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A portfolio of powertrains for the UK: An energy systems analysis

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ABSTRACT

There has recently been a concerted effort to commence a transition to fuel cell vehicles (FCVs) in Europe. A coalition of companies released an influential McKinsey-coordinated report in 2010, which concluded that FCVs are ready for commercial deployment. Public−private H$_2$Mobility programmes have subsequently been established across Europe to develop business cases for the introduction of FCVs. In this paper, we examine the conclusions of these studies from an energy systems perspective, using the UK as a case study. Other UK energy system studies have identified only a minor role for FCVs, after 2030, but we reconcile these views by showing that the differences are primarily driven by different data assumptions rather than methodological differences. Some energy system models do not start a transition to FCVs until around 2040 as they do not account for the time normally taken for the diffusion of new powertrains. We show that applying dynamic growth constraints to the UK MARKAL energy system model more realistically represents insights from innovation theory. We conclude that the optimum deployment of FCVs, from an energy systems perspective, is broadly in line with the roadmap developed by UK H$_2$Mobility and that a transition needs to commence soon if FCVs are to become widespread by 2050.

Introduction

Road transport has mostly relied on the same petroleum fuels and the same internal combustion engine (ICE) designs since the advent of the passenger car more than 100 years ago [1]. Petroleum fuels have high energy densities, which is important for maximising on-board storage and hence the vehicle range. They are also cheap to produce, easy to handle and fast to refill; moreover, ICE powertrains are also cheap to manufacture. However, existing road vehicles produce a large amount of CO$_2$ and other emissions that affect air quality, and there is strong pressure on the automotive industry to reduce emissions from cars [2,3].

Three strategies are generally employed to reduce emissions in Europe. First, in the short term, energy efficiency improvements have reduced fuel use and vehicle CO$_2$ emissions [4], partly as a result of European regulations [5]. Second, biofuels are being produced to replace fossil fuels, although the direct and indirect emissions resulting from their

production are uncertain [6] and there is controversy around their broader sustainability implications. Third, in the longer term, manufacturers have been developing new vehicle designs with novel powertrains, including battery electric, plug-in hybrid and hydrogen fuel cell vehicles.

Novel powertrains

The introduction of novel powertrains has accelerated over the last few years. The Toyota Prius ICE hybrid was introduced in 1997 and global cumulative sales have exceeded 3 million units [7]. Since 2010, more than ten plug-in hybrid models have been launched; previously, most plug-in vehicles were converted hybrid vehicles. While battery electric vehicles (BEVs) pre-date ICE vehicles and are already present in some niche markets (e.g. delivering milk quietly at night in the UK), more than 20 modern battery electric cars are now available from a range of prominent manufacturers.

The first commercial hydrogen-powered fuel cell vehicle (FCV) has only recently been launched by Hyundai, with other manufacturers expected to follow in the coming years. FCVs have negligible emissions and do not suffer from the short range and long refuelling time of BEVs. There has recently been a concerted effort to commence a transition to FCVs in Europe. In 2010, a large consortium of automotive and energy companies released an influential report, coordinated by the consulting firm McKinsey [8], here called the Coalition study,[1] that examines the potential role for different powertrains in the European fleet. The study concludes that a portfolio of different vehicle types might be expected to co-exist in a decarbonised road transport sector and that FCVs are ready for commercial deployment. Subsequently, public–private H2Mobility programmes have been established in several European countries to build businesses cases for the introduction of FCVs and to coordinate the deployment of hydrogen fuel infrastructure. The first report of the UK H2Mobility programme, released in 2013, establishes a roadmap for FCV introduction in the period to 2030 [9].

Comparison of the FCV reports with the literature

Both the Coalition and H2Mobility studies examine the implications of different vehicle deployment scenarios using scenario-modelling approaches with total cost of ownership (TCO) calculations. These studies use proprietary data from manufacturers and could therefore be considered to have more reliable estimates of vehicle cost and performance data than other studies, but possible industry bias in such cases always needs to be considered. The data and assumptions that underpin the calculations are only partially disclosed in the Coalition study and are not disclosed in the H2Mobility report, which makes it impossible to independently test the conclusions.

This lack of transparency is important because other UK studies using different methodologies have produced conflicting insights. Ref. [10] combines a vehicle stock model (the

UK Transport Carbon Model) with the UK MARKAL energy system model and does not find an economically-optimal role for FCV cars in any of four scenarios. Two studies using a spatially-disaggregated version of UK MARKAL find a role for liquid hydrogen ICE cars but not fuel cell cars [11,12]. Another study, using a more recent version of UK MARKAL, does find a role for FCVs in a portfolio of different vehicle types that is similar to the Coalition report conclusions, but FCVs are not introduced until 2035 [13]. More widely, studies using global energy system models conclude that hydrogen will have only a small role prior to 2050 [14] unless very high emission reductions are required [15]. There is clearly more uncertainty about the most appropriate method of reducing emissions from the transport sector than is suggested by the Coalition and H2Mobility studies.

Contribution and outline of this study

In this study, we try to reconcile the conflicting insights from the TCO and energy systems methodologies. We use a new version of the UK MARKAL energy system model which has a revised transport sector that is based on vehicle cost data from the Coalition study [8]. This version has a number of major improvements over the versions used in the previous studies cited above. The car sector is partially disaggregated and has growth constraints applied to all new powertrains, which enables us to gain valuable insights into the timing of transitions to alternative powertrains. Moreover, a full and consistent representation of all fuel supply infrastructure is now implemented and technologies that require major up-front investments, such as a hydrogen transmission network, are simulated using fixed-size 'lumpy' investments. We use the revised model to identify the optimal vehicle fleet for a series of energy system scenarios. To further reconcile the methodologies, we calculate the TCO using the energy systems approach and compare it to the Coalition and H2Mobility approaches. This helps us to understand whether the conflicting insights described above are more likely to be caused by using different methodologies or different data assumptions.

In Section Review of industry-led and energy systems analyses, we review the Coalition and H2Mobility reports and discuss the differences between their scenario/TCO approaches and the energy systems approach. We describe our methodology for this study in Section Methodology and examine our base scenario and the importance of growth constraints and vehicle data assumptions in Section Energy system analysis of powertrains. In Section Total cost of ownership, we compare the base scenario results with results from the TCO methodologies. We consider the importance of broader UK energy system uncertainties on the results in Section Alternative energy system scenarios and discuss our findings in Section Discussion.

Review of industry-led and energy systems analyses

Most long-term transport sector studies are driven by three overarching questions:

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[1] This report is commonly referred to as the "McKinsey report" but McKinsey do not claim authorship so we refer to it as the Coalition study in this paper.

Table 1 – Coalition study scenarios for the European vehicle fleet in 2050.

Scenario	ICE	PHEV	BEV	FCEV
Conventional	60%	25%	10%	5%
EV dominated	5%	35%	35%	25%
FCEV dominated	5%	20%	25%	50%

1. What is the most appropriate powertrain? ICE, electric drive or a hybrid combination? Should the electric drive be powered by a fuel cell or only batteries?
2. What is the most appropriate fuel? There is a choice of conventional hydrocarbons, biofuels, hydrogen, electricity, or a combination of these.
3. How can a transition to alternative powertrains be achieved, taking into account infrastructure requirements, early markets, consumer acceptance, lock-in of existing technologies and other influences?

The Coalition and H_2Mobility studies produce scenarios for the first two questions while the energy systems approach uses an optimisation framework to identify the cheapest scenario and transition. The H_2Mobility work primarily concentrates on the third question. In this section, we review the Coalition and H_2Mobility studies and then briefly discuss the energy systems approach.

Coalition study

The Coalition study is built on the premise that it will not be possible to decarbonise the transport sector through improvements in ICE technology and greater use of biofuels [8]. It aims to perform a fact-based analysis of the relative merits of BEVs, FCVs and plug-in hybrid electric vehicles (PHEVs) using the best-available proprietary industry data. Future vehicle component cost forecasts are based on projected learning rates. The chosen methodology is a scenario-modelling approach that examines the implications of different deployment scenarios using static TCO calculations for each powertrain. Table 1 describes the three scenarios, which differ according to the proportions of each powertrain in the fleet in 2050. The study focuses on three car market segments: small (A/B), medium (C/D) and SUV (J1/J2), where the brackets contain the EU classification.

The study concludes that the TCO for all powertrains will converge after 2025 and that a portfolio of different powertrains will meet the needs of consumers and the environment, with no single powertrain satisfying all key criteria for economics, performance and the environment. However, it also forecasts a cost to society in the early years of a transition to build the initial underutilised hydrogen fuel infrastructure and to subsidise the capital costs of different powertrains to make them competitive with ICEs.[2]

The Coalition study forecasts that hydrogen refuelling infrastructure will represent 5% of the overall costs of FCVs. BEVs and PHEVs are assumed to have similar fuel

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[2] The UK already subsidises 25% of the cost of BEVs and PHEVs, up to a maximum of £5000.

infrastructure costs to FCVs, for electric charging, but this assumes that widespread public charging would be necessary as home charging is very cheap. We examine the impact of charging these vehicles only at home in a sensitivity study in Section 4.2.

Biofuels are already mixed with hydrocarbon fuels across Europe and the Coalition study assumes 6% biofuels in 2020 and 24% in 2050 for ICEs and PHEVs, with the 2050 figure reflecting an imposed biofuel supply constraint. In an energy systems analysis, biofuel availability depends on the availability of raw resources and imports, and the competition for biomass from other parts of the economy. We take this approach in our study and do not impose an arbitrary limit on the proportion of biofuels in the fuel mix. A wide range of domestic and imported biomass feedstocks are represented in UK MARKAL, with availabilities based on a government biomass strategy report [16] and a full review of the UK MARKAL bioenergy chains [17]. The transport sector competes with other sectors to convert this resource into biofuels; in addition, processed biofuels can also be imported with import limits based on Ref. [16].

UK H_2Mobility Phase 1 study

Like the Coalition study, the UK H_2Mobility Phase 1 study was coordinated by McKinsey, together with Element Energy [9]. The study also adopts a TCO approach and much of the data in this study is from the Coalition study so the conclusions are unsurprisingly similar, with the TCO of FCVs approaching parity with diesel ICEs by 2030. None of these data are disclosed in the report.

The main aim of the H_2Mobility study is to produce a roadmap for the introduction of FCVs to the UK, concentrating on how to achieve a transition to hydrogen-fuelled FCVs. The study surveyed 2000 consumers about their opinions on different powertrains to identify market segments that are particularly attractive for FCVs. It also examined refuelling habits and analysed these in a hydrogen refuelling station (HRS) model, concluding that an initial network of 65 HRSs would be required to commence a transition in the UK, increasing to more than 1000 by 2030. Ref. [18] uses an energy system model to show that the low initial utilisation of a network of this size is not an impediment to the transition.

Energy systems studies

The energy systems approach calculates the optimum fleet composition over time from an economic perspective that accounts for changes in energy supply and demand across the entire economy. One weakness of the TCO approach is the assumption that changes to the wider energy system do not affect the transport sector. This means that fuel prices and availability are assumed to be independent of the choice of vehicle technology in each scenario. In contrast, energy system models represent commodity flows and demands through the entire energy system and calculate fuel prices in commodity markets, so fuel prices reflect the evolution of the energy system in each scenario and account for demand elsewhere in the energy system. While the TCO approach requires the modeller to decide the appropriate level of

decarbonisation at the outset, an energy system model calculates the optimum decarbonisation in each sector to meet the overall emissions target, which often varies depending on the scenario. Energy system models thus offer an important complementary perspective to other approaches that focus on the transport sector in isolation.

Methodology

We use the UK MARKAL energy system model in this study. UK MARKAL has been developed over the last 10 years and has provided much evidence to underpin UK energy policy [19]. MARKAL is a widely-applied partial equilibrium, bottom-up, dynamic, linear programming optimisation model [20]. MARKAL models are used to identify the energy system that meets energy service demands with the lowest discounted capital, operating and resource cost, subject to constraints such as greenhouse gas emission targets and government policies. Demands are specified exogenously and the impact of price rises on consumer behaviour is represented in this study by varying these demands using demand elasticities, with reductions of up to 25% allowed in UK MARKAL. While the fixed demand version of the model minimises the total system cost, the elastic demand version used here instead maximises welfare (defined as the sum of producer and consumer surplus) so that energy service demands and energy supply reach equilibrium.

A schematic diagram of a typical MARKAL model is shown in Fig. 1. Resources are converted into useful commodities in processing plants and then consumed by demand technologies in order to meet all energy service demands each year. Thousands of processing plants and commodities are often represented in a single model, with numerous unique routes from resources to energy service demands and with no limits on the number of processing plants in each route. In UK MARKAL, vehicles are defined as demand technologies with exogenous demands specified in billions-km/year. Numerous exogenous parameter inputs are specified for each technology including capital and operating costs, the commodity conversion efficiency, the availability factor and the technology lifetime.

MARKAL represents only the annual flows of most commodities, using the assumption that there is sufficient energy storage at negligible cost to cope with demand peaks and supply interruptions. An exception is electricity flows, which are tracked using the seasonal and intra-day time-slices.

Revised transport sector

The revised UK MARKAL transport sector that we use in this study is described in Ref. [18] and in Appendices A and B of the Supplementary information to this paper. Here, we provide a short overview and a comparison with the assumptions of the Coalition study. We cannot compare our approach with the UK H$_2$Mobility study as it does not disclose any underlying data, but that study builds on the data collected for the Coalition study so is likely to have similar assumptions. While we apply a similar methodology across all transport modes (cars, motorbikes, light and heavy goods vehicles and buses) for consistency, we only report cars in this paper as they represent by far the largest part of the market and are the only mode considered by the Coalition and H$_2$Mobility studies.

Vehicle capital costs and fuel efficiencies

We calculate the capital cost of each powertrain using a bottom-up approach. For each powertrain, we define a typical specification of vehicle components and calculate the total vehicle cost as the sum of the costs of each component. This methodology was also used for previous versions of UK MARKAL and the principal changes to the revised version are updated vehicle specifications and costs.

The component costs are taken from the Coalition study [8] where possible; a full list of sources is presented in the Supplementary information. The Coalition study assumes that electric powertrain costs will reduce substantially in the future through worldwide technology learning. While global energy system models have been used to examine the plausibility of this assumption [21], such an approach is not appropriate for a study of the UK as the total demand for cars is too small to materially affect component costs. For this reason, the Coalition study assumptions are also adopted in this study and BEV, PHEV and FCV powertrain costs are assumed to reduce over time.

The Coalition study does not examine all of the powertrains that we include in UK MARKAL so we use fuel efficiency data from other sources, primarily Ref. [22], so that the model is internally consistent. These data are scaled so that they represent the UK fleet. While the Coalition study does not publish the fuel efficiency data that they assume for different powertrains, it is possible to estimate these values from other data presented in their report (Exhibits 27, 29–31 and 34 in Ref. [8]). Fig. 2 compares Coalition ICE and FCV fuel consumption data against UK MARKAL data. The Coalition study assumes that petrol and diesel hybrid vehicles gradually
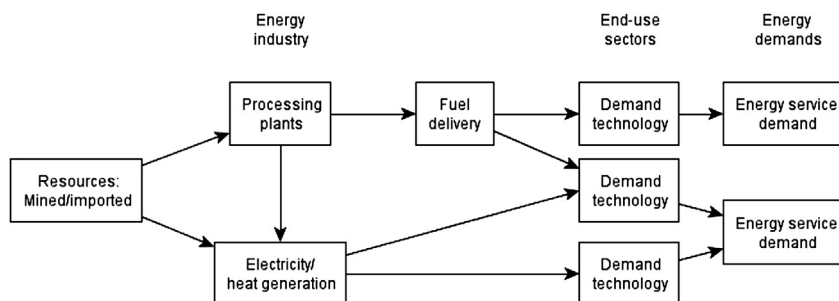

Fig. 1 – Schematic diagram of a typical MARKAL energy system model.

penetrate the ICE fleet over the coming decades, yet the ICE fuel consumption is consistently lower than the UK MARKAL consumption in all years and is similar to FCV consumption by 2050, which seems unlikely given the much greater efficiency of fuel cells compared to ICEs. For FCVs, the Coalition study assumes no improvements in fuel consumption over time while UK MARKAL has a gradual reduction in line with other vehicles. These differences would have important implications were the fuel cost to greatly influence the total cost of providing transport services.

Car sector disaggregation

In this study, the UK MARKAL representation of the car fleet is split into two segments to represent small and medium/large vehicles. In the previous UK MARKAL studies cited in Section Comparison of the FCV reports with the literature, cars are represented using a single homogeneous market segment, with no differentiation of size or classes of car and hence little account of non-cost factors on different market segments. Disaggregating gives us additional insights into the optimal timing of a transition in different sectors [18]. It also enables us to better represent the non-linear relationship between battery capacity and car weight for BEVs; larger cars require proportionally larger batteries to achieve the same range as batteries comprise a substantial proportion of the total vehicle weight, a phenomenon called mass compounding, which makes electric powertrains cheaper and more efficient, relative to other powertrains, for smaller vehicles [25]. All of the component sizes other than BEV batteries are scaled for small and medium/large cars according to the average weights of the different vehicle sizes.

Capital costs for each segment are calculated using the scaled component sizes. Vehicle fuel efficiencies are estimated for each segment by scaling the average motive force using efficiency data for each segment from EEA [23], adjusted to reflect the UK average efficiency from DfT [24].

Dynamic growth constraints

The diffusion of alternative powertrains in optimisation models is often overly optimistic because real-life limitations on the deployment of supporting infrastructure (e.g. fuel supply, repair centres) are not represented and because consumer heterogeneity is not considered. In a real transition, there are always early adopters who are much more willing to accept new technologies than the mainstream population. For this reason, transitions often have an s-shaped adoption curve that proceeds in three stages: after a slow initial take-up by early adopters, mainstream consumers start to use the technology and growth is constant until only laggards are not part of the market [26].

Some energy system models use static growth constraints that set a maximum limit on the market share of technologies each year (e.g. [27,28]). This approach has the disadvantage that the modeller must estimate when the transition will take place: an earlier transition than estimated could not take place with a static constraint, even if it were the cost-optimal strategy, while a later transition could proceed too quickly. Another static approach is to limit the adoption of new technologies each year (e.g. [14,29]). A better approach is to use dynamic growth constraints to represent an s-curve in which new technology adoption each year is limited according to the existing capacity. However, we are aware of only one energy system model that uses dynamic constraints for the transport sector [30].

In this study, dynamic growth constraints for hydrogen and battery powertrains are introduced to UK MARKAL. These constraints are defined as an annual growth rate depending on existing capacity using the GROWTH attribute. We use maximum growth rates of 15%/year for each technology, which is comparable with the diffusion of new powertrains previously, for example the adoption of diesel cars in France. One study argues that a diffusion rate of 20%/year for powertrains is reasonable, using diffusion rates of solar generation as a comparative example [30], but we believe that even 15%/year might be optimistic for FCVs given the greater complexities of introducing new hydrogen production and delivery infrastructure. We assume that 50,000 cars may be deployed each year that are not subject to the 15% growth rate (the MARKAL GROWTH_TID attribute), as the growth constraint would otherwise prevent any new powertrains being adopted. We examine the impact of applying dynamic growth constraints in Section Energy system analysis of powertrains.

Base scenario

We use UK MARKAL v3.26, which is calibrated to UK energy consumption in the year 2000 [28,31,32]. The energy service demands to 2050 are fully described in Usher and Strachan [33]. In this study, we run the model to 2100 under the
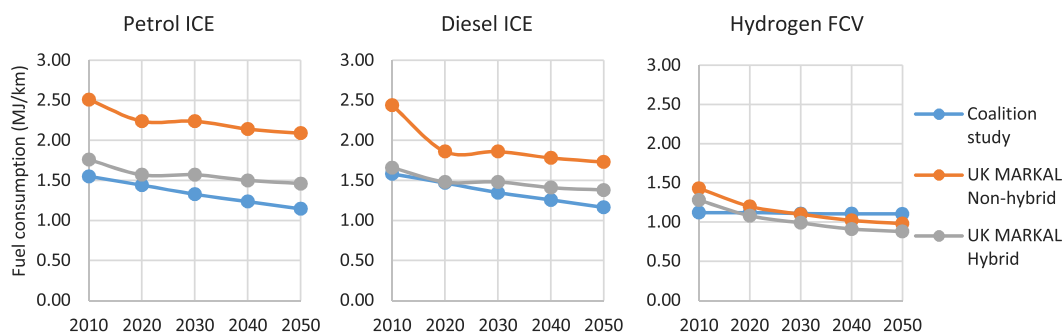
Fig. 2 – **Fuel consumption of ICE and hydrogen FCV cars in the Coalition study [8], scaled to the UK average using data from Refs. [23,24], and in the revised version of UK MARKAL.**

assumption that demands and technologies do not change after 2050, which allows us to gauge the stability of the post-2050 model solutions. As well as revising the transport sector, as described in this Section and in Appendices A and B in the Supplementary information, we also include improved representations of the hydrogen and gas infrastructure described in Refs. [34–37].

UK MARKAL is most often used to identify strategies to reduce CO_2 emissions to meet government targets. The mandated 80% emissions reduction target in 2050 is represented by a 90% reduction in CO_2 in the model in both Usher and Strachan [29] and Hawkes et al. [32] to recognise the uncertainties in the contribution of non-CO_2 GHGs, the emissions from land-use change and emissions from international bunker fuels [29]. In this study, our base scenario has an 80% target to be consistent with UK policy and does not include the UK share of international aviation and shipping energy demands. We also examine a reference "business-as-usual" case in which there are no constraints on CO_2 emissions.

Following HM Treasury [38], we use a social discount rate of 3.5% for future costs. We use the MARKAL elastic demand variant in which energy service demands are reduced as the prices of meeting these demands increase due to the imposition of the CO_2 emissions constraint.

Biofuels are assumed to have zero lifecycle CO_2 emissions in all scenarios. The direct and indirect emissions associated with biofuels are uncertain [6] and the Coalition study also assumes that biofuels have zero emissions for this reason. Including the lifecycle CO_2 emissions for biofuels would reduce the competitiveness of ICE vehicles relative to other powertrains.

UK MARKAL includes the option of supplying hydrogen through a national transmission pipeline network and we use the lumpy investment feature of MARKAL to prevent the model from building such a network incrementally, following the guidance of Ref. [18].

Energy system analysis of powertrains

The change in the optimum evolution of the car fleet that is caused by moving from the original to the revised version of the UK MARKAL transport sector is examined in Refs. [18], so we do not repeat that analysis here. In this paper, we instead compare the conclusions from the energy systems approach

with the conclusions from the Coalition and H$_2$Mobility studies.

The optimum evolution of the car fleet in the base scenario is shown in Fig. 3 for small and medium/large cars. For small cars, ICEs are replaced by ICE hybrids after 2020 and FCVs replace ICE powertrains from 2040. The medium/large segment has a more complicated transition with a small number of petrol, diesel and hydrogen PHEVs deployed as transition technologies after petrol and diesel hybrid ICEs, and with hydrogen FCVs deployed from 2020. In contrast to the portfolio of powertrains assumed in the Coalition study scenarios, FCVs come to dominate the whole fleet in the same way that ICE cars dominate at present and there is no role for BEVs. FCVs are the most competitive powertrain even if no CO_2 constraint is applied, as shown in Fig. 4. The only substantive difference in results between Figs. 3 and 4 is the absence of PHEVs in the medium/large segment when there is no CO_2 constraint.

The importance of applying dynamic growth constraints to better represent the transition to alternative powertrains is highlighted in Fig. 5. With no growth constraints, FCV deployment does not commence until 2040, after which all cars use hydrogen. With a 15%/year growth constraint, it is necessary for FCVs to be introduced into the market from 2015 in order to achieve the optimum penetration by 2050. The transition with growth constraints is consistent with the transition to FCVs in the H$_2$Mobility roadmap [9] for the period to 2030, and therefore may be taken to represent a realistic, if relatively fast, take-up rate.

The transition to FCVs is quite different in the small and medium/large segments, as shown in Fig. 6. Larger cars are converted to FCVs from 2015 but FCVs do not diffuse into the small car segment until after 2040. Larger cars travel 73% further each year than smaller cars on average, meaning that the capital cost per km is lower for larger cars despite the total cost being higher. The initial transition therefore focuses on the medium/large segment. This is also consistent with the H$_2$Mobility roadmap, which also examines cars within this segment [9].

Powertrain cost assumptions

FCVs come to dominate the base scenario but this conclusion is built on the assumption that the cost reductions for alternate powertrains that are forecast in the Coalition study will
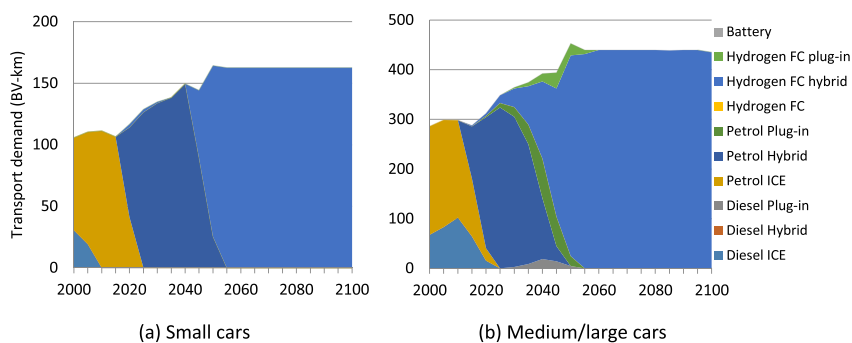
Fig. 3 – Optimum evolution of the car fleet in the base scenario with an 80% reduction in CO_2 emissions in 2050 relative to 1990.

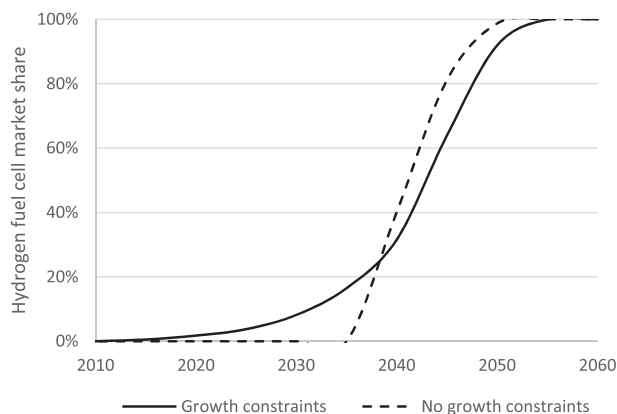(a) Small cars   (b) Medium/large cars
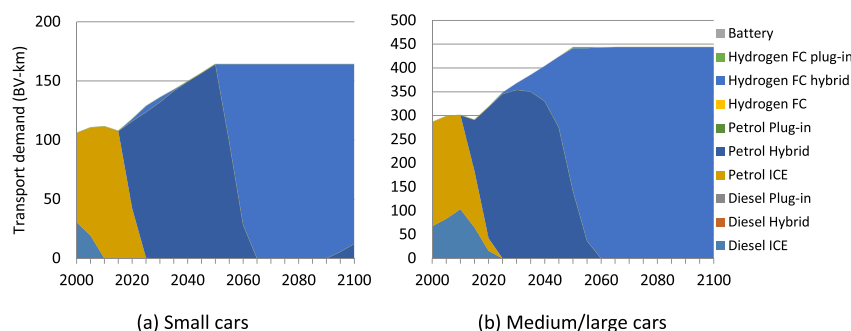
Fig. 4 − Optimum evolution of the car fleet in the base scenario with no constraint on CO$_2$ emissions.

be achieved. The Coalition study states that the conclusions are robust to these assumptions [8]. Yet there is much uncertainty, even in the short term. BEVs and FCVs are currently very expensive to produce but the costs are expected to reduce by an order of magnitude by 2020 if large-scale production commences on assembly lines. The Coalition study estimates fuel cell costs in 2020 in the range €16/kW to €98/kW (€43/kW best estimate) and battery costs in the range €230/kWh to €450/kWh (€300/kWh best estimate). The fuel cell best estimate target is likely to be met but it is less likely that the battery target will be achieved [39]. Between 2020 and 2050, costs are expected to further reduce by up to 50%, as shown in Fig. 7, bringing the capital costs in line with ICE vehicles.

We test the impact of powertrain cost assumptions using two sensitivity studies with two cost trajectories that are described below and shown in Fig. 7:

1) No cost reductions are achieved after 2020 for any technologies. This scenario assumes that technology costs are not reduced beyond the benefits of large-scale manufacturing.
2) Fuel cell and battery costs are 50% higher in 2050 than the base scenario best estimate. In this scenario, cost reductions continue to 2050 but technological progress is less successful than forecast in the base scenario.
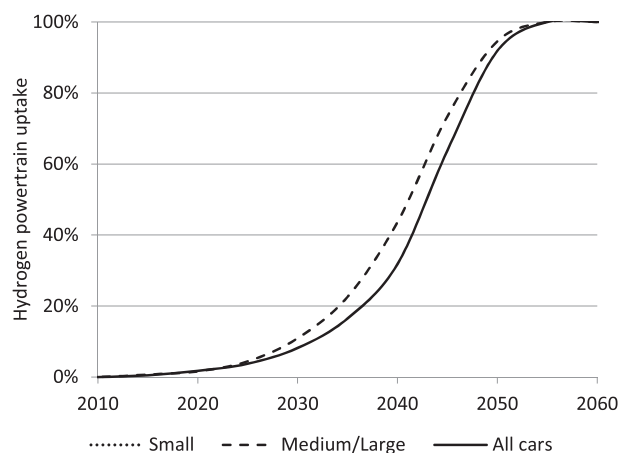
The impacts on the optimal vehicle fleet composition and on fuel consumption in 2050, for both cases, are shown in Tables 2 and 3.

With no cost reductions after 2020, FCV and BEV powertrains are too expensive to compete with biofuel-driven ICEs and PHEVs. In 2050, the vehicle mix is dominated by E85 ethanol-fuelled ICEs and biodiesel-fuelled PHEVs. In this scenario, it is economically-optimal to switch much of the bioenergy available to the UK to the transport sector, which runs counter to the Coalition study assumption that biofuels can only supply 24% of ICE fuel in 2050. The higher costs of providing transport lead to car use reducing by 4%, compared to a 1% reduction in the base scenario (with both compared to the base scenario with no CO$_2$ constraints).

In the less pessimistic scenario with costs 50% higher in 2050, FCVs continue to dominate the medium/large segment but the increased costs make biofuels a more competitive option for small cars. Increased costs in this scenario lead to diverging trends across the market and a portfolio of different powertrains in 2050.

Fuel supply infrastructure cost assumptions

In Section UK H$_2$Mobility Phase 1 study, we noted that the Coalition study assumes high electricity infrastructure costs

Fig. 5 − Impact of applying dynamic growth constraints on the diffusion of hydrogen FCVs into the car fleet.

Fig. 6 − Transition to hydrogen powertrains in the base case for small and medium/large car segments.
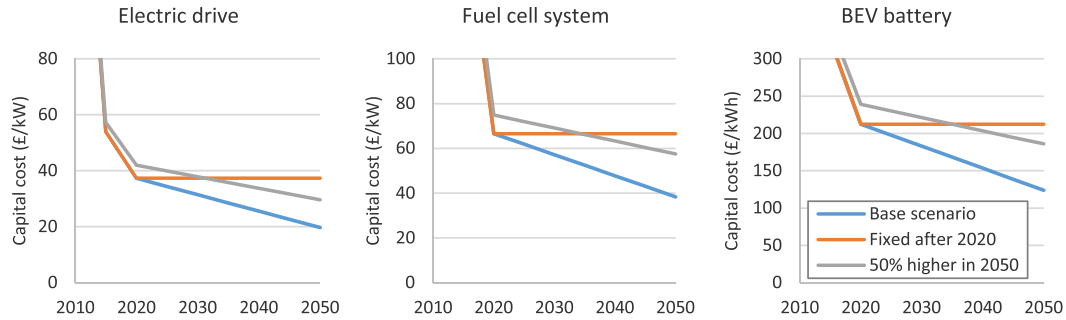
Fig. 7 — Vehicle component capital cost trajectories in the base and sensitivity scenarios. Electric powertrains and hydrogen storage, which are not shown here, have similar cost trajectories to the electric drive.

for BEVs and PHEVs resulting primarily from the provision of public charging points. In our first fuel supply sensitivity scenario, we examine the consequences of not requiring public charging infrastructure (i.e. cars are charged only at home or work). Tables 2 and 3 show that the optimum fleet in 2050 with lower electricity infrastructure costs is still dominated by FCVs but that some BEVs are added to the portfolio, all in the small cars segment where BEVs are more competitive.

Our second fuel supply scenario considers the impact of hydrogen refuelling costs being higher than assumed in Appendix B. We assume a lower rate of technology learning: instead of learning rates of 2%/year for hydrogen storage and 1%/year for other components in the base scenario, we use rates of 1%/year for storage and no learning for other components. Tables 2 and 3 show that this change has only a minor impact on the optimum vehicle fleet, with FCVs still dominating, so our conclusions are robust to uncertainties in hydrogen supply infrastructure costs.

Total cost of ownership

Both the Coalition and H$_2$Mobility studies base their conclusions on TCO analyses. In this section, we compare the TCO methodologies adopted in these studies with a TCO based on an energy systems methodology, using the same data, to understand whether the differences between studies are more a consequence of the choice of methodology or data assumptions.

Methodology

The Coalition study calculates the TCO assuming a 15-year lifetime and a 12,000 km annual travel distance [8]:

$$\text{TCO}_{\text{Coalition}} = \text{Purchase price} + 15 \times (\text{Maintenance} + \text{Fuel cost}) \tag{1}$$

The purchase price includes sales costs and manufacturer profit. No taxes (i.e. VAT, vehicle tax and fuel duty) are included and the running costs after the first year are not discounted.

The H$_2$Mobility study takes a different approach to TCO by only considering the first four years of ownership, assuming that the car will be sold by the first owner at this point [9]:

$$\text{TCO}_{\text{H2Mobility}} = \text{Net capital cost} + 4 \times (\text{Operating costs} + \text{Fuel cost}) \tag{2}$$

The net capital cost is the purchase price and the cost of capital less the residual value, while the operating costs include maintenance, insurance and vehicle tax.

The most appropriate energy systems approach to TCO mimics the cost calculation performed by energy system models. This means that the whole-lifetime approach used by the Coalition study is more appropriate than the first-buyer approach adopted by H$_2$Mobility. Since the revised version of UK MARKAL uses capital cost data from the Coalition study, the capital costs assumed by the two studies are similar. Operating and fuel costs in future years are discounted using the HMRC social discount rate (3.5%) and the energy systems TCO is calculated over the whole lifetime of the vehicle:

Table 2 — Impact of cost changes on the optimal vehicle fleet composition in 2050 for an 80% reduction in CO$_2$ emissions relative to 1990. Transport demand in this table is measured in billion vehicle kilometres (Bv-km). The base scenario demand is 608 Bv-km, for a case with no CO$_2$ emissions constraint, but demand reductions occur in each case shown here as CO$_2$ constraints are applied that increase the cost of transport provision. The magnitude of the overall demand reduction is proportional to the cost differential.

	ICE	ICE hybrid	ICE plug-in	Battery	Hydrogen hybrid	Hydrogen plug-in	Total
Base scenario	0	2	2	0	596	3	603
Vehicle costs							
(a) Fixed 2020 costs	161	9	340	0	74	0	584
(b) 2050 cost targets not achieved	151	3	12	0	429	1	596
Infrastructure costs							
(a) No public EV charging infrastructure	0	2	5	61	512	24	603
(b) High hydrogen infrastructure costs	3	7	7	0	570	19	605

Table 3 – Impact of cost changes on car fuel consumption in 2050 for an 80% reduction in CO$_2$ emissions relative to 1990. All figures have units PJ. The total fuel consumption varies much more between scenarios than the total fleet composition because each scenario has a different powertrain portfolio and the fuel use efficiencies of different powertrains vary substantially.

	Hydrocarbon	Biofuels	Electricity	Hydrogen	Total
Base scenario	4	1	1	556	562
Vehicle costs					
(a) Fixed 2020 costs	63	528	15	73	679
(b) 2050 Cost targets not achieved	49	245	1	423	718
Infrastructure costs					
(a) No public EV charging infrastructure	5	1	34	497	537
(b) High hydrogen infrastructure costs	10	10	6	540	566

$$\mathrm{TCO_{Energy\ systems}} = \mathrm{Capital\ cost}$$
$$+ \mathrm{Sum(Discounted\ operating\ and\ fuel\ costs)}$$
$$(3)$$

Results

The TCOs for several powertrains in 2050 using Equations (1)–(3) are compared in Table 4 using cost data from the revised version of UK MARKAL and the marginal fuel costs from the base scenario in each case. Although the absolute values differ widely between methods, the trends are similar in each case with FCVs the cheapest powertrains followed by BEVs and then ICEs. Since all three methods use the same data, these results suggest that the data assumptions have more influence than the choice of methodology. We test this assertion in Table 4 by repeating the energy systems TCO calculation using vehicle data from Refs. [11], which used the 2008 version of UK MARKAL. BEV powertrains, rather than FCVs, are the most economical using the older data, again suggesting that data assumptions have the greatest influence.

Only BEV and PHEV results differ substantially between the versions of UK MARKAL; moreover, the cost differences between all of the powertrains are so small that non-cost factors that are not considered by the model might have the greatest influence on consumer choice. Fig. 8 shows that all powertrains have comparable costs from 2025 in the base scenario and the cheapest powertrain changes over time from ICEs to ICE hybrids and finally FCVs. These results are reflected in the scenario results in Fig. 3. The exception is hydrogen ICE hybrids (HICEH), which do not feature in the results between

2020 and 2030 despite being the cheapest powertrain because the cost of building fuel supply infrastructure for such a short period is too high. This is another example of where an energy system model adds value over the TCO approach.

The breakdown of the TCO into capital, operating and fuel costs for ICE, BEV and FCV powertrains is shown in Fig. 9. Even in 2050, capital costs of newer powertrains account for around 50% of the total cost, which explains why higher capital costs affected the optimum fleet in our sensitivity study in Section Powertrain cost assumptions. Fuel and infrastructure comprise only a small proportion of the total cost, explaining the robustness of the results to supply cost increases in Section Fuel supply infrastructure cost assumptions.
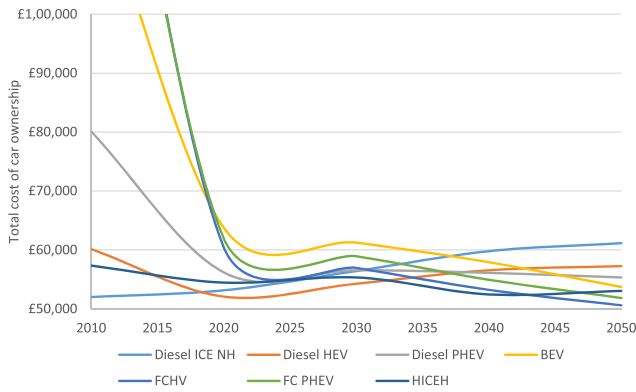
Alternative energy system scenarios

In this section, we examine the robustness of the base scenario to wider UK energy system perturbations. It is important to understand the extent to which the transport sector is insulated from changes in the wider energy system, and energy system models are best placed to explore such questions. Other types of model make broad assumptions about factors such as commodity prices and transport sector emissions, but these are modelled endogenously in energy system models. We examine three scenarios:

1. Low demand: Car energy service demand increases only with population growth due to behavioural changes. The base scenario assumes that demand increases as a function of both population and GDP.

Table 4 – Comparison of the TCO for principal powertrains using the three methods described in the text, all calculated using data from the revised version of UK MARKAL except for the last column which uses data from Ref. [11] instead. All costs are have units £1000s in the year 2012.

	Coalition study	H$_2$Mobility study	UK MARKAL in this study	UK MARKAL in Ref. [11]
Diesel ICE	48	23	61	57
Diesel hybrid ICE	44	21	57	56
Diesel plug-in hybrid ICE	38	19	55	51
Battery electric vehicle	37	18	54	43
Hydrogen FC hybrid	37	17	51	47
Hydrogen FC plug-in hybrid	37	17	52	n/a
Hydrogen hybrid ICE	42	20	53	53

Fig. 8 — TCO for principal powertrains using the energy systems method, for the scenario with an 80% reduction in CO_2 emissions in 2050 relative to 1990.

2. No hydrogen: Hydrogen cars are not available due to safety concerns. This scenario examines how the transport sector evolves in the absence of the most competitive long-term technology.

3. No CCS: Carbon capture and storage (CCS) is technically infeasible. CCS has not been proven commercially but is important for both hydrogen production and electricity generation.

Fig. 10 shows the optimal fleet composition for the base scenario and the three alternative scenarios. Total demand for car travel reduces in all three cases, in the latter two due to higher prices. A portfolio of technologies replace FCVs in the "No hydrogen" scenario while there is a move towards hydrogen PHEVs in the "No CCS" scenario as low-carbon hydrogen can only be produced by electrolysis when CCS is not available. This increases the cost of hydrogen by 54% as shown in Table 5, which lists the transport sector commodity prices in each scenario. The higher costs of biofuels and electricity in the "No hydrogen" scenario are caused by the additional demand being met from more expensive sources than in the base scenario. These results show that the commodity prices are sensitive to wider changes in the UK energy system.
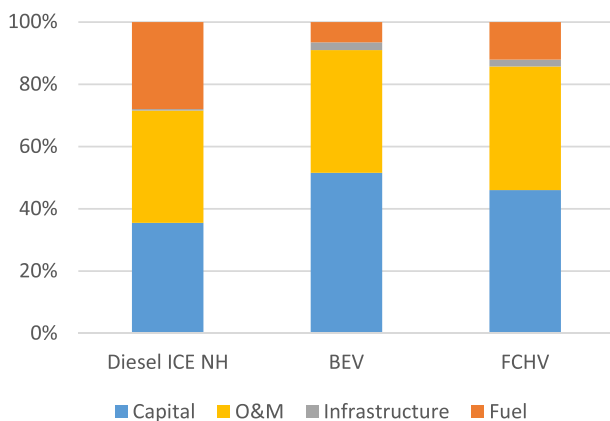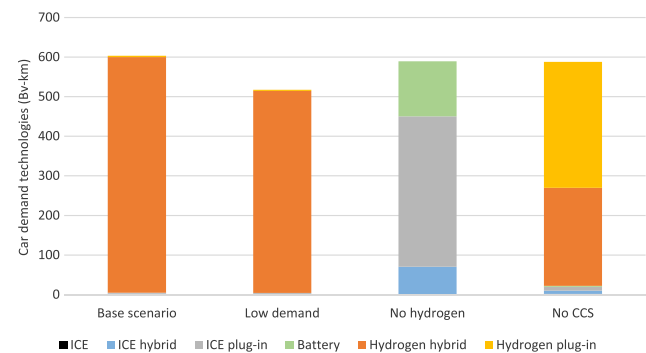
CO_2 emissions and marginal CO_2 prices in 2050 are shown in Table 6. Well-to-wheel emissions in the scenarios range between 8 $MtCO_2$ and 25 $MtCO_2$ as the model switches emissions between sectors of the economy, depending on the scenario. This means that the transport sector accounts for between 7% and 21% of CO_2 emissions in 2050, highlighting the difficulty of choosing an appropriate yet optimal fixed emissions target for transport.

Discussion

The principal aim of this study was to reconcile the conflicting insights from the TCO and energy systems methodologies that we identified in Section Comparison of the FCV reports with the literature. By comparing TCO and energy systems analyses, we have shown that capital cost uncertainties have the greatest influence on the overall TCO and that using consistent cost data assumptions in different TCO calculations produces consistent results. Moreover, while previous UK energy system studies have indicated that the optimum time for introducing FCVs is from 2040, we have shown that applying dynamic growth constraints to UK MARKAL to represent the early diffusion of new powertrains into the market brings forward the date of introduction from 2040 to 2015 in order to achieve the optimum penetration by 2050. The resulting transition is consistent with the transition to FCVs in the H_2Mobility roadmap [9] for the period to 2030 and has the same initial focus on the medium/large segment.

Forming scenarios for the transport sector

The Coalition study identifies three scenarios, each with a different portfolio of powertrains. The variety of powertrains in each scenario is quite different to the existing dominance of ICE vehicles. Yet while the proportion of FCVs does not exceed 50% in any of the Coalition study scenarios, our UK MARKAL base scenario suggests that the cost-optimal approach could be to convert the whole fleet to FCVs by 2050, so we question whether the scenarios chosen by the Coalition study are sufficiently broad. It is possible that their choice of scenarios has been influenced by the perceptions of those automotive

Fig. 9 — Breakdown of the TCO in 2050 using the energy systems method.

Fig. 10 — Impact of alternative energy system scenarios on the optimal vehicle fleet technology composition in 2050, for an 80% reduction in CO_2 emissions relative to 1990.

Table 5 — Marginal commodity prices in the base and alternate energy system scenarios in 2050, for an 80% reduction in CO_2 emissions relative to 1990. All prices have units £/GJ.

	Biodiesel	Ethanol	Hydrogen	Electricity
Base scenario	29	2	24	37
(a) Low demand	29	2	23	36
(b) No hydrogen	36	20	n/a	47
(c) No CCS	28	6	37	47

manufacturers who have invested more in BEVs and PHEVs than in FCVs.

Our analysis of wider energy system scenarios shows that transport fuel commodity prices and the optimum level of CO_2 emissions from cars can vary substantially if there are changes elsewhere in the energy system, so we recommend a flexible approach to setting scenario targets that accounts for such uncertainties. Energy system models help us to identify boundary ranges for such key parameters and can be used to inform scenario generation.

If the technology learning curves for vehicle components in the Coalition study prove accurate then Section Results shows that the TCO of different powertrains will converge with that of ICEs from around 2025. Energy system models such as UK MARKAL are susceptible to tipping point (or 'penny-switching') behaviour resulting from minor assumptions or cost variations. Consumers take a variety of factors into account when purchasing a vehicle, including cost, size (including luggage capacity), colour, safety, features, design and maintenance support. These are particularly important for new powertrains whose performance (in terms of range, refuelling time, etc.) is worse than that of existing ICEs and they could influence consumer purchasing decisions where cost differentials between powertrains are small. In reality, there are many different types of vehicles, with different features, fulfilling different purposes and travelling different annual distances, which is why real-life stocks of vehicles contain many different vehicle types. Such variety is better represented by transport stock models e.g. [40], which provide a useful avenue for identifying the most appropriate decarbonisation strategies at greater levels of vehicle disaggregation while meeting overall emission targets derived from energy system models.

Uncertainties and risk management

The Coalition and UK H_2Mobility studies present clear visions of the future and state that their conclusions are robust to uncertainties. While such an easily-digested message is ideal for engaging a wide audience, it is not a comprehensive roadmap for the introduction of different powertrains because it does not consider how to deal with inaccurate assumptions, whether within the transport sector or in the wider energy system. For example, we have shown in Section Powertrain cost assumptions that while FCVs are the cost-optimal powertrain by 2050, biofuels represent a viable alternative should FCV and battery costs be higher than forecast. We suggest that a comprehensive roadmap should have cost targets and decision points to manage the risk of innovation failure and energy system evolution outside of the transport sector. Moreover, the case for introducing FCVs now should assess the potential short-term and long-term value to the UK and balance this against the risks and potential losses of subsidies that might result from an unsuccessful transition. It would be useful to examine the costs and benefits of investing in a hedging strategy to keep battery and fuel cell options open for the future.

Policy issues

The UK transport sector is likely to change substantially over the coming decades. After 100 years of dominance, ICEs are likely to be replaced by hybrid ICEs in the medium-term and by other powertrains in the long term. If the assumed fossil fuel costs and technology learning rates are accurate then the new powertrains would become cheaper than existing ICEs even if there were no need to reduce CO_2. The transport sector is unusual as decarbonisation is not forecast to greatly increase the cost of transport provision and there are important side benefits of BEVs and FCVs such as ceasing emissions of local pollutants and reducing noise pollution. A transition to different powertrains offers great potential benefits to the UK but requires government action to build initial infrastructure and develop standards, codes and markets.

As we have explained in Section Dynamic growth constraints, new vehicle technologies have historically had slow rates of diffusion into commercial markets and it might be necessary to commence a transition to FCVs in the next few

Table 6 — CO_2 emissions (MtCO_2) and the marginal price for CO_2 emissions in the base and alternative energy system scenarios in 2050, for an 80% reduction in CO_2 emissions relative to 1990.

	Well-to-wheel emissions[a] (MtCO_2)	Tailpipe emissions (MtCO_2)	Marginal CO_2 price (£/tCO_2)	Total system cost overall years (£bn)
Base scenario	15	3	416	7065
(a) Low demand	13	3	406	6900
(b) No hydrogen	8	7	413	7137
(c) No CCS	25	7	385	7102

[a] Emissions related to fuel production and use only, excluding those from vehicle production.

years in order to achieve the cost-optimal energy system by 2050. An important first step will be to identify market niches; while these could be particular market segments, an alternative strategy could identify urban areas such as London, which have high levels of air pollution caused predominantly by ICE vehicles [41], and use regulatory instruments to promote alternative powertrains. London is already testing hydrogen buses.

Finally, there is a question of whether the UK should pursue all of the different powertrains discussed here or concentrate developments on a single powertrain, and whether such a decision should be embodied in a formal automotive industry strategy that includes the value of the various powertrains to UK manufacturing.

Conclusions

Using a combination of energy system modelling and TCO analysis, we have shown that the differences between the Coalition and UK H_2Mobility studies (which use TCO methodologies) and energy system modelling studies are caused by different cost data assumptions rather than the choice of methodology. Using the same cost data assumptions with a range of TCO methodologies produces consistent results. Moreover, while previous energy system studies have indicated that the optimum time for introducing FCVs to the UK is from 2040, we have shown that applying dynamic growth constraints to UK MARKAL, to improve the representation of early diffusion of new powertrains into the market, shifts the date of introduction from 2040 to 2015 in order to achieve the optimum FCV penetration by 2050. The resulting transition is consistent with the transition to FCVs in the H_2Mobility roadmap [9] for the period to 2030 and has the same initial focus on the medium/large segment.

As the costs of different powertrains are projected to converge from 2025 if large-scale manufacturing commences, it is difficult to identify the likely long-term composition of the car fleet. Non-cost factors, which are not well represented by either energy system models or the TCO approach, could have an important influence. Energy system models can usefully identify boundaries for the future vehicle fleet that account for uncertainties in the wider energy system, but other approaches such as stock models are more appropriate for understanding transport sector scenarios within these boundaries. Our sensitivity studies have shown that a wider range of scenarios is possible than suggested in the Coalition study. While it seems to be appropriate to commence a transition to FCVs now, the optimum choice of powertrain in the future is likely to depend on both future technological achievements and the influences of non-economic factors, and transport sector strategies should reflect these uncertainties.

Acknowledgements

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ijhydene.2014.06.128.

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