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King Abdullah Petroleum Studies and Research Center

Will Current Electric Vehicle Policy Lead to Cost-Effective Electrification?

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Key Points

Passenger cars are responsible for a large and steadily growing share of global energy-related greenhouse gas (GHG) emissions. Electric vehicles (EVs) powered by renewable electricity have the potential to provide a substantial contribution to the decarbonization of passenger car transport. Unless carbon capture and storage technologies become cost competitive, EVs are likely to form a growing share of the personal mobility solution. But what is the lowest cost path to achieving high levels of EV penetration?

Encouraged by the falling cost of batteries, EV policy today focuses on expediting electrification, paying comparatively little attention to the cost of the particular type of EVs and charging infrastructure being deployed. This paper argues that, due to its strong influence on EV innovation paths, EV policy could be better designed if it paid more attention to future cost and technology development risk. In particular, key findings include:

- EV policy with a strong bias toward long-range battery electric vehicles (BEVs) risks leading to a higher cost of electrification in the 2030 timeframe, possibly exceeding the ability of governments to sustain the necessary incentives until battery cost drops sufficiently.

- Plug-in hybrid electric vehicles (PHEVs) with long electric range could allow intermediate decarbonization targets to be met while being less sensitive to the rate of development of battery technology. The BEV option could be pursued in parallel by targeting specific segments where shorter ranges are acceptable to their users.

- Promoting a balanced mix of BEVs and PHEVs could set the electrification of passenger cars on a lower risk, lower cost, path that is more likely to become self-sustained before government support is withdrawn.

- Examining EV policy in the U.K. and in California, we find that it is generally not incompatible with achieving balanced mixes of BEVs and PHEVs. However, this may not be sufficient and some fine tuning would enable better balancing of medium-term risks and long-term goals.

Summary

Governments around the world are seeking absent cost competitive carbon capture and storage or other decarbonization strategies to expedite the electrification of passenger cars, to meet their environmental protection targets while at the same time developing local value chains. Despite some early success stories and the growing momentum behind the transition to electric vehicles EVs, reaching a high level of penetration rapidly on a global scale will be challenging. For this reason, in today's policy discourse much emphasis is placed on identifying those mixes of policy instruments that are most effective at accelerating the deployment of EVs and related charging infrastructure. Comparatively little attention is devoted to clearly articulating any vision of future self-sustained electrification of passenger car transport that does not solely rely on the cost of EV batteries rapidly falling. However, due to the path dependent nature of the development and adoption process of new technology like EVs, the type of vehicles and infrastructure initially deployed will influence the technology's further evolution, possibly locking it in to a certain path. Hence we argue that EV policy today could be better designed if it recognized the need to guide the EV transition toward pathways involving low technology risk.

In this study we consider whether current EV and infrastructure policy is conducive to cost-effective electrification of passenger car transport. To investigate this, we have developed a model that estimates the total incremental cost of different EV and infrastructure mixes over the whole passenger car fleet, relative to a base case where only internal combustion engine vehicles (ICEVs) are present. We have applied our model to two case studies, the U.K. and California, which we chose because both are aggressively pursuing electrification of passenger cars and are illustrative of the different North American and European market conditions and policy frameworks. We base our analysis in the 2025-2030 timeframe. For both the U.K. and California we have developed a set of key scenarios that are broadly consistent with current policies. All scenarios are characterized by the same overall number of EVs and similar fleet average CO_2 tailpipe emissions, though they differ in the type of EVs and infrastructure deployed.

Despite the substantial differences in the passenger car market structure and vehicle usage between the U.K. and California, the results we have obtained show important similarities. In both cases it is apparent that rapidly achieving high levels of BEV penetration risks making the incremental cost of electrification in the 2030 timeframe hundreds of millions of US dollars per year higher than other, more balanced, mixes of EVs with similar overall CO_2 emissions. This is because it will most likely involve making the functionality of these vehicles as similar as possible to that of the ICEVs that they aim to replace, which means equipping them with large batteries and providing extensive charging infrastructure networks so they can travel anywhere without restrictions. The future cost of large batteries is strongly dependent on technology development, which is inherently uncertain. Extensive charging infrastructure also adds to the cost, due to its likely low utilization which makes its economics problematic.

We also find that an approach where BEVs are limited to a relatively short-range role, supported by mainly urban charging infrastructure networks, and where the rest of the EV fleet comprises relatively long all-electric range (AER) PHEVs, could substantially reduce the risk of the cost of the EV transition becoming unsustainable by year 2030. Long AER PHEVs have most powertrain components in common with BEVs, so technology development and scale economies could still be realized that

would pave the way for possible future substitution by long-range BEVs, should battery technology improve sufficiently. At the same time, continuing to support BEVs where they are less costly would allow this option not to become locked out and also enable user practices and institutions to gradually adapt, thus better preparing for long-range BEVs to be rapidly rolled out.

It is clear from current U.K. and California policy that neither government is prepared to sustain EV incentives indefinitely and both will seek ways of achieving their policy goals at the least cost. It is also apparent that vehicle cost considerations are increasingly reflected in EV policy. However, in different ways, current EV policy both in the U.K. and California is not guaranteed to set the transition on a low cost, low risk, pathway. A fleet-wide cost analysis of the type we have performed may therefore provide insights to assist governments to make their EV policy more robust under uncertainty.

Background and Scope

Why electric vehicles?

Road transport accounted for 21 percent of global energy consumption and 17 percent of global CO2 emissions in 2013 (IEA 2015c). GHG emissions from road transport globally have been growing steadily over the last few decades and will continue to do so if road transport is not progressively decoupled from fossil fuels (EIA 2014). In particular, unless large-scale carbon capture or liquid fuels with significantly reduced carbon content become economically viable, stabilizing the global temperature rise to below 2 °C relative to pre-industrial levels – as set out in the 2015 Paris Agreements – will require a combination of electric vehicles, low-carbon electricity and, to a lesser extent, hydrogen. This would be in addition to improved fuel efficiency and deployment of alternative fuels in road transport, particularly advanced biofuels, (IEA 2015a, Kahn Ribeiro et al. 2012). Even if sustainable low carbon liquid fuels were to become available at scale, their value would be higher in displacing GHG emissions from aviation, shipping and heavy duty road vehicles (IEA 2011). Electricity may therefore have a decisive role to play in passenger car transport (Kahn Ribeiro et al. 2012). Electrification of passenger car transport also has the added benefits of diversifying transport fuel supplies and of reducing emissions of local air pollutants in urban areas, the impacts of which on public health are of growing concern in both developed and developing countries (OECD 2014).

Figure 1 shows across different studies the rate at which road transport needs to be electrified in order to keep the global temperature increase below 2 °C relative to pre-industrial levels varies significantly, as a multitude of energy technology pathways are possible (IPCC 2014).

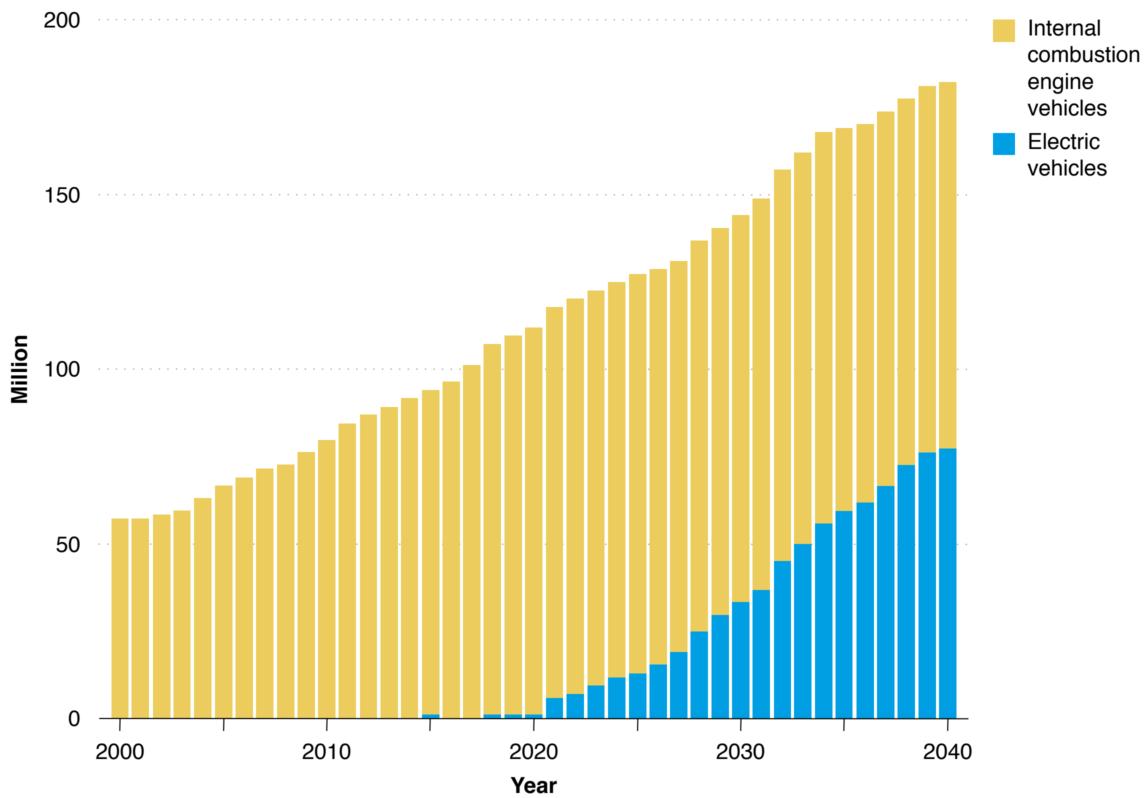

Figure 1. Global EV light duty vehicle market share in the 450 scenario of the IEA.

Source: (IEA 2015a).

Some studies suggest that EV sales will have to grow extremely rapidly in the coming decades, reaching more than 40 percent share of light duty vehicles sold globally in 2040, in order to compensate for the soaring motorization level in developing countries; see in particular the 450 Scenario of the IEA (IEA 2015a). Scenarios may differ, though it is generally accepted that electric vehicles will have a major role to play if global climate stabilization goals are to be achieved, especially in large markets such as the U.S., Europe, China and India.

Aim, scope and structure of study

The aim of our work is to assess whether today's EV policy represents the most cost-effective future use of this technology, considering the policy objectives it aims to achieve, particularly GHG emission reduction. We do so by exploring the incremental costs of future mixes of EVs and charging infrastructures that are broadly compatible with today's policy and market trends and that can provide similar GHG emission reductions. We use the results of our cost analysis as a basis for discussion of key features and possible implications of current EV policy, and to identify opportunities for making it more robust under uncertainty.

It is worth noting that current EV policy is informed by the idea of carbon budgets. It seeks to promote the level of EV penetration that is required in order to sufficiently reduce future emissions from transport, based on analysis that also takes into account other low carbon transport technologies and the broader energy system. In our study we do not seek to appraise the cost-effectiveness of governments' EV deployment targets per se; instead we analyze the economic implications of achieving the same EV deployment and emission reduction levels through different types of EVs and charging infrastructure.

We also discuss the effect that policy has on the development of different types of EV and charging infrastructure. The following section introduces the methods used for our techno-economic assessment of EV policy. Current EV policy for the two case studies we have chosen, the U.K. and California, is then considered. This provides the rationale for developing the future EV and infrastructure mix scenarios that we analyze in the final section and from which we derive policy recommendations.

Electric Vehicle Deployment Policy and its Effect on Innovation

Government support to electric vehicles

For the reasons noted, electrification of passenger car transport is receiving strong support from several national governments worldwide, which seek not only to meet their environmental protection goals but also to develop national value chains in this emerging industry (Lutsey 2015). Alongside aspirational targets set by several governments, the deployment of EVs and charging infrastructure is increasingly being driven by regulation. Most notably, the California Zero Emission Vehicle mandate sets targets for EV sales with enforceable fines for the automotive manufacturers that fail to meet them; this type of regulation is increasingly being adopted across the U.S. and Canada. In the European Union, the directive on the deployment of alternative fuels infrastructure (European Union 2014) mandates that member states must develop national policy frameworks and targets for future EV charging infrastructure rollout.

In order to achieve their targets, both aspirational and legally binding, national and local governments are deploying sets of incentives to EV adoption, including purchase grants, tax exemptions, non monetary incentives such as free parking and access to restricted lanes and financial support for the development of extensive charging infrastructure (IEA 2013, Lutsey 2015). Incentives are necessary to overcome the substantial cost gap currently existing between EVs and conventional ICEVs and the first mover disadvantage that characterizes the development of alternative fuel infrastructures (NRC 2015). For their part, automotive original equipment manufacturers (OEMs) are producing an increasingly diverse range of EV models in order to comply with mandates and standards and to gain an edge over their competitors in this new market. Although fleet penetration on a global level is still low, the market share of electric vehicles is growing fast (IEA 2015b). In some countries, such as Norway and the Netherlands, the market share of EVs has reached substantial levels, while the U.S., Japan and China lead the way in terms of the absolute size of their EV stocks and several new markets are starting to develop (IEA 2015b).

Despite some early success stories and the growing momentum behind the EV transition, reaching a high level of EV penetration rapidly on a global scale will be challenging because of the strong economic, institutional and behavioral barriers, together with the inherent slow turnover rate of passenger car stocks (Element Energy, Ecolane, and University of Aberdeen 2013, NRC 2015, Struben and Sterman 2008). For this reason, in today's policy discourse much emphasis is placed on identifying those mixes of policy instruments that are most effective at accelerating the deployment of EVs and related charging infrastructure (Lutsey 2015). Comparatively, little attention is devoted to clearly articulating a vision of future self-sustained electrification of passenger car transport that does not solely rely on the cost of EV batteries rapidly falling. However, considering that the current high levels of government incentives cannot be sustained indefinitely, we argue that policy should also be designed taking account of the need to guide the EV transition toward low technology risk pathways.

Policy is shaping technology adoption

Due to the specific characteristics of each market, the widely differing underlying taxation of conventional vehicles and fuels and the lack of generally accepted best practices, different approaches have so far been used in different countries to stimulate rapid EV adoption. As a result, different patterns of deployment of EVs and charging infrastructure have begun to emerge in the most active countries and regions, i.e., China, Europe, Japan and the U.S. (IEA 2013, 2015b, Lutsey 2015).

In particular, different ratios of pure BEVs and PHEVs and of rapid charging and slow charging infrastructure can be observed across leading countries (IEA 2013, 2015b). BEVs operate solely on electricity drawn externally and stored in a battery under any mode of operation. PHEVs can operate both on battery power drawn externally but also on an internal combustion engine, especially once the battery is depleted. In a PHEV the internal combustion engine and electric components of the powertrain can be arranged either in parallel or in series; the latter are also referred to as range extended electric vehicles (RE-EVs). In this paper we will use the term PHEVs for both types, unless otherwise specified. The term slow chargers is here used to indicate charging points of 3-7 kW power; rapid chargers supply power of the order of 40-50 kW. Figures 2 and 3 below provide an illustration of the different patterns of EV and charging infrastructure deployment observed today.

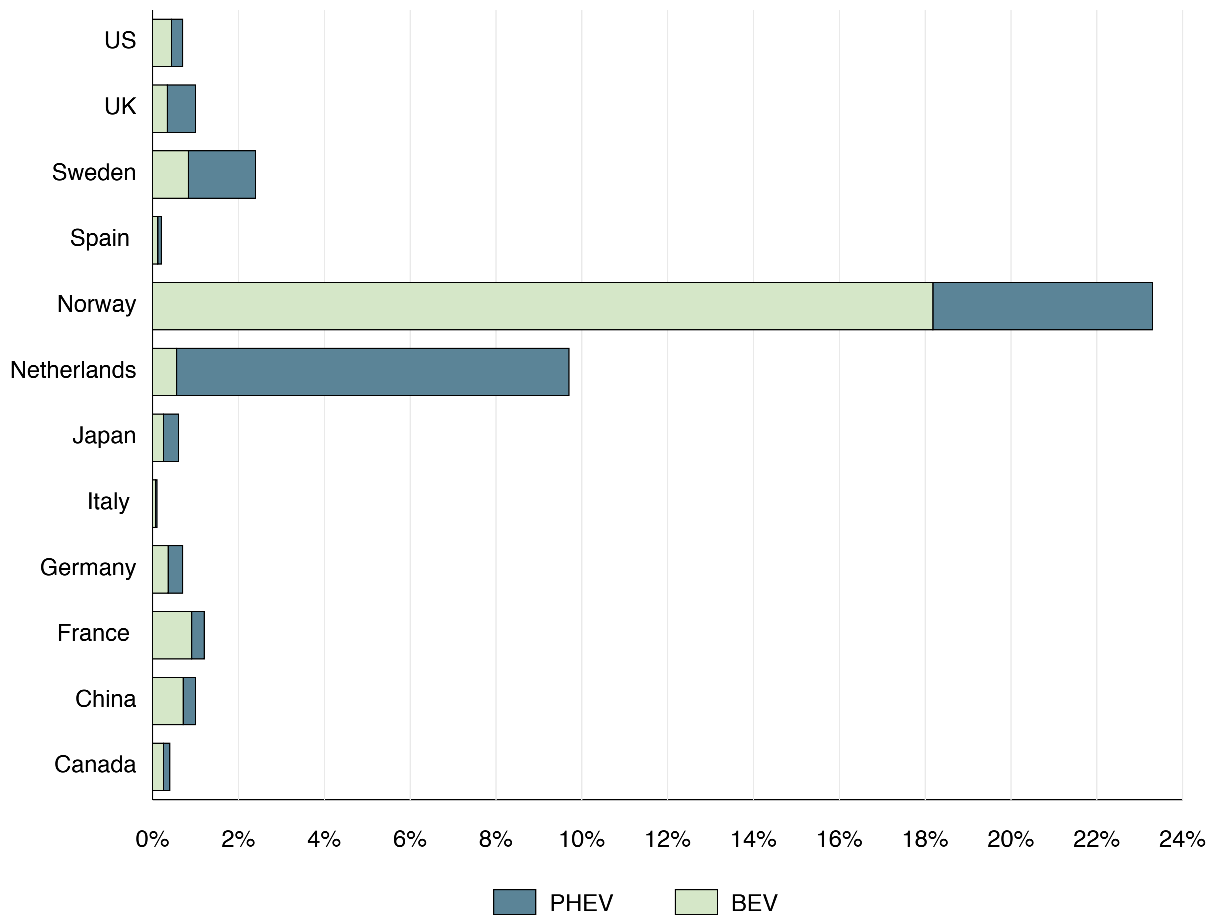

Figure 2. Market share of EVs in 2015, broken down by BEVs and PHEVs.

Source: adapted from IEA (2016).

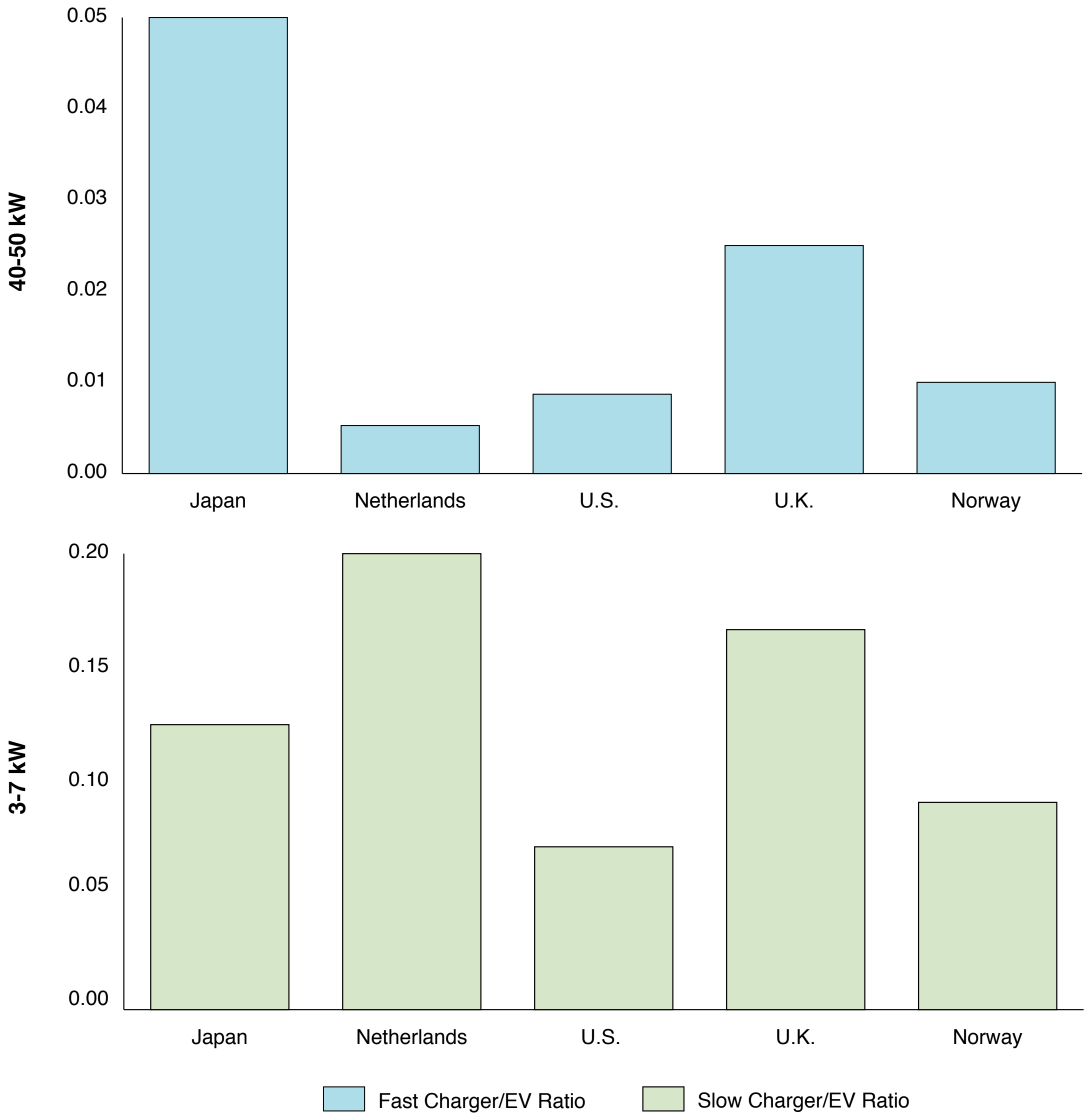

Figure 3. Charging point/EV ratio in selected countries in 2015, respectively, for fast (top) and slow chargers (bottom).

Source: Adapted from (IEA 2016).

Evidence shows that the value of incentives is one of the main factors influencing the overall rate of EV uptake, as well as the relative market shares of BEVs and PHEVs (Mock and Yang 2014). In Norway, for example, BEVs have been eligible for a range of generous monetary and non-monetary incentives for some time, whereas PHEVs have only recently become eligible for some of them, hence the rapid rate of uptake of BEVs and their dominance over PHEVs. In the Netherlands, incentives for BEVs and PHEVs have been similar, which explains why the market is dominated by PHEVs that offer better functionality. In California, where BEVs qualify for higher financial incentives than PHEVs, their market shares are comparable (Brook Lyndhurst 2015). Hence, government incentives to EV purchase, both monetary and non monetary, combined with the underlying taxation of conventional fuels and vehicles, determine the type of EVs that are most competitive and also the market segments in which the value they offer relative to ICEVs is highest. This in turn influences the EV types and models that automotive OEMs will manufacture and commercialize in order to achieve highest possible sales.

Moreover, the available evidence suggests that public charging infrastructure is a strong enabler of BEV adoption (Sierzchula et al. 2014); so an approach being taken in some countries is that of building an extensive network of public chargers, be they rapid or slow, that anticipates possible user needs before these are fully known (Brook Lyndhurst 2015, NRC 2015). The particular type, density and location of charging points deployed is intended to reduce users' range anxiety, increase the perceived utility of BEVs and allow users to perform most journeys that ICEVs are capable of, with minimum inconvenience. However, it is difficult to know in advance how well this will work in practice and the extent to which the infrastructure will actually be utilized (Brook Lyndhurst 2015, NRC 2015).

The market trends observed so far can change in future as policy support measures are periodically adjusted by governments in response to both domestic and international developments. In particular, at least in part encouraged by recent evidence showing a rapid rate of decrease of EV battery cost (Nykvist and Nilsson 2015), a growing number of countries are currently increasing their support for BEVs relative to PHEVs, which are seen by some as a transitional technology. However, to the best of our knowledge, the relevant policy documents do not explicitly discuss the overall cost of the particular EV and charging infrastructure mixes they seek to promote. Because the emphasis is on rapidly electrifying passenger car transport, it is therefore possible that the EV and charging infrastructure mixes that will be deployed in the short and medium term will not provide the most practical and cost-effective way of achieving the intended energy and environmental policy goals.

This is problematic because the process of development and adoption of new technology such as EVs exhibits path dependence and is prone to lock in effects (Åhman and Nilsson 2008). In other words, the type of EVs and infrastructure initially deployed will influence the behavior and preferences of adopters and the development of related institutions, and hence will contribute to pushing future EV technology and infrastructure development down a certain path. This will, in turn, further influence consumer adoption of new EV models and the development of policy and regulation in a process that in technology studies is generally referred to as co-evolution (Dijk and Yarime 2010, Geels 2012). This is schematically illustrated in Figure 4 below.

As policy and regulation co-evolve with the new technology and the preferences of its users become entrenched, the electrification of passenger cars will become increasingly locked into certain mixes of EV and charging infrastructure types. In the early phases of the EV transition, these mixes are made competitive by the policy incentives that support the electrification process. However, as higher levels of adoption are reached and policy support measures are withdrawn, costs will increasingly be passed on to EV users.

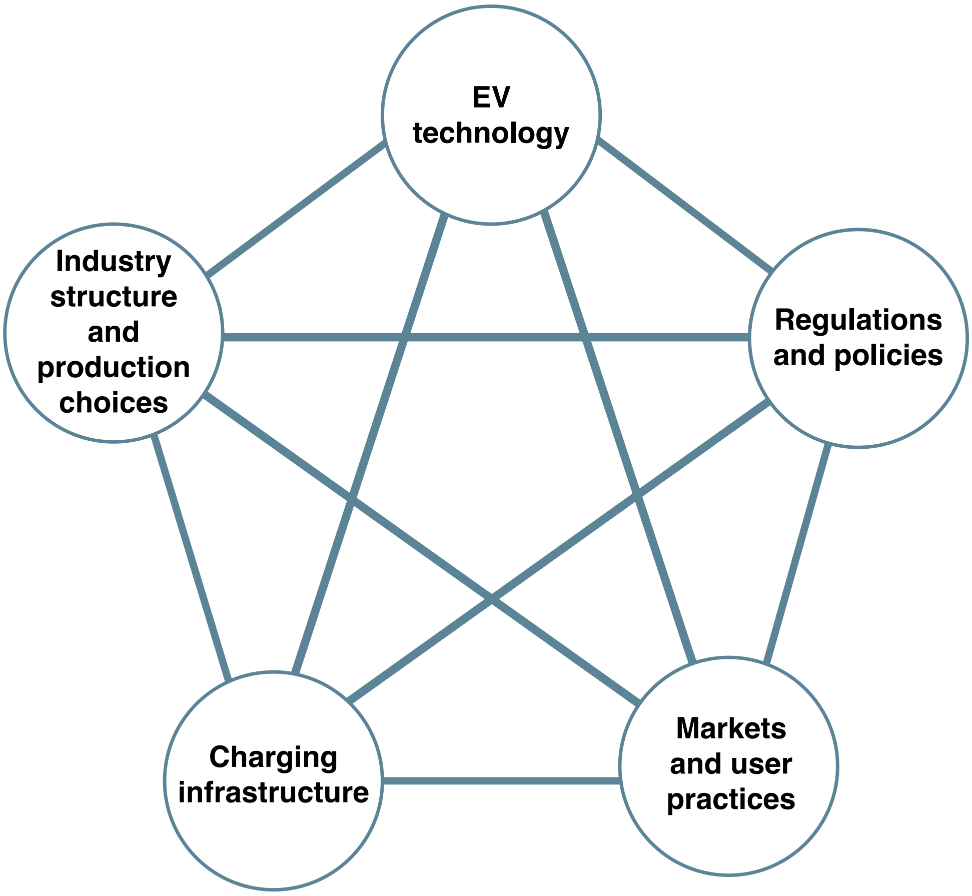

Figure 4. Schematic representation of the complex interlinkages among the multiple dimensions of the EV socio-technical system.

Source: Adapted from (Geels 2012)

The actual cost of EV and infrastructure mixes will then become very important in determining whether or not the EV transition will be able to sustain itself. Switching to more cost-effective mixes of EVs and charging infrastructures later on will still be possible, but expensive and time consuming. Meanwhile the whole EV transition could risk stalling. In light of this, posing the question whether today's EV and infrastructure policy is conducive to cost-effective electrification of passenger cars becomes more important.

Choice of Analytical Approach

The future cost and emissions of different types of EVs has been the subject of much research over the last decade. A large number of studies can be found in the literature that cover the whole spectrum of economic assessments of EVs, from detailed powertrain cost and performance modeling aimed at guiding the design of systems or components, to studies comparing the lifetime cost and emissions of different EV types in order to inform policymaking. Common to most of these studies is the use of the relative cost of ownership (RCO) metrics that enable estimation of the cost of individual EVs over their lifetime and comparison across different powertrain types. As the name suggests, RCO does not consider all costs but only those that are relevant to the comparison being made. A brief critical review of the main studies in this area is provided in the accompanying KAPSARC methodology paper. These studies have generated a large amount of knowledge on the economics of EVs, both present and future. However, they tend to focus on single vehicles as opposed to whole fleets and tend not to consider the cost of EV charging infrastructure. Moreover, the results they generate are based on the use of fairly complex models, which may lack transparency and flexibility and may not be easy to communicate or update when new evidence becomes available.

In order to address the gaps we identified, we decided to develop a model that calculates the incremental cost and emission savings of future EV and charging infrastructure mixes. In other words, we developed a model that performs RCO calculations for single vehicles and integrates them over the whole fleet by including all the key factors with the minimum possible level of detailed complexity. Hence our model relies on inputs from a number of specific studies and technical modeling activities, which can be easily integrated and updated as appropriate. By following this approach we aim to create a tool that is flexible, transparent, and that can facilitate discussion around policy support to EVs and EV charging infrastructure. It is worth mentioning that, due to the relative nature of the analysis performed, all those cost elements that are common to both EVs and ICEVs are not considered in the model. Nor are vehicle and fuel taxation accounted for in our study. This corresponds to assuming that non CO_2 related taxation of EVs will be the same as that of ICEVs. CO_2 taxation is not included either. However, to ensure our analysis is meaningful, we compare only EV mixes that are characterized by similar average tailpipe CO_2 emissions across the whole fleet. In this way our results are not influenced by assumptions as to the price of CO_2 emissions. A full description of the model can be found in the accompanying KAPSARC methodology paper.

Moreover, considering that the cost of EV and infrastructure mixes depends in part on the technology inputs and in part on the specific vehicle market examined; in our analysis we take a case study approach. We selected the cases of the U.K. and California because both are aggressively pursuing electrification of passenger cars and their markets are illustrative of large European countries such as France and Germany and of North America, respectively. Another reason for choosing these two cases is the availability of the required information and data in English. Finally, by comparing and contrasting two rather different cases such as the U.K. and California, we test the extent to which general lessons can be learned about the cost-effectiveness of policy driven EV and infrastructure mixes. We base our analysis around year 2030, because: a) current policy targets tend to refer to the 2025-2030 timeframe; b) the level of adoption foreseen is such that lock-in effects may begin to occur; and c) technology projections become very uncertain beyond 2030.

Choice of Analytical Approach

As part of our case study analysis, we develop a set of EV and charging infrastructure scenarios for both the U.K. and California in 2030 that are broadly consistent with the policy approaches currently being taken and with the technology trajectories that could follow from them. The scenarios are based on narratives we have developed around current policy and market trends, and are illustrative of the possible consequences of certain policy choices. It is worth stressing, though, that they are not intended as accurate predictions of the composition of EV and infrastructure mixes in 2030 as those follow from particular choices made by policymakers.

In fact, policymaking in the U.K., California and elsewhere is flexible enough to allow shifting direction should it be required – and anticipating future decisions of policymakers and the effects that these will have on the adoption of EV and charging infrastructure mixes is beyond the scope of our research. However, due to lock in effects, major changes in direction will no doubt involve time lags and incremental costs. Hence the aim of our analysis is to better inform policymakers so as to enable them to make decisions today that will help set the EV transition on lower risk, more cost-effective, pathways from the onset.

EVs in the UK and California: Current Policy and Future Deployment

The UK

The U.K. is subject to EU transport and environmental regulation and policy – although this may change in future as a result of the U.K.'s recent referendum vote to leave the EU. In particular, the post 2020 EU fleet average CO_2 emission standards for passenger cars, currently under negotiation, and the alternative fuels infrastructure directive will provide the strongest drivers for the deployment of EVs and charging infrastructure at European level. In addition to that, the U.K. has set itself the legally binding target of reducing total GHG emissions, to which transport is a major contributor, by 80 percent relative to 1990 levels in 2050. In order to fulfill its domestic and European obligations, the U.K. is committed to supporting the development and deployment of ultra low emission vehicles (ULEVs), particularly EVs, which the government also sees as an opportunity to revive the country's automotive industry (Chase, Wells, and Alberts 2014). The U.K. government aspires to achieve near complete decarbonization of passenger car transport by 2050. However, it has not committed to any particular EV deployment target. Instead, it supports the deployment of EVs and charging infrastructure through financial and non financial incentives, which are periodically revised, based on observed market and technology development (Table 1).

Table 1. Current deployment, policy support measures and future estimated EV and charging infrastructure deployment needed in order to meet the U.K.'s GHG emission reduction targets.

	Current deployment level	Current government incentives	Future government targets/ deployment requirements
EVs	1 percent market share in 2015 (1/3 BEVs, 2/3 PHEVs)	Plug-in car grant amounts to up to 35 percent of the vehicle's retail price for a maximum of £4,500 for EVs with AER of at least 110km (currently BEVs) and £2,500 below 110km (currently PHEVs). The grant originally offered a maximum of £5,000 per EV, irrespective of AER, and was amended in Mar 2016. Exemption from road user charges, notably London's Congestion Charge.	Aspirational target of 100 percent ULEV new car registrations in 2040. No mandated EV targets. The Committee on Climate Change estimates that meeting the U.K.'s GHG emission targets requires between 4-8 million EVs on the road in 2030.
Charging infrastructure	Circa 30,000 home charging points, 7,000 workplace (open access) and 8,000 public charging points (7,100 slow and 900 fast) as of Feb 2015.	Grant for home chargers covering 75 percent of cost up to £700. Government matches funding for private and public entities that deploy chargers in selected locations (Plugged-in Places). Highways Agency committed to investing £15 million in order to add 1,000s of new charging points on the Strategic Road Network. The aim is that motorists will be no more than 30 km from a charge point 95 percent of the time.	EU regulation currently requires the U.K. to develop a rollout plan for charging infrastructure. The directive indicates a target density of 0.1 chargers/vehicle, depending on the type of EVs and chargers deployed. It is estimated that a network of 2,100 rapid charging sites (10 charging points per site) could provide U.K. wide coverage. Around 70 percent of U.K. households have access to private parking; however, this is as low as 10 percent in certain urban areas.

Source: OLEV 2016, Element Energy 2015, Brook Lyndhurst 2015, Element Energy, Ecolane, and University of Aberdeen 2013, DfT 2015.

The U.K. government's approach to ULEVs is in general technology neutral, though the recently revised EV grant now has different levels for long and short AER EVs, which is intended to increase BEV over PHEV sales. In addition, at present the maximum number of grants available is capped at the same level for BEVs and PHEVs, which also suggests a desire to balance the sales of either EV type. Table 1, showed an overview of current EV and infrastructure deployment, current government incentives supporting it and future estimated EV and infrastructure levels required in order to support the U.K. achieve its climate change policy goals.

Evidence gathered from current EV users in the U.K. so far suggests that adoption of EVs is mainly by affluent, multi-vehicle households in urban areas. EVs are typically used as the main car, relied upon for the majority of daily trips, whereas the ICEVs in the households are used more for infrequent, longer journeys (Hutchins et al. 2013). It also appears that EVs are being driven annually for mileages comparable to those of ICEVs. EV consumer research conducted in the U.K. suggests that key barriers to EV adoption remain price and, for BEVs, also range, with users expressing desire for longer range vehicles so as to enable infrequent, longer trips (Brook Lyndhurst 2015).

EV owners have shown a strong preference for charging overnight at home and much less for public or workplace facilities. This is due to convenience and not much influenced by availability of infrastructure (Hutchins et al. 2013). However, a fully developed charging infrastructure, particularly rapid, is also perceived as required for further BEV market expansion (Brook Lyndhurst 2015). Analysis conducted suggests that, to complement private residential charging, the most valuable charge points will be rapid chargers. However, the business case for this type of public infrastructure is still challenging, due to the expected low utilization rate. Continued government support will therefore be required in order for the rapid charging infrastructure to develop in the U.K. (Element Energy 2015).

California

Like the U.K., California has set itself the target of achieving an 80 percent reduction of GHG emissions by 2050 relative to 1990 levels (Governor's Office 2015b), with an interim target of 40 percent reduction by 2030. This complements strong air quality policy, including the Low Emission Vehicle standards of the California Air Resources Board. In order to facilitate the achievement of the intended reduction in emissions of GHGs and air pollutants from road transport while supporting the development of a clean car industry in California, in 2012 Governor Brown issued an executive order aimed at facilitating the rapid commercialization of zero emission vehicles (ZEVs) (Governor's Office 2012). The executive order sets specific EV deployment targets, the strategy for achieving which is set out in the 2013 ZEV Action Plan of February 2013 (Governor's Office 2013), updated in 2015 based on a review of the progress achieved until then (Governor's Office 2015a). The strategy includes providing incentives for EV adoption and infrastructure deployment as well as studying future infrastructure needs. A study of future infrastructure needs was conducted by the National Renewable Energy Laboratory (NREL) in 2014. The targets and key elements of the strategy are summarized in Table 2. It is also worth mentioning that the 2015 ZEV Action Plan explicitly states that incentives should be cost-effective and withdrawn as early as possible: “Financial incentives continue to play a

Table 2. Current deployment, policy support measures, future EV mandates and charging infrastructure needs in California.

	Current deployment level	Current government incentives	Future government targets/ deployment requirements
EVs	3.2 percent market share in 2015 (1/2 BEVs, 1/2 PHEVs). 120,000 EVs on the road in Jan 2015.	ZEV mandate currently forces the commercialization of BEVs and PHEVs in sufficient numbers for individual car manufacturers to generate the necessary number of credits. Federal tax rebate of up to $7,500 (proportional to EV battery size). California Clean Vehicle Rebate, a state rebate of $2,500 for BEVs and $1,500 for PHEVs. Non-financial incentives such as access to high occupancy vehicle (HOV) lanes and parking benefits.	Executive order sets a target of 1 million ZEVs on the road by 2020 and 1.5 million ZEVs by 2025, and for new vehicle purchases in light duty fleets of government agencies to reach 10 percent ZEVs by 2015 and 25 percent by 2020. Post 2018, ZEV credits are earned by BEVs and BEVx with AER> 80 km proportional to their AER (e.g., 160 km AER=1.5 credits; 480 km AER=3.5 credits). PHEVs with AER between 16 km and 120 km also earn credits proportional to their AER (0.4 to 1.10 credits respectively). Large volume car manufacturers have to earn the majority of their credits from pure ZEVs (i.e., BEVs, BEVx and FCEVs).
Charging infrastructure	3,224 public charging stations for a total of 9,577 public charging points in California as of March 2016.	The California Energy Commission administers a number of programs providing funding for new charging infrastructure. It also conducts and commissions studies on the future need for charging infrastructure across the State. The California Building Code requires all recently constructed parking lots or housing to put electrical capacity in place to easily install EV chargers.	Executive order mandates the rollout of the necessary charging infrastructure to support the ZEV targets. NREL study estimates that, to support the 1 million EVs by 2020 target, between 20-50 thousand public chargers will be needed. It suggests two alternative options: 'Home dominant': 100 thousand workplace and 22,250 public chargers (of which 550 rapid). 'Public access': 167 thousand workplace and 48,600 public chargers (of which 1,550 rapid).

Source: OLEV 2016, Element Energy 2015, Brook Lyndhurst 2015, Element Energy, Ecolane, and University of Aberdeen 2013, DfT 2015.

critical role in making ZEVs cost competitive with conventional vehicles during the early phases of their deployment, until economies of scale lead to cost reductions and a fully self-sustaining market. […] As the ZEV market continues to grow, the State will refine its financial incentive programs to most effectively target incentives where they motivate consumer decisions." (Governor's Office 2015a).

The executive order targets are broadly in line with the EV penetration levels required by the ZEV mandate, the well known EV supply side policy first introduced in California in 1990 and subsequently amended various times; although the exact EV numbers required by the latter will depend on the compliance strategy chosen by the OEMs. In particular, the ZEV mandate sets a minimum number of credits that large and intermediate volume manufacturers have to earn or purchase in order to comply with the regulation and avoid fines. The credits are earned through manufacturing pure ZEVs (i.e., BEVs, a newly introduced category of range extended BEVs called BEVx and fuel cell electric vehicles (FCEVs); the latter are not discussed in this paper) and other ULEVs (such as PHEVs, also referred to in the regulation as transitional ZEVs or TZEVs) for the Californian market. BEVx are full BEVs that are also equipped with a small ICE auxiliary power unit enabling them to operate at reduced power when the AER is exhausted, and their non electric range cannot exceed their AER; hence the structure of the powertrain is similar to that of a RE-EV, but the components are sized differently and the utility of the vehicle is substantially lower. The number of credits for each EV is awarded proportional to its AER, based on different formulas for ZEVs and ULEVs. Although the regulation allows OEMs a certain degree of flexibility in the way they meet their credit obligations, minimum ZEV credit floors apply. A synthesis of the ZEV mandate credit mechanism is provided in Table 2; we refer the reader to the relevant regulation for full details (California Secretary of State 2013a, b). However, it is important to note that the ZEV mandate will play a strong role in defining the future split between BEVs and PHEVs in California, ensuring that BEVs – either pure BEV or BEVx – retain a substantial share of the market. Moreover, the mechanism by which credits are assigned to ZEVs has been one of the factors contributing to the emergence of the long AER BEVs manufactured by Tesla Motors Inc., and will most likely continue to influence future OEM decisions about the AER of their EVs. As in the U.K., EV owners in California are predominantly affluent, highly educated, multi vehicle households and use their EVs as the main car for frequent, shorter journeys, with similar annual mileages to ICEVs (Center for Sustainable Energy 2013). BEV users in California report that for full satisfaction their vehicles would need to have a range of more than 250 km (Center for Sustainable Energy 2013).

In California, charging of EVs takes place mainly at home, as is also the case in the U.K. The extent to which PHEVs actually run on electricity is currently being investigated, but early results suggest that long AER PHEVs are used on electricity as much as possible. EV users generally were not entirely satisfied with public charging infrastructure, although this is improving as infrastructure coverage increases (Brook Lyndhurst 2015, Center for Sustainable Energy 2013).

Analysis and Discussion

Driving patterns and fleet structure: comparing the UK and California

Among the key differences between the passenger car transport systems in the U.K. and California are the structure of the fleet and the vehicle usage patterns.

We modeled the structure of the 2025-2030 fleet in a simplified way. We have assumed that the overall size of the fleet will stay the same as today. We divided the fleet into four main market segments, with their sizes based on new passenger car sales for a reference year and modeled based on the characteristics of the best-selling cars for that same year (California Auto Outlook 2016, SMMT 2013). A stock model would provide more accurate projections of future fleet compositions. However, we consider our simplified approach adequate given the purpose of our analysis. See Table 3 and Table 4 for the details of how the future fleets in the U.K. and California are modeled in our study. In the tables, the vehicle segments are named following the most common usage in the U.K. and U.S. respectively. Note that in our incremental cost model, the reference vehicle weight is reduced relative to today's based on future scenarios on the use of lightweight materials (Lotus Engineering Inc. 2010), and the powertrain size is downscaled accordingly (Aaron Brooker 2013, Pagerit, Sharer, and Rousseau 2006).

Table 3. Structure of the U.K. market in 2030— main segments and their key attributes.

Segment	Reference model	Weight (kg)	Power (kW)	Annual mileage (km)	Fleet share (percent)
Mini/Supermini (A/B)	Ford Fiesta	1,050	64	12,950	40.6
Medium (C/D)	Volkswagen Golf	1,300	92	14,950	40.8
Executive/Luxury (E/F)	Mercedes C class	1,550	135	17,450	4.8
Dual purpose/ MPV (H/I)	Vauxhall Zafira	1,550	105	22,200	11.3

Source: KAPSARC scenario, based on DfT 2008, SMMT 2013, whatcar.com.

Table 4. Structure of the California market in 2025 — main segments and their key attributes.

Segment	Reference model	Weight (kg)	Power (kW)	Annual mileage (km)	Fleet share (percent)
Small	Toyota Corolla	1,270	98	19,850	26.8
Medium	Honda Accord	1,475	140	18,900	31.1
Luxury	Mercedes E class	1,735	224	20,600	10.7
SUV	Ford Explorer	2,010	216	21,000	20.1

Source: KAPSARC scenario, based on California Auto Outlook 2016, U.S. News Best Cars, cars.com, DoT 2009.

As for the vehicle usage patterns, we analyzed data from the U.K. National Travel Survey and the U.S. National Household Travel Survey, respectively, and we derived the frequency distributions of daily distances driven shown in Figure 5 and Figure 6. These distributions are used when calculating utility factors for PHEVs and relative shares of home compared with public charging for BEVs.

As can be observed from the tables and figures above, the U.K. and California passenger car markets today have very different characteristics, in terms of both the relative shares and attributes of their main segments and the usage patterns of the vehicles. In particular, the structure of the passenger car fleet in California is slanted toward larger, and hence heavier, vehicles compared with the U.K. This is generally the case comparing North America with Europe. In addition, in the U.K. larger vehicles are on average driven more frequently for longer distances and have higher annual mileages than smaller vehicles, whereas in California all segments are on average driven similarly and have comparable annual mileages. In our study we make the simplifying assumption that this will not change until 2030.

Finally, it is worth noting that modeling the passenger car fleet as we did, using the attributes of best-selling vehicles to represent large segments and averaging daily distances driven within segments, has its limitations. However, as previous studies have shown (Offer et al. 2011), even a relatively simple segmentation approach like ours can provide substantial additional insight compared with treating the whole passenger car market as homogenous.

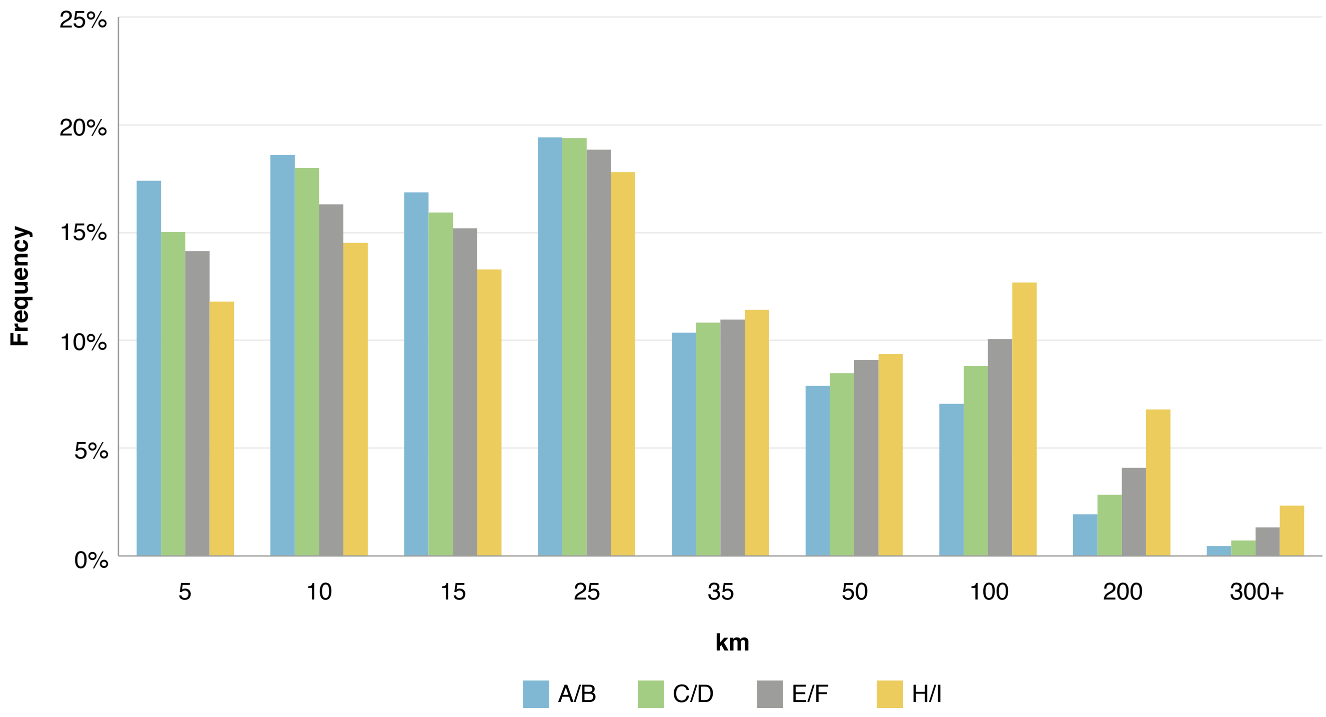

Figure 5. Frequency distribution of daily distances driven in the U.K. (in km), by vehicle segment.
Source: KAPSARC analysis of U.K. National Travel Survey data (DfT 2008).

Figure 6. Frequency distribution of daily distances driven in California (in km), by vehicle segment.

Source: KAPSARC analysis of U.S. National Household Travel Survey data (DoT 2009).

UK scenario analysis

Based on the current status and future targets for the deployment of EVs and charging infrastructure discussed in the previous section, we built a set of key scenarios for year 2030 and we have estimated their incremental user cost relative to a base case where the whole passenger car fleet is composed only of ICEVs.

All scenarios are consistent with the U.K. government target of 60 percent EV market share, or 8 million EVs on the road by 2030, but they differ in terms of the EV types and related infrastructure deployed. It is also worth noting that, despite the difference in EV types across scenarios, average fleet tailpipe CO_2 emissions are comparable, of the order of 55 g CO_2 /km New European Driving Cycle (NEDC). This is well below the 75-65 g CO_2 / km range currently being discussed at EU level for the 2030 CO_2 fleet average standard for passenger cars. The key elements of each of the 4 scenarios modeled are listed below and further illustrated in Table 5.

> Scenarios 1 and 2 are based on the current trend of seeking to balance the relative shares of BEVs and PHEVs through incentives. Hence we assume a 40/60 split between BEVs and PHEVs and the countrywide charging infrastructure coverage needed to achieve rapid adoption of BEVs.

Table 5. U.K. 2030 EV and infrastructure scenarios modeled.

Scenario	BEV share (percent)	BEV segments	PHEV share (percent)	PHEV segments	BEV AER (km)	PHEV AER (km)	Slow chargers	Fast chargers
1	40	C/D, E/F, (H/I)	60	C/D, E/F, H/I	250	50	300,000	20,000
2	40	C/D, E/F, (H/I)	60	C/D, E/F, H/I	250	50	0	20,000
3	0	-	100	C/D, E/F, H/I	--	100	-	-
4	20	A/B	80	C/D, E/F, H/I	150	100	-	5,000

Source: KAPSARC.

In Scenario 1, the rapid charging infrastructure is modeled based on the analysis by (Element Energy 2015); the size of the slow charging infrastructure is based on the indicative target of the European Commission directive (European Union 2014), i.e., the equivalent of at least 0.1 public charging points per EV.

In Scenario 2, only rapid charging infrastructure is present, because this is seen by users as most valuable, and hence the public charging point per EV ratio becomes 0.01.

Taken together, Scenarios 1 and 2 represent possible upper and lower bounds for a countrywide charging infrastructure in the U.K. that is capable of supporting the particular EV fleet considered.

In Scenarios 1 and 2, the fleet consists of a mix of 250 km range BEVs and 50 km AER PHEVs. A 250 km range may be the least required for BEVs to offer similar functionality to ICEVs. Finally, we assume that BEVs will penetrate the market across all segments, with the exception of the small car segment (A/B) where fuel efficient ICEVs currently benefit from a relatively low level of taxation and where a long range BEV will be both expensive and not required. PHEVs are also present in all segments except A/B, due to the same reasons of cost competitiveness with ICEVs.

Scenario 3 meets the target of 60 percent EV penetration by 2030 with the least amount of battery capacity and infrastructure installed. This means only using 100 km AER PHEVs that do not require public charging infrastructure at all. Long AER PHEVs of the series type (or RE-EVs) can use the same type of batteries as BEVs and share with them all other components of the electric powertrain. Thus on the vehicle side they could generate the necessary scale economies that would also be needed in order for BEVs to become competitive. However, by not developing the charging infrastructure and user preferences for BEVs, the latter could become locked out, hence potentially delaying the achievement of full electrification of passenger cars post-2030. A PHEV-only scenario is also clearly not consistent with current policy trends.

Scenario 4 offers a compromise where 100 km AER PHEVs dominate the market, with the exception of the A/B segment where only 150 km range BEVs are present. This is in principle not incompatible with the current structure of the plug-in vehicle grant that does not favor longer AER BEVs and potentially rewards long AER PHEVs in the same way as BEVs. In this way the BEV option would remain open but, by targeting the smaller vehicles typically used for shorter distances in urban areas, expensive long AER BEVs and a countrywide infrastructure would no longer be needed. Adoption of BEVs as urban vehicles can be further encouraged by developing extensive charging infrastructures in urban areas while limiting extra urban coverage.

Figure 7 shows the incremental user cost of the scenarios, as calculated using our model. The error bar indicates the full range of uncertainty associated with future battery technology development. In particular, the highest cost corresponds to today's battery technology cost ($300/kWh) and energy density (100 Wh/kg), as reported by the leading industry players, while the lowest cost corresponds to battery technology meeting its long-term cost reduction target ($100/kWh) and doubling its energy density. The midpoint case falls exactly in between with respect to both battery cost and energy density; as far as cost is concerned, $200/kWh is considered as a plausible scenario for 2025-2030, based on recent projections (Nykvist and Nilsson 2015). The same logic applies to PHEV batteries. While it is unlikely that battery technology will not improve at all

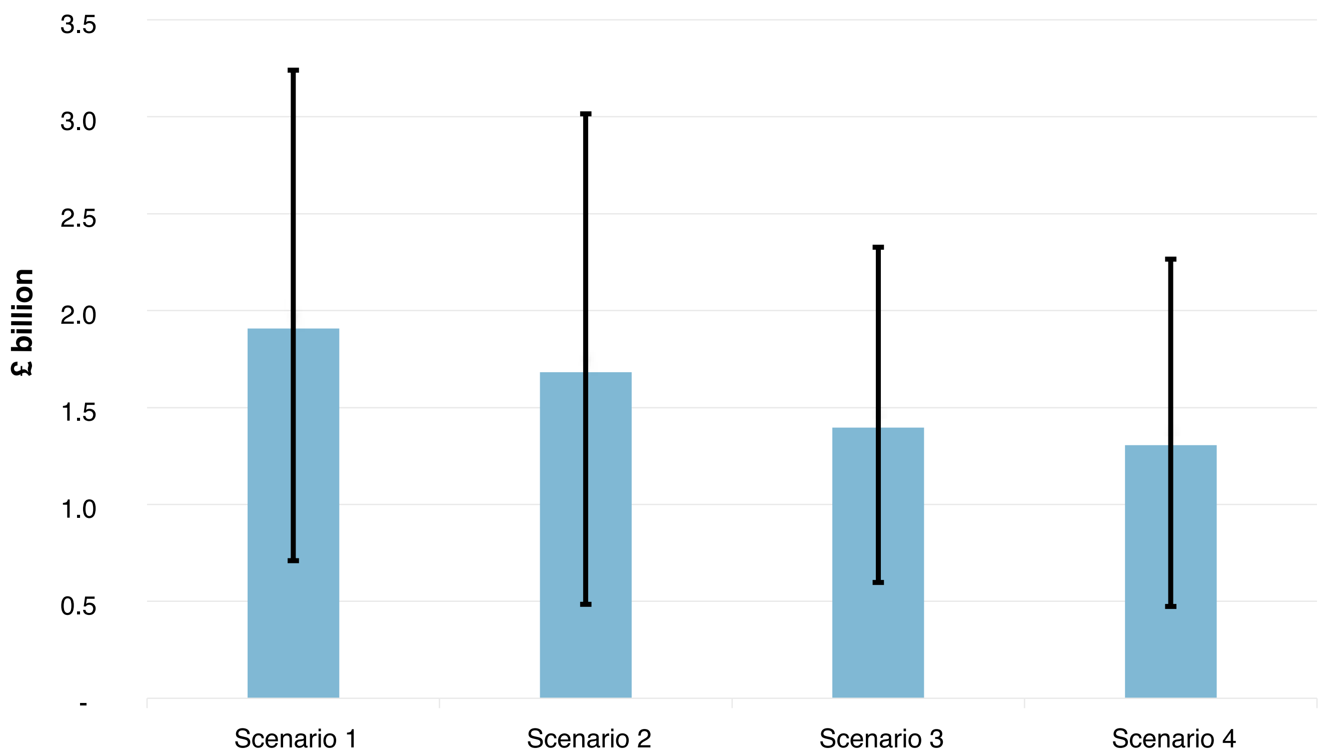

Figure 7. Incremental annual user cost of the U.K. EV and infrastructure scenarios modeled (in GBP). The error bars indicate uncertainty associated with future battery technology development.

Source: KAPSARC.

by 2025-2030, using today's state of the art as worst case scenario also gives a sense of the extent to which different EV mixes will require policy support while battery technology develops, and hence of the transition cost and technology risk associated with each particular scenario.

It is worth noting that the absolute value of the incremental cost of EV scenarios as shown in Figure 7 is influenced by the relative cost of gasoline and electricity as well as other variables, and hence should be regarded as only indicative. Based on the type of analysis conducted, the most important insight that can be gleaned is the relative cost of the different EV scenarios. This is particularly sensitive to battery technology development, less so to other parameters. Accordingly, only the effect of the former is discussed. However, when examining the results obtained, it is also important to note that they are based on assumptions that particularly favour BEVs over PHEVs. Specifically, we assume EV batteries in general to last the whole lifetime of the vehicle – due to the larger size of the BEV battery pack, having to replace it would incur a much higher cost penalty than in the case of PHEVs. Moreover, possible grid reinforcement costs associated with public charging infrastructure are excluded, which also favours BEVs over PHEVs. So, in effect, the risk associated with scenarios including large numbers of long range BEVs could be much higher. As can be seen from Figure 7:

> Scenarios 1 and 2 show the greatest cost sensitivity to future battery development; around 40 percent higher than Scenario 3 and 4. This means that initially a similar EV mix would have to be subsidized substantially more than one dominated by long AER PHEVs.

> Even at a BEV battery cost of $200/kWh, Scenarios 1 and 2 would cost around £400-£600 thousand a year more than Scenario 4. Only with batteries that cost in the order of $100/kWh and have double the energy density of today's best in class would the cost of all scenarios converge.

> By comparing Scenarios 1 and 2 we can see that the effect of reducing infrastructure coverage to rapid chargers only is relatively minor, in the order of £200 thousand a year. However, based on our model, it appears that even in Scenario 2 the utilization level of the charging infrastructure would still be low; with an average of less than two rapid charging events a day per charger if the AER of BEVs was used in full, the business case for it would be problematic.

> Scenario 4 is cheapest and allows the BEV option to be kept open while not being more sensitive to battery technology development than Scenario 3. Moreover, by strategically siting the rapid charging infrastructure in and around urban areas, better utilization levels could be achieved at around four charges a day on average. It therefore follows from our analysis that pursuing an EV and charging infrastructure mix of the kind in Scenario 4 would provide a relatively low cost, low risk, electrification path for the U.K.

California scenario analysis

Based on the discussion of current state and future EV targets in California provided in the previous section, we built a set of key scenarios for year 2025 and estimated their incremental user cost, applying the same logic as for the U.K. case.

All scenarios are consistent with the target of 1.5 million EVs on the roads in 2025 set by the executive order of the Governor of the State of California. Although they differ widely in terms of the types of EV and infrastructure deployed, all scenarios are characterized by comparable average fleet tailpipe CO_2 emissions. The key elements of each of the five scenarios modeled are outlined below and further illustrated in Table 6; their respective incremental user cost are shown in Figure 8. It is worth noting that, with the exception of Scenario 1, all other scenarios mirror those chosen for the U.K., which makes comparing the two case studies easier.

Scenarios 1, 2 and 3, in addition to meeting the Governor's target, also broadly fulfill the requirements of the ZEV mandate in terms of meeting the overall number of ZEV credits and the related ZEV floor. Our scenarios assume the ZEV mandate requirements are met using BEVs only. We do not model BEVx due to their reduced utility, though we will later discuss their possible role from a qualitative standpoint and we do not consider the effect of possible deployment of FCEVs.

We assume the BEV/PHEV ratio to be 40/60, although in reality this will vary somewhat depending on the compliance strategy chosen by the OEMs. In particular, longer AER EVs qualify for more credits, hence fewer of them would be required. For simplicity, though, we ignore the few percentage points difference between compliance scenarios and fix the BEV/PHEV ratio as above.

In our scenarios, both BEVs and PHEVs feature in all segments of the passenger car market, which is not incompatible with today's rapidly growing offer of new EV models.

The only difference between Scenarios 1 and 2 is the range of the BEVs, which is 300 km and 250 km respectively. A longer range BEV earns more credits, so it could provide OEMs with a cheaper way of complying with the ZEV mandate, while at the same time better meeting the stated preferences of Californian BEV users. A shorter range BEV that does not fully satisfy the desire of the users in terms of range, however, allows higher utilization of the battery installed and hence is more economical.

We also assume that the remaining ZEV credits are earned with 50 km AER PHEVs, which qualify for circa 0.8 ZEV credits each and enable the overall 1.5 million EV target to be met.

Table 6. California 2030 EV and infrastructure scenarios modeled.

Scenario	BEV share (percent)	BEV segments	PHEV share (percent)	PHEV segments	BEV AER (km)	PHEV AER (km)	Slow chargers	Fast chargers
1	40	all	60	all	300	50	75,000	2.250
2	40	all	60	all	250	50	75,000	2,250
3	0	all	60	all	250	50	30,000	750
4	20	-	100	all	-	100	-	-
5	20	small	80	medium, luxury, SUV	150	50	35,000	1,000

Source: KAPSARC.

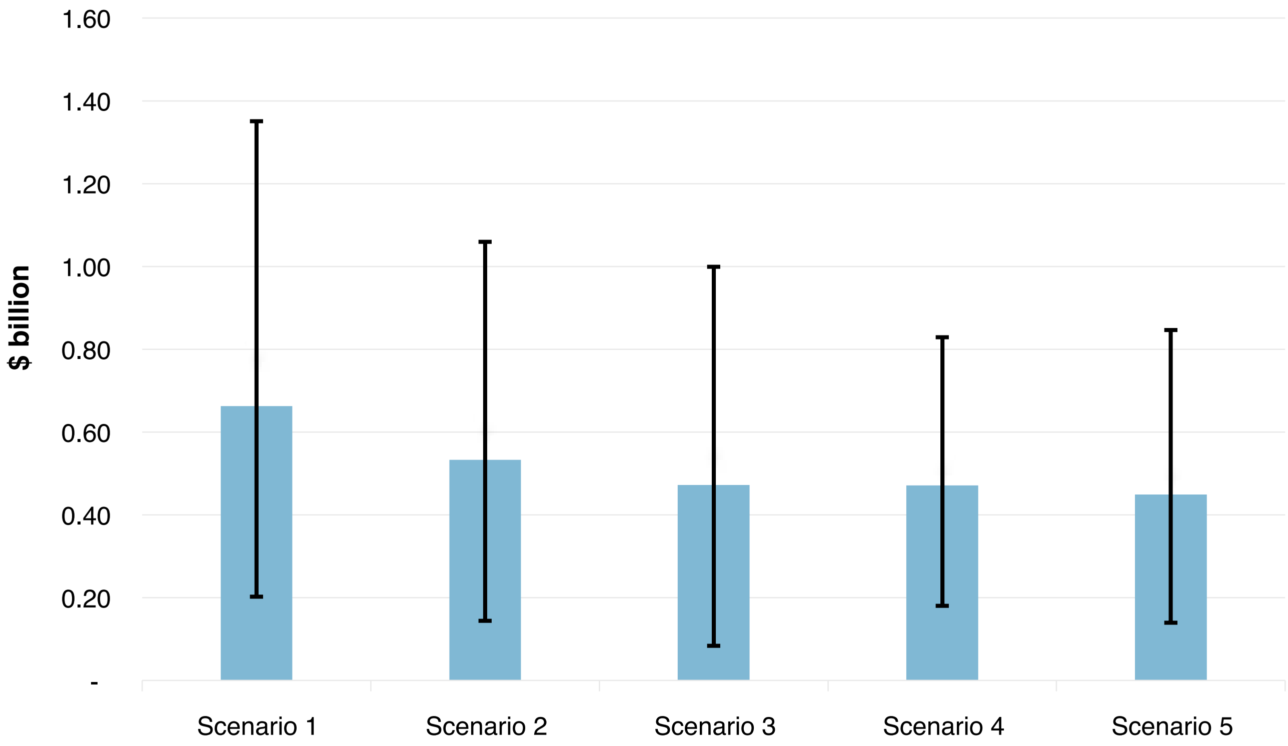

Figure 8. Incremental annual user cost of California EV and infrastructure scenarios modeled. The error bars indicate uncertainty associated with future battery technology development.

Source: KAPSARC.

In both cases we assume that public infrastructure is provided based on the 2020 'public access' scenario of the NREL study (NREL 2014), scaled up to 2025 as appropriate.

Comparing Scenarios 1 and 2 allows us to test the effect of BEV range on the incremental user cost of passenger car electrification.

Scenario 3 is the same as Scenario 2, except that the public infrastructure provision is reduced based on the 'home dominant' scenario of the NREL study.

Comparing Scenarios 2 and 3 allows assessing the impact of different types of public charging infrastructure in California on incremental user costs.

Scenarios 4 and 5 meet the Governor's target but do not comply with the ZEV mandate. Scenario 4 is based on the same logic as the corresponding one for the U.K., i.e., to achieve electrification with the least deployment of battery capacity and charging infrastructure. This means using 100 km AER PHEVs and no public charging infrastructure at all.

Scenario 4 also mirrors the corresponding one for the U.K., with 150 km range BEVs adopted in the small vehicle segment, complemented by 100 km AER PHEVs in all other segments.

Comparing Figure 8 with Figure 7 it can be observed that:

The trend that emerges from the scenarios explored is similar for both California and the U.K.

One difference in the case of California is that we have added a scenario (Scenario 1) with longer range BEVs that are more likely to meet the requirements of their users while at the same time qualifying for more ZEV credits. The incremental user costs of Scenarios 1 and 2 show that increasing BEV range even by a small amount has a strong impact on battery technology risk.

Another difference is that the economics of long AER PHEVs in California are overall worse than in the U.K., also due to the effect of the extra weight of the series PHEV powertrain in large, powerful cars, which affects fuel economy relative to BEVs as battery technology improves. This explains why, as battery technology improves, the incremental cost of Scenarios 2 and 3 converge toward those of Scenarios 4 and 5 more rapidly than the corresponding scenarios for the U.K.

From Figure 8 we can also see that:

Comparing Scenarios 2 and 3 shows that the effect of reducing public infrastructure provision is small, albeit not negligible.

The cost of Scenario 3, in particular, could start to converge with those of Scenarios 4 and 5 which are already at a battery cost of $200/kWh, assuming that battery lifetime was not an issue. Whether rapid uptake of BEVs with a 250 km range can be achieved without extensive public charging infrastructure, though, is not known.

Scenario 4 shows that, if not complying with the ZEV mandate were an option, the same level of tailpipe emissions and EV penetration could be achieved at potentially lower risk using only PHEVs with 100 km AER that have a utility factor in the order of 85 percent if fully charged at home every day, and without using public infrastructure. And that these would, at least initially, require substantially less support than the other scenarios discussed so far.

Scenario 5, which combines 100 km AER PHEVs with 150 km range BEVs, may be preferable as it is only marginally riskier than Scenario 4 while probably sufficient to continue promoting BEV innovation.

Policy Implications

Despite the substantial differences in terms of passenger car market structure and usage patterns in the U.K. and California, we find that the incremental user cost of the different EV and charging infrastructure mixes we explored follows a similar pattern in qualitative terms. Specifically, it appears that lower cost, lower risk, electrification of passenger cars in the 2030 timeframe can be achieved through a balanced mix of relatively short range BEVs and long AER PHEVs. This can be broadly extrapolated to the North American and European markets in general. While it is apparent that once BEV batteries achieve their cost reduction target and increase their energy density substantially, long range BEVs have the potential to outstrip PHEVs on a cost basis, to rely on this happening rapidly is potentially risky. Hence the main implication of our findings is that: by designing policies primarily aimed at accelerating complete electrification of passenger car transport by means of supporting the rapid rollout of long AER BEVs and extensive charging infrastructures, the EV transition may be set on a higher cost, higher risk, path which could eventually result in its losing momentum and possibly stalling altogether.

In general, EV policy in both the U.K. and California today shows, to different degrees, signs of favoring the rapid development of the BEV market alongside that of PHEVs. The U.K. approach is generally cautious and no commitment has so far been made for the long term, particularly on EV incentives, which are reviewed periodically. On the infrastructure side, however, the development of a countrywide network of chargers may soon be underway. Hence we argue that, due to the path dependent nature of EV innovation processes, even a relatively cautious approach, based on monitoring market and technology development and periodically revising EV and infrastructure support measures accordingly, may unintentionally lead to higher cost, higher risk, pathways being taken. The probability of this happening is higher, though, in the case of California, where the unique technology forcing approach of the ZEV mandate has already had a strong effect on EV innovation and will continue to do so in the foreseeable future. Based on our analysis, we also infer that the specific design of both EV and infrastructure incentives and mandates can potentially have a strong impact on the cost of future EV pathways and is therefore worth considering carefully. Specific aspects of the U.K. and California policy are here briefly discussed in turn.

The UK

In the case of the U.K., comparing the fleet average CO_2 emission associated with the scenarios we have modeled with the post-2020 EU fleet average standards for passenger cars currently under discussion, we notice that there is insufficient regulatory pressure to force the deployment of EVs on this scale by 2030. Therefore, in the absence of a U.K. equivalent to the California ZEV mandate that influences the direction of EV innovation, the type of EV and infrastructure deployed in the U.K. under the current policy framework will largely depend on the combined effect of the incentives provided by the government, EV models offered by the automotive OEMs and users' needs and preferences. In this context, the recently introduced two tier incentive system for EVs, with a step in the value at the 110 km AER mark, arguably favors shorter AER over longer AER PHEVs. This could be rebalanced by either moving the plug-in vehicle grant step to an AER of 100 km or slightly below, so that long AER PHEVs could also benefit from the higher grant available to BEVs, or by making the value of the grant for PHEVs proportional to their AER. As for BEVs, the flat rate of the grant currently provided is, in principle, favorable to short range BEVs in the city car segment, although these face tough competition from small, fuel-efficient ICEVs that benefit, compared with larger ICEVs, from particularly favourable CO_2 based taxation. In all other segments, based on current driving patterns, it is plausible that BEV users will require their vehicles to have relatively long ranges if they are to penetrate the market rapidly, for which a higher grant than is currently offered may be initially required. The other important policy driver of BEV adoption in the U.K. is the EV charging infrastructure strategy, which is currently under development. Focusing on providing extensive urban and suburban charging infrastructure, particularly of the rapid type, could further support the uptake of short AER BEVs in the small car segment. On the contrary, providing a countrywide infrastructure may indirectly encourage adoption of long AER BEVs in larger car segments and probably also result in low infrastructure utilization levels that only compound the problem.

California

In California, the ZEV mandate provides strong supply side policy that shapes EV innovation and forces the deployment of substantial numbers of these vehicles. In particular, the current structure of the ZEV credits strongly supports longer-range BEVs and is likely to have played an important role in the development of such vehicles, initially by Tesla Motors Inc. and increasingly also by other OEMs. Post 2018 the ZEV credit structure will change and the support for longer range BEVs will weaken but continue to exist. The effect that this will have on the compliance strategies of the OEMs remains to be seen, though it is plausible that they will continue to manufacture BEVs with sufficiently long AER that appeal to customers expecting BEVs to have similar functionalities to ICEVs and which will earn the manufacturer more ZEV certificates per vehicle. On the other hand, short-range BEVs are not a natural fit in California, not even in the small vehicle segment as, based on our analysis of passenger car use patterns, these vehicle are driven for similar distances as larger vehicles. As for PHEVs, the way in which ZEV credits and EV incentives are designed favors longer AER PHEVs. However, the ZEV floor present in the mandate currently limits the contribution that these will likely make to the overall EV fleet. Despite the increased flexibility granted by the recently introduced category of BEVx, which is allowed to generate up to half of the credits needed to meet the ZEV floor, the tension between supporting strong BEV innovation and achieving the necessary level of CO_2 emission reduction at a low cost remains.

In conclusion, observing how the California ZEV mandate is evolving suggests that costs are increasingly being taken into consideration. However, given the strong influence that this has on EV innovation in the U.S. and beyond, we argue that more could be done to guide the EV transition toward a path that is robust under uncertainty. One option could perhaps be that of rewarding actual electric miles driven as opposed to range. The analysis we have conducted suggests that a balanced mix of EVs in California should include long AER PHEVs to play a bigger role, at least in the short to medium term, to complement relatively short-range BEVs, possibly targeting market segments where they may be competitive, such as shared urban car fleets. In this context, BEVx, if adequately supported, could also form part of a gradual, lower risk, transition path from long AER PHEVs to BEVs.

Finally, it is worth mentioning that in our analysis we have not taken into account new technology paradigms such as autonomous vehicles, shared ownership and mobility services. In the long term, these could have a profound effect on the passenger car market structure and use patterns. However, our modeling approach also lends itself to this type of analysis and we recommend that these effects are accounted for, especially if extending the timeframe of the analysis beyond 2030.

Conclusion

In this study we have considered whether current EV and infrastructure policy is conducive to cost-effective electrification of passenger car transport. To investigate this, we developed a model that estimates the incremental user cost of different EV and infrastructure mixes over the whole passenger car fleet, compared with a base case where only ICEVs are present. We have applied our model to the two case studies we have selected, the U.K. and California, because both are aggressively pursuing electrification of passenger cars and are illustrative of the different North American and European markets and policy approaches. We base our analysis in the 2025-2030 timeframe. For both the U.K. and California we have developed a set of key scenarios that are broadly consistent with current policy approaches. All scenarios are characterized by the same overall number of EVs and similar fleet average CO_2 tailpipe emissions, however they differ in the type of EVs and infrastructure deployed.

Despite the substantial differences in the passenger car market structure and usage between the U.K. and California, the results we have obtained are qualitatively similar. In both cases it is apparent that strongly backing BEV innovation by promoting rapid uptake of a near equal split between BEVs and PHEVs exposes the passenger car transport system to a higher risk in relation to future battery technology development. This is because rapidly achieving high levels of BEV penetration will most likely involve making the functionality of these vehicles as close as possible to that of the ICEVs that they aim to replace, which means equipping them with large batteries so they can travel long distances on electricity, and providing extensive charging infrastructure networks so they can travel anywhere without restrictions. While the contribution of extensive charging infrastructure to the incremental cost of electrification may be relatively minor compared with the risk associated with the cost of large batteries, their level of utilization is likely to be low, hence making their economics problematic.

We also find that an approach where BEVs are limited to the relatively short-range, small vehicle segment, supported by mainly urban charging infrastructure networks, and where relatively long AER PHEVs are supported in all other segments, is one that could substantially reduce the risk of the cost of the EV transition becoming unsustainable by 2030 or earlier. Long AER PHEVs have most powertrain components in common with BEVs, so technology development and scale economies could still be realized that would pave the way for possible future substitution by long-range BEVs should battery technology improve sufficiently. At the same time, by continuing to support BEVs where they are less costly, this option would not become locked out and would allow more time for user practices and institutions to adapt, thus better preparing for BEV uptake to be rapidly expanded if battery technology develops to the extent necessary.

It is clear from U.K. and California policy that neither government is prepared to sustain EV incentives indefinitely and both will seek ways of achieving their policy goals at the least cost. As the case studies of the U.K. and California show, by assessing the future incremental user cost of EV mixes that follow from current policy we have identified possible criticalities that, if addressed, could contribute to making EV policy more robust under uncertainty.

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About the Project

After decades of development and false starts, electric vehicles have now become commercial. However, they still rely on strong policy support for their further development and adoption.

The project assesses the effectiveness of current electric vehicle policy in leading the technology toward self sustained market competitiveness. The multi-method approach chosen involves techno-economic, strategy and innovation systems analysis. In particular, we have developed a bottom-up electric vehicle fleet cost model in order to assess the economic implications of electric vehicle policy

Notes

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