adoption, it is anticipated that battery storage will need to increase by a factor of four (from 5 kWh to 20 kWh) while costs will need to drop 70% (US$1,000 per kWh to US$300 per kWh) over the next 10 years[2,4] representing a challenge for research and development. This further highlights how behaviour interacts with technology to influence diffusion. Much of the uncertainty stems from heterogeneous consumer behaviour, and our poor understanding of the motivating factors behind adoption and how consumers can be incentivized.

Consumer adoption behaviour

Willingness to pay. Consumers often cite high fuel prices and environmental benefits as key reasons for preferring BEV attributes[49]. A recent industry survey assessed the top factors across different vehicle markets (United States, Japan, European Union, China) that would favourably influence BEV adoption[41]. Although fuel savings and the environment ranked highest, government incentives to lower ownership cost was also an important factor. The survey also indicated that lack of access to charging stations, high price and range anxiety were key deterrents to adoption. Charging convenience features strongly across different surveys[39,41,49], where respondents expressed a willingness to pay for faster home charging and >50% were willing to pay <US$500–1,000 to reduce charge time from eight to four hours[39]. But we know from empirical work that there is often a discrepancy between what consumer's state they prefer, and what they are actually willing to pay[39,41].

A recent European Union survey reported that 16% of respondents were first movers likely to buy or lease a BEV, 53% might be willing to consider and 31% would not likely adopt[39]. This implies that over half the respondents could be incentivized to adopt. But when probed further, Fig. 3a shows that less than half, or 43%, were actually willing to pay a price premium, and Fig. 3b shows that 58% expected to pay <€15,000 after government incentives, implying that BEVs would have to be cost competitive with ICE vehicles to trigger adoption[39].

Informing consumers. The lack of willingness to pay a premium for fuel savings and environmental benefits suggests that many consumers are poorly informed over the cost savings of BEVs and the causal link between fuel efficiency and CO_2 emissions. Although consumers cite fuel efficiency as a top criteria in purchasing decisions, they heavily discount (18–30%) future cost savings from increased fuel economy while expecting short payback periods (two to three years)[13,50]. This suggests that there are important market failures in consumer decision-making about fuel economy. In the United States, research found that consumers typically account for only the first three years of fuel savings, which understates the true economic value of a 14-year vehicle life by 60% (ref. 50).

What may contribute to this market failure is the lack of timely and targeted consumer information on vehicle CO_2 emissions, distance travelled and cost savings. Consequently, at the point of purchase, vehicle attributes such as performance, power, engine size and brand image are given higher priority than vehicle emissions and fuel savings[13,51]. Although information on CO_2 emissions is mandatory on car advertising material in the UK, it is only first seen in the showroom, which is too late in the decision-making process. In the UK, nearly 80% of car buyers do not look at the vehicle's emission rating before purchase[52].

Social norms. The lack of consumer understanding of BEV cost advantages coupled with the current market structure, where high-emission performance-branded cars are associated with social status, is an important barrier for BEV adoption. Consumer research has shown a strong link between purchasing behaviour and social norms surrounding ownership, identity and status[53,54]. Social norms can influence purchasing decisions where buyers discount financial savings through improved fuel economy in preference for higher-specification cars[13,55]. This is reflected in surveys indicating that consumers are not willing to compromise vehicle performance and style[52].

We are now beginning to acquire some understanding of the purchasing motivations of the early adopters of hybrids, which could give information on how to incentivize BEV adoption. Empirical research shows that there are a wide range of factors motivating hybrid adoption, including interest in new technology, financial gain, environmental values and policy-related benefits[40,56–58]. Lifestyle and attitude factors also have a strong influence on vehicle-purchasing decisions. The symbolic image conveyed by driving a hybrid has been shown to be a strong adoption factor[57], which can create an ideology or perception that hybrid-car ownership reflects a particular community's values and norms[53]. More research is required to decouple

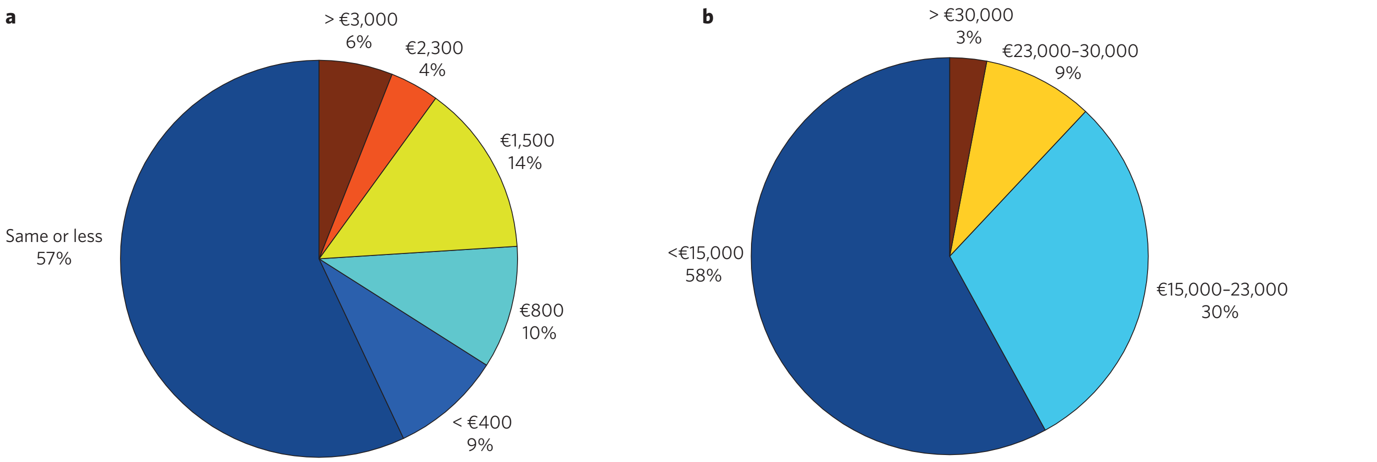

Figure 3 | Consumer price expectations for BEV adoption. a, Proportion of consumers stating acceptable BEV purchase price premium relative to ICE vehicles. **b**, Proportion of consumers stating expected BEV purchase price after government incentives (2011). Data taken from ref. 39.

consumer behaviour from the social norms of identity and status[40,54,56] surrounding ICE-vehicle ownership, and incentivize BEV adoption.

Recent UK research also indicates that exposure to hybrids through social networks gave buyers confidence in the technology, which positively influenced adoption[40]. Empirical and theoretical work on innovation diffusion and environmental behaviour shows that consumers are influenced by their social groups and willing to comply with their norms[55]. These findings indicate that government and industry need to more effectively communicate how BEVs can address both the financial concerns and social aspirations of potential adopters. There is scope for policy to be informed by new understanding of how information and innovations spread through social networks[59–65] to identify potential adopters, and increase exposure, familiarity and knowledge about the benefits of BEVs.

Conclusions

What has become increasingly clear is that the scale of BEV diffusion necessary to decarbonize transport will not be realized without immediate and sustained policy support, industry investment and fundamental changes in consumer behaviour. This Review has highlighted the importance of interactions between technology and behaviour across different scales, and how that will influence market diffusion. There is need for an integrated approach to decarbonize transport that will depend on both the technical and behavioural sciences. Recent research shows the importance of standards[66], policy and consumer incentives[67,68], technology impacts[69,70], constraints[71] and advancements[72], and inter-market competition[73–75] for BEV diffusion.

Even with the most ambitious assumptions, BEVs may only provide a niche market over the next 20 years. Even then, this niche market will need to be supported during the early phases of diffusion. Policy can assist by providing free charging using renewable energy at publicly accessed parking places, but investors will need to anticipate under-utilization of charging infrastructure until the market matures. Industry could assist by exploring new business models such as vehicle leasing, which already makes up a share of US and UK vehicle markets. At present, BEVs are sold as a complete purchase, purchase of vehicle and lease of battery, and combined lease of vehicle and battery. Other models could include shared ownership or pay-as-you-go schemes similar to mobile phones[20].

Further attention should be given to the potential market for small short-range city BEVs, where there is opportunity to reduce range anxiety through public charging points or battery-swap stations. The costs of providing a low-speed leased BEV for local city use is far less than trying to replicate the current ownership model of an all-purpose long-range ICE vehicle. Much of the literature assumes that the market is homogenous, but car manufacturers have been very successful in demonstrating a huge heterogeneity in the market. Within such an embryonic market we need to know more about the diffusion process, the characteristics of early adopters, and how potential buyers and leasers can be identified and incentivized.

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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.

Additional information

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