

Will current EV and charging infrastructure policy lead to cost-effective electrification of passenger car transport?

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Summary

Governments around the world are seeking to expedite the electrification of passenger cars. Due to the particular policy approaches taken and market conditions, different mixes of BEVs and PHEVs and of rapid and slow public charging infrastructure are starting to emerge in different countries. The question is whether this will lead to a cost-effective use of the technology. In this study we explore the relative private cost of likely future EV and charging infrastructure mixes for two case studies, the UK and California, with the aim of formulating recommendations for EV and charging infrastructure policy that is robust under uncertainty.

Keywords: California, cost, infrastructure, policy, UK

1 Background and motivation

1.1 Government support to electric vehicles

Driven by growing concern about global climate change and urban air quality, electrification of passenger car transport is receiving strong support by several national governments worldwide, who while meeting their environmental protection goals are also seeking to develop national value chains in this emerging industry [1]. The rate at which road transport needs to be electrified in order to keep global temperature increase below 2 °C relative to pre-industrial levels varies significantly across different studies, as a multitude of energy technology pathways are possible [2]. However it is generally accepted that a substantial market penetration of electric vehicles will ultimately be required, especially in large markets such as the US, Europe, China and India.

Alongside aspirational targets set by several governments, legally-binding targets are also in place in some countries and under development in others. Most notably, the California Zero Emission Vehicle mandate sets targets for EV sales with enforceable fines for those automotive manufacturers who fail to meet them. In the European Union the Directive on the deployment of alternative fuel infrastructure [3] mandates that Member States set their own legally binding targets for EV and other alternative fuel infrastructure by the end of year 2016.

In order to achieve their EV targets, national and local governments are deploying a set of incentives to stimulate their adoption, including purchase grants, tax exemptions, non-monetary incentives such as free parking and access to restricted lanes, and financial support to the development of extensive charging infrastructure [1, 4]. On their part, automotive OEMs are producing an increasingly diverse range of EV models in order to comply

with mandates and standards and gain an edge over their competitors in this new market. Although market penetration on a global level is still low, the share of electric vehicles is growing fast [5]. In some countries, such as Norway and the Netherlands, the market penetration of EVs has reached substantial levels, while the US, Japan and China lead the way in terms of the size of their EV stocks, and several new markets are starting to develop [5].

Despite some early success stories and the growing momentum behind the EV transition, though, it is generally accepted that reaching the desired level of EV penetration globally in a timely manner is going to be challenging, due the presence of strong technological, institutional, financial and behavioural barriers, together with the inherent slow turnover rate of passenger car stocks [6-8]. For this reason much emphasis in the policy discourse is placed on identifying those mixes of policy instruments that are most effective at accelerating the deployment of EVs and related charging infrastructure [1]. Aside from contributing to meeting the relevant policy targets, a rapid deployment has the added benefit of reducing break-even times for EV manufacturing and infrastructure investments, which in turn reduces investment risk and the overall need for financing the transition to electric mobility. In this perspective, it is clear why comparatively less attention is paid to the particular type of EVs and charging infrastructure deployed in the short term, as long as they are adopted rapidly. As it will be argued in the remainder of the paper, however, the type of EVs and infrastructure adopted early on can have potentially serious cost implications in the medium to long term, which can ultimately hinder the EV transition.

1.2 Different patterns of adoption are emerging

Due to the specific characteristics of each market and the lack of generally accepted best practices, different mixes of policy support measures are being used in different countries in order to stimulate rapid EV adoption. As a result, different patterns of deployment of EVs and charging infrastructure are emerging in the most active countries and regions, i.e.: China, Europe, Japan and the United States [1, 4, 5].

In particular, different ratios of pure battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) and of rapid charging and slow charging infrastructure can be observed across leading countries [4, 5]. Evidence suggests that relative value of incentives for BEVs and PHEVs is one of the factors influencing their market shares [9]. In other words, government incentives to EV purchase, both monetary and non-monetary, combined with conventional fuel and vehicle taxation, determine the type of EVs that are most competitive and the market segments in which the price differential with ICEVs is smallest. This will in turn influence the EV types and models that automotive OEMs will manufacture and commercialise in order to achieving highest possible sales.

Moreover, the available evidence suggests that public charging infrastructure is an enabler of EV adoption, 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 [7, 10]. The particular type, density and location of charging points deployed is intended to reduce range anxiety, increase the perceived utility of EVs and allow their users to perform most journeys that internal combustion engine vehicles (ICEVs) are capable of doing, with minimum inconvenience. However, it is difficult to know in advance how well this will work practically and the extent to which the infrastructure will actually be utilised, which given its high cost has potentially significant economic consequences [7, 10].

It is therefore likely that, shaped by the combined effect of EV-specific policy support measures mainly aimed at accelerating adoption and underlying conventional fuel and vehicle taxation that does not adequately internalize externalities, the type of EVs and charging infrastructure that will be deployed in the short term will likely not be the most cost effective in achieving the intended long-term policy objectives. This would not be a significant problem if the process of development and adoption of new technology like EVs did not exhibit path-dependence and was not prone to lock-in effects [11]. In other words, the type of EVs and infrastructure initially deployed contribute to pushing future EV technology and infrastructure development down a certain path, as they shape the behaviour and preferences of adopters and the development of related institutions; this in turn influences the development and deployment of new EV models and infrastructure architectures, in a process that in technology studies is generally referred to as co-evolution [12]. As policy and regulation also co-evolve with the new technology and the preferences of its users become entrenched, the electrification of passenger cars could become locked into sub-optimal mixes of EVs and charging infrastructure types. Although such mixes

could at first appear cost-competitive to the final user due to the policy incentives that support them, their true cost will be borne by society and eventually passed on to EV users when policy support measures are discontinued. This is likely to impact negatively later phases of the transition to EVs, possibly preventing it from reaching the ultimate goals intended by policymakers.

2 Aim of the research and methods

2.1 Aim and objectives

The aim of our work is to assess whether today's EV policy is conducive to a future cost-effective use of this technology, with a view to understanding whether it puts the EV transition on an economically sustainable path or otherwise. We will do so by exploring the relative costs of future portfolios of electric vehicles and charging infrastructures that are consistent with today's policy and market trends, and comparing them with lower cost scenarios that could be achieved through different policies. We will use the results of our analysis to formulate recommendations, particularly with regard to EV and charging infrastructure deployment policy, but also other passenger car policy areas where relevant.

2.2 Choice of analytical approach

In order to choose the methods by which to achieve the above objectives, we have first examined the EV economics literature¹. A large number of studies can be found that cover the whole spectrum of economic assessments of EVs, from detailed powertrain cost and performance modelling aimed at optimizing the design of powertrains or specific components, to studies assessing the societal costs of the transition to electromobility under a range of scenarios with the aim of guiding long-term policy making. Common to most of these studies is the use of the Total Cost of Ownership (TCO) method for assessing the cost of EVs over their lifetime and comparing across different powertrain types. This method is sometimes also referred to as Relative Cost of Ownership or Relevant Cost of Ownership (RCO), to highlight that not all costs are considered in the analysis but only those that are relevant to the comparison being made.

The studies we have reviewed have generated a large amount of knowledge on the economics of EVs, both present and future, and on the important factors that should be included when assessing it. In particular, several studies consider the effect of both powertrain and non-powertrain future efficiency improvements; as for the latter, the most important ones are vehicle weight reduction through the use of lightweight materials, improvements in vehicle aerodynamics and reduction of tyre rolling resistance. Several studies also analyse the passenger car market by dividing it into segments, which is important particularly when comparing the relative economics of different EV types. Some studies also consider vehicle use statistics, such as daily distances driven and their variation across vehicle segments, which matter particularly in the case of bi-fuel vehicles such as PHEVs and RE-EVs. However, only few studies go beyond the cost comparison of individual vehicles and also assess the total cost of the whole passenger car fleet, including market structure effects. Finally, charging / fuelling infrastructure costs are generally either ignored or modelled in a basic way; with very few exceptions, the different types of chargers (slow v rapid) and their utilization levels are not accounted for.

Given the aim of our study, we found the RCO modelling approach to be suitable. We have therefore built a RCO model that allows calculating the relative cost of different EV fleet and infrastructure portfolios, and that includes all the key factors discussed above². The model also allows calculating CO₂ Well-to-Wheel emissions, so that abatement costs can also be estimated. Novel elements of our approach are that: a) infrastructure costs are accounted for based on its type, size and utilisation level; b) the relative cost of different portfolios is calculated over the whole vehicle fleet. Moreover, the model has particularly been designed so as

¹ we do not cite and discuss the literature in detail here for the sake of brevity; instead we refer the interested reader to a forthcoming KAPSARC working paper by the same authors, available on www.kapsarc.org

² For a detailed description of the model and input data used, please refer to the above-mentioned working paper

to ensure transparency, flexibility and ease of use for third parties interested in reproducing our results or testing different scenarios. In order to achieve this, we have excluded from the model some of the detailed complexity of the problem, while seeking to adequately capture within it those factors that have a stronger influence on the cost of EV and infrastructure portfolios. Finally, the model has been designed so that inputs from more technical studies can be easily integrated and updated as appropriate when new evidence becomes available.

Although the model lends itself to estimating different metrics, in our study we decided to focus our attention on relative private costs of the EV and infrastructure fleet. Environmental external costs are not included in our analysis, however to ensure our comparisons of different scenarios are meaningful, we will only compare scenarios that are characterised by similar total CO₂ emissions. In doing so our results are not influenced by assumptions on the external cost of CO₂ emissions. Moreover, all costs in the model exclude emissions-related taxes, which currently are not proportional to actual emissions and therefore distort the market. However, once identified cost-effective mixes of EVs and infrastructure, with the model we can then analyse EV costs at the level of the single vehicle as well as across market segments, and assess how compatible is current taxation with achieving those mixes.

Finally, considering that the cost of an EV and infrastructure portfolio depends in part on technology and in part on the particular vehicle market considered, we take a case study approach for our analysis. We choose the UK and California in particular because both are aggressively pursuing electrification of passenger cars and their markets are illustrative of large European countries (such as France and Germany) and North America respectively. Another reason for choosing these two cases is the availability of the required information and data in English. Moreover, by comparing and contrasting two rather different cases such as the UK and California, we test the extent to which general lessons can be learned on 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 by those targets is sufficiently high for lock-in effects to take place; and c) because technology projections become very uncertain beyond 2030.

3 EVs in the UK and California: current status and policy scenarios

3.1 The UK

The UK, like France and Germany, is subject to EU transport and environmental regulation and policy; in particular the post-2020 EU CO₂ emission standards for passenger cars and the Clean Power for Transport directive harmonizing the rollout of alternative fuel infrastructure throughout the EU will provide the strongest drivers to the deployment of EVs and charging infrastructure at European level. These are complemented by the EU Air Quality targets and the policy objectives set by the EU Transport White Paper. In addition to EU policy, the UK has set itself the legally binding target of reducing total GHG emissions by 80% relative to 1990 levels by 2050, of which transport is a major contributor. In order to fulfil its domestic and European obligations, the UK is committed to supporting the development and deployment of low carbon vehicles, particularly EVs [6], which the government also sees as an opportunity to revive the country's automotive industry [13]. In the UK government, the Office for Low Emission Vehicles (OLEV) oversees all policy related to the development and deployment of EVs, and especially provides a range of incentives as a result of which in the last few years adoption of EVs has been growing rapidly and a substantial network of charging places has been deployed across the country.

In particular, the UK government provides a direct incentive to the adoption of EVs through the Plug-In Vehicle grant, a technology neutral grant that covers up to 35% of the vehicle's retail price, up to a maximum of £5,000 per vehicle. The effect of this grant, combined with underlying vehicle and fuel taxation and general passenger car market conditions in the UK, has resulted in EVs reaching 1% share of new passenger car sales in 2015, which is not dissimilar to that of France and Germany. In the UK to date PHEVs account roughly for two thirds and BEVs for one third of total EV sales, with the relative share of PHEVs growing in recent years. Adoption of EVs is mainly by affluent, multi-vehicle households in urban areas (single vehicle households are a minority in the UK). EV 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 [14]. It also appears that EVs are being driven annually for mileages comparable to those of ICEVs. Evidence suggest that the demographic profile of EV buyers is not going to change much in the coming years, however more evidence is needed in order to better understand the different characteristics of BEVs and PHEVs adopters, the use they make of the vehicles and the effect that policy support has on them [10].

Incentives have also been provided to the development of a charging infrastructure, in the form of a grant for EV drivers to install a home charging point covering 75% of cost, up to £700, as well as match-funding for private and public entities that deploy charging infrastructure in selected regions of the UK (Plugged-In Places). The result is that by February 2015 circa 8,000 public charging points (of which circa 2,400 slow, 4,700 fast and 900 rapid), circa 7,000 workplace charging points (open access) and over 30,000 domestic charging points (over 90% of EV adopters had access to domestic charging points) had been deployed across the UK [15]. EV owners have shown a strong preference for charging overnight at home, much less at public or workplace facilities. This is due to convenience and not much influenced by availability of infrastructure [14]. However there seems to be increasing request from current EV owners for more extensive and fast public charging, in order for them to be able to undertake longer journeys [10].

In terms of future deployment of EVs and charging infrastructure, the UK government has to date not committed to any specific target although it aspires that by year 2040 all new passenger cars should be ultra-low emission vehicles [6, 10]. The Committee on Climate Change (CCC), an independent body advising the UK government on GHG emissions targets, has developed scenarios consistent with the overall UK energy decarbonisation target, which suggest that the EV share of the passenger car market in 2030 should be between 30% (low case) and 60% (high case). Using their passenger car stock model, Element Energy [6] estimates that the corresponding stocks of EVs in 2030 should be respectively 4m (low case) and 8m (high case). In either scenario, the 2030 fleet modelled by Element Energy using a choice model based on the result of a new car buyer survey will consist of roughly 60% PHEVs and 40% BEVs, also assuming that BEVs and PHEVs will be widely available throughout the market, and that BEVs will be offered particularly in the small car segment with some models also available in the medium and large car segments, and PHEVs will be mostly offered in the medium and large car segments [6].

To complement existing roadmaps for EV technology and low-carbon fuels, a roadmap for alternative fuel infrastructure also including EV charging infrastructure has recently been developed in the UK [15]. According to the roadmap, private residential charging will remain the cheapest and most convenient option, with a potential reach of circa 19m households, as in the UK around 70% of households have a garage or off-street parking, and therefore should be prioritised; however this is as low as 10% in certain urban areas where alternative solutions will be required. Should the Committee on Climate Change high 2030 target be met, Element Energy estimates that a network of 2,100 rapid charging sites (10 charging points per site) could provide national coverage [6]. In the meanwhile, the UK government is continuing to support the development of charging infrastructure, with the Highways Agency alone committed to investing £15M in order to add 1,000s of new charging points on the Strategic Road Network, with the aim that motorists will be no more than 20 miles from a charge point 95% of the time; where possible, these will typically be rapid charging points [16]. 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, while it is expected that the public slow charging network will also continue to grow, especially in urban areas [15].

Finally, EV consumer research conducted in the UK suggests that key barriers to EV adoption remain price and range, with users expressing desire for longer range vehicles so as to enable infrequent, longer trips ideally only charging their vehicles at home. A fully developed charging infrastructure, particularly rapid, is also perceived as required for further market expansion [10].

3.2 California

As part of the State of California's climate change policy, in Jan 2015 Governor Brown announced that he wants to reduce the use of petroleum fuels in cars and truck in California up to 50% by 2030 [17]. On this basis,

California has a target of 1.5m ZEVs on the road in 2025 (Executive Order B-16-2012), the strategy to achieve which is set out in the “2013 ZEV Action Plan” of Feb 2013 [18]. The California Energy Commission was identified as the lead agency for a number of initiatives, including delivering the Alternative and Renewable Fuel and Vehicle Technology Program (ARFVT Program) is aimed at supporting the goals of climate change policy in California, which also includes the provision of EV charging infrastructure. In order to support the achievement of the 2025 ZEV target, the California’s ZEV infrastructure will have to be built so that is able to support 1m ZEVs by 2020.

The market share of EVs in California in 2015 was one of the highest in the world, at 3.2% of new passenger car sales, with a roughly equal split between BEVs and PHEVs. The California passenger car market is large, with 1m new car sales in 2014. Similarly to the UK, EV owners in California are predominantly affluent, highly educated, multi-vehicle households, and use their EVs as the main car for frequent, shorter journeys, therefore with similar annual mileages to ICEVs. In addition to the California Zero Emission Vehicle mandate, requiring car manufacturers to sell a set number of EVs per year, EV buyers can benefit from a federal tax rebate of up to \$7,500 (depending on the EV battery size) and a state rebate of \$2,500 for BEVs and \$1,500 for PHEVs. Overall financial and non-financial incentives in California are stronger for BEVs than for PHEVs, which explains the current near equal split of market shares between the two technologies.

As of 2014, there were 6,700 public charging points in California. Charging of EVs also in the US happens mainly at home: home charging accounts for 80% of BEV and 86% PHEV charging events. Like in the UK, PHEVs are reported to be used on electricity as much as possible.

The EV adoption target that California sets itself is 1m EVs on the road by 2020, as an interim target to the ZEV mandate target of 1.5m ZEVs by 2025. EV owners in California demand longer ranges, particularly 200 miles for BEVs as opposed to current 80, and 100 miles for PHEVs as opposed to current 40.

In 2014 the National Renewable Energy Laboratory (NREL) conducted a study for the California Energy Commission and in collaboration with several stakeholders estimating that, should the 1m EVs by 2020 target be met, anywhere between 20k-50k public chargers will be needed. This very high number relative to the UK can be explained by the fact that only a minority of the charging points will be rapid. In particular NREL has built two infrastructure scenarios for 2020, namely the Home Dominant scenario and the High Public Access scenario:

Home Dominant: 876k home chargers (of which 511k L1 and 365k L2), 102k work chargers (20k L1 and 82k L2) and circa 22k public chargers (1,620 L1, 20,100 L2 and 551 fast – in 275 fast charging stations)

High Public Access: 806k home chargers (of which 517k L1 and 289k L2), 167k work chargers (23k L1 and 144k L2) and circa 50k public chargers (2,100 L1, 46,500 L2 and 1,550 fast – in 775 fast charging stations)

4 Analysis and discussion

4.1 Driving patterns and fleet structure: comparing the UK and California

In the model the key inputs that distinguish the UK and California case studies are the passenger car fleet structure and the vehicle usage patterns. We have used today’s fleet size and new passenger market shares to model the structure of the 2030 market³. For both the UK and California, we have divided the fleet in four main segments, and modelled each one of them based on the characteristics of their most popular models; see Tables 1 and 2. In our model, the weight of the vehicle is then reduced based on the expected future use of lightweight materials and the power adjusted accordingly.

³ For a detailed discussion of how this was done please refer to the forthcoming KAPSARC working paper

Table1: Structure of the UK market in 2030 – Main segments and their key attributes

Segment	Weight (kg)	Power (kW)	Stock share (%)
A/B	1,050	64	40.6
C/D	1,300	92	40.8
E/F	1,550	135	4.8
H/I	1,550	105	11.3

Table2: Structure of the California market in 2030 – Main segments and their key attributes

Segment	Weight (kg)	Power (kW)	Stock share (%)
Small	1,270	90	26.8
Medium	1,475	140	31.1
Luxury	1,735	224	10.7
SUV	2,010	216	20.1

As for the vehicle usage patterns, we have analysed data from the UK National Travel Survey and the US National Household Travel Survey respectively and we have derived the frequency distributions of daily distances driven shown in Figures 1 and 2⁴. These distributions are used when calculating utility factors of PHEVs and RE-EVs and relative shares of home vs public charging for BEVs.

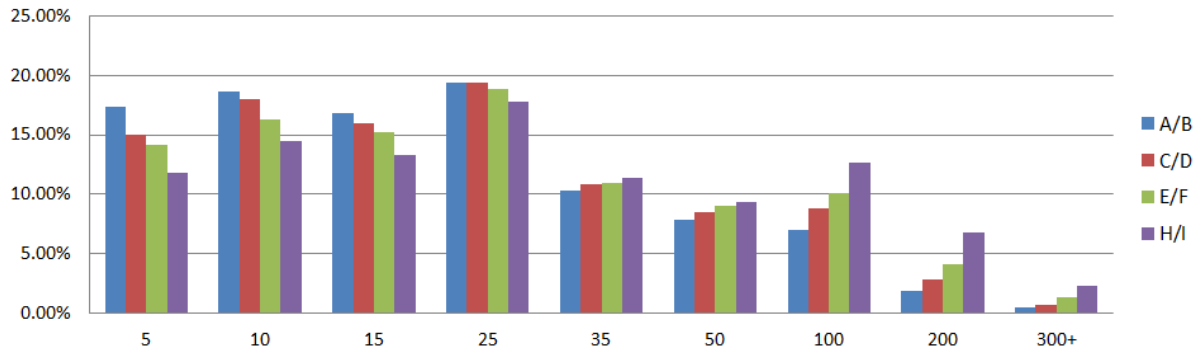


Figure1: Frequency distribution of daily distances driven in the UK, broken down by vehicle segment (source: own analysis of the UK National Travel Survey data)

⁴ Please refer to the forthcoming KAPSARC working paper for all details

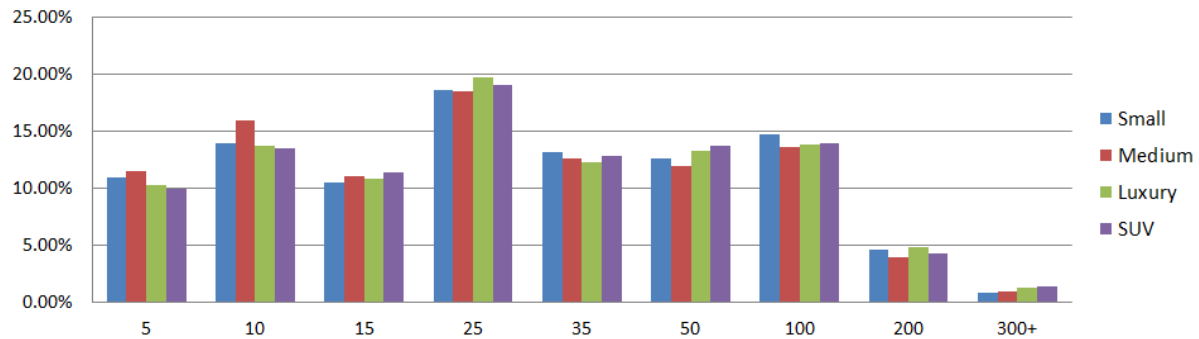


Figure2: Frequency distribution of daily distances driven in California, broken down by vehicle segment (source: own analysis of the US National Household Travel Survey data)

As can be noticed, the UK and California markets have very different characteristics in terms of the attributes of their main segments and their relative shares, as well as the usage patterns of the vehicles. We particularly noticed that, unlike the UK where larger vehicles tend to be driven more on longer distances and have higher annual mileage than smaller vehicles, in California all vehicles tend to be driven similarly and different segments have comparable annual mileages.

4.2 Initial results of UK scenario analysis

Based on the current status and future targets for the deployment of EVs and charging infrastructure discussed in Section 3.1, we have built a set of plausible scenarios and we have estimated their private costs, relative to a base case where the whole passenger car fleet is only composed of ICEVs. An overview of the cost of the scenarios modelled is provided in Figure 3, where the error bar indicates uncertainty associated with future battery technology development.

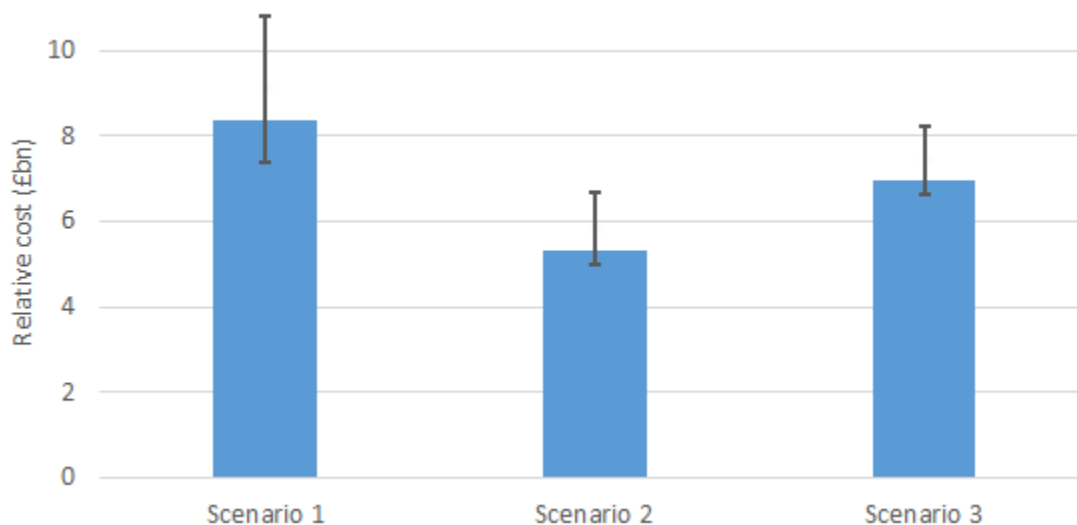


Figure3: Relative cost of UK EV and infrastructure scenarios modelled

All scenarios are consistent with the UK government target of 60% EV market share, or 8m EVs on the road, by 2030 but differ in terms of the EV types and related infrastructure deployed. It also worth noting that, despite the difference of EV types across scenarios, the average fleet CO₂ emissions are comparable, which means that

any of the scenarios presented potentially meets the UK government's CO₂ emission reduction goals. The key elements of each of the 5 scenarios modelled are provided in Table 3.

Table3: UK 2030 EV and infrastructure scenarios modelled

Scenario	BEV share (%)	BEV segments	PHEV share (%)	PHEV segments	BEV range (km)	PHEV range (km)	# slow chargers	# fast chargers
1	40	A/B, C/D	60	C/D, E/F, H/I	200	100	120,000	20,000
2	0	-	100	C/D, E/F, H/I	-	50	-	-
3	20	A/B	80	C/D, E/F, H/I	100	50	60,000	10,000

As we can notice from Figure 3, Scenario 1 reflecting the BEV/PHEV ratio extrapolated by current policy, the full infrastructure coverage and the long all-electric range expected by EV users is the most costly, and is highly exposed to uncertainties related to future battery technology development. Moreover, the utilisation level of the public charging infrastructure based on our estimates would be very low. On the other end of the spectrum Scenario 3, only made of shorter range PHEVs and no public charging infrastructure, would achieve similar CO₂ emission reductions at 40% less cost and much less exposure to battery technology development risk. However both scenarios can potentially lock the UK into undesirable states, the former in a state where EV users expect, but not use, large battery capacities and extensive infrastructure coverage, the latter in one where BEVs do not develop at all, potentially hindering future complete electrification of passenger car transport.

However Scenario 3 shows that by balancing EV policy and harmonising vehicle CO₂ taxation so as to favour uptake of BEVs only in the small vehicle segment, for use mostly in shorter trips as is the case today, and by strategically siting infrastructure so that a full national coverage is not required, the relative cost of achieving the UK government's target would reduce substantially. Most importantly the exposure to battery technology uncertainty would drop, thus making this scenario more robust than Scenario 1. We are currently analysing in the detail the policy implications of this scenario, so as to assess its practical feasibility and to derive policy recommendations. Full results of this analysis will be presented at the conference.

4.3 Initial results of California scenario analysis

Based on the discussion of current state and future EV targets in California provided in Section 3.2, we have built a set of plausible scenarios and estimated their relative private cost, applying the same logics as for the case of the UK. An overview of costs of key scenarios is provided in Figure 4. Scenarios are described in Table 4.

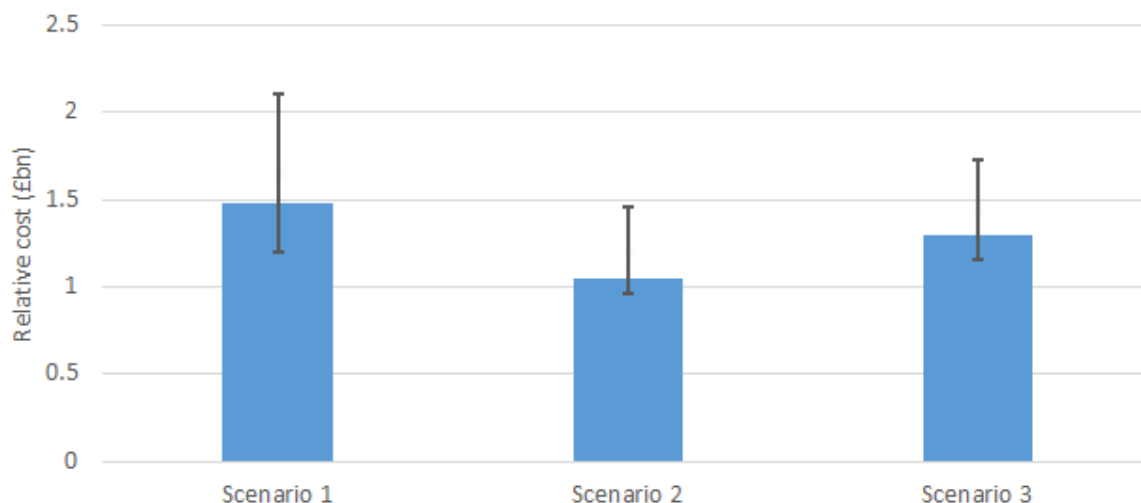


Figure4: Relative cost of California EV and infrastructure scenarios modelled

Table 4: California 2030 EV and infrastructure scenarios modelled

Scenario	BEV share (%)	BEV segments	PHEV share (%)	PHEV segments	BEV range (km)	PHEV range (km)	# slow chargers	# fast chargers
1	50	Small, medium, luxury	50	all	200	100	48,450	1,150
2	0	-	100	all	-	50	-	-
3	20	small	80	Medium, luxury, SUV	100	50	35,000	600

The trend that emerges from the scenarios explored is similar to that observed for the UK, however the cost differences are here less pronounced. The detailed cost and policy implications of these scenarios are currently being analysed and will be presented at the conference.

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