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Are scenarios of hydrogen vehicle adoption optimistic? A comparison with historical analogies

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ABSTRACT

There is a large literature exploring possible hydrogen futures, using various modelling and scenario approaches. This paper compares the rates of transition depicted in that literature with a set of historical analogies. These analogies are cases in which alternative-fuelled vehicles have penetrated vehicle markets. The paper suggests that the literature has tended to be optimistic about the possible rate at which hydrogen vehicles might replace oil-based transportation. The paper compares 11 historical adoptions of alternative fuel vehicles with 24 scenarios from 20 studies that depict possible hydrogen futures. All but one of the hydrogen scenarios show vehicle adoption faster than has occurred for hybrid electric vehicles in Japan, the most successful market for hybrids. Several scenarios depict hydrogen transitions occurring at a rate faster than has occurred in any of the historic examples. The paper concludes that scenarios of alternative vehicle adoption should include more pessimistic scenarios alongside optimistic ones.

1. Introduction

There is a substantial existing empirical literature examining the rates at which technologies have historically diffused into markets (Hirooka, 2006; Rogers, 2003). A number of authors have studied energy technologies in particular, including both supply and demand technologies (Grübler et al., 1999; Lund, 2006; Nakicenovic, 1986; Wilson, 2010). This literature makes clear that the diffusion of new energy technologies is frequently characterized by inertia (Fouquet, 2010; Grubler, 2012; Kramer and Haigh, 2009). Incumbent socio-technical regimes are durable, for a number of technical, social and economic reasons (Geels, 2002). The apparent stability of observed diffusion rates for power generation technologies has even led Kramer and Haigh (2009) to propose that the relatively slow rates of adoption of energy technology can be described as "laws" (Kramer and Haigh, 2009). In particular, barriers associated with the deployment of complementary goods – such as new vehicles and the infrastructure to supply them with fuel – are important in determining the dynamics and speed of alternative vehicle adoption (Meyer and Winebrake, 2009).

How well do scenarios of future energy technology adoption represent this inertia? Studies of long-term technology futures are an important source of evidence for policymakers considering interventions in R&D and technology deployment. While many such studies have examined the potential for transitions to new low-carbon vehicles, very few have focused on

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Abbreviations: AFV, alternative fuel vehicle; FCV, fuel cell vehicle; CNG, compressed natural gas; LPG, liquefied petroleum gas; SUV, sports utility vehicle; HEV, hybrid electric vehicle.

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the rate at which such a transition might be expected to occur. Over-optimistic rates of transition depicted in the literature, if believed by policymakers to represent possible or likely futures, create two risks for policy. First, over-optimistic expectations of transition rates may lead to disappointment and perceived failure of an attempt to foster a new fuel. This could lead to policy support being abandoned even when a technology has a good long-term potential. Second, if new technologies are required to meet emissions goals but transitions are slow, action to initiate adoption of such vehicles must be taken sooner rather than later. In contrast, over-optimistic adoption rates may lead to policymakers adopting a wait-and-see approach, since such scenarios imply that the vehicle market is more responsive to interventions than is in fact the case, and that policymakers can wait and act later when more information is available about the relative performance and costs of particular technologies.

Furthermore, scenarios of possible transitions (to hydrogen or other low carbon systems) are widely used as inputs into analyses of the costs and implications of such transitions. In the case of hydrogen, many studies have used exogenous adoption scenarios as an input to calculations of the possible costs of hydrogen infrastructure, yet few have tested the sensitivity of their findings to this assumption (Agnolucci and McDowall, 2013). One of the few studies to do so (Murthy Konda et al., 2011) showed that the costs are indeed rather sensitive to assumptions about the rate at which a transition might take place, with costs up to 40% higher in scenarios with slower demand growth. Others have used projections of hydrogen demand as inputs into macro-economic analysis (Jokisch and Mennel, 2009).

Understanding whether the rates of alternative fuel vehicle adoption in scenarios are possible or likely is clearly desirable, and one approach to attempt such validation is to examine historical precedents. Indeed, a number of recent authors have taken this approach, both exploring future scenario consistency with historic patterns of the same technology (such as historic and possible future deployment of nuclear), and also deriving insights from comparing future scenarios with historic diffusion of analogous technologies. Wilson et al. (2012) describe the rationale for comparing historical technology diffusion rates with those observed in long-term global energy modelling studies (using the MESSAGE and REMIND models), arguing that learning from the past is important for testing the feasibility of future scenarios. Similarly, Höök et al. (2012) compare two sets of global energy scenarios to historic global growth rates of fossil fuel and nuclear technologies. While Wilson et al. (2012) find that the scenarios they examine have been conservative with respect to technology deployment rates and extents, Höök et al. (2012) show that the scenarios they examine have been optimistic compared with the slow pace of historic energy resource growth. Other recent examples include van Sluisveld et al. (2015) and Iyer et al. (2015).

However, it is also clear that transitions in the past are conditioned by social, economic and technological contexts that will change in future. How can evidence from the past then be used to inform our judgements about whether these scenarios do indeed represent possible, or even likely, futures? Betz (2010) provides some guidance here, by clarifying different domains of 'possibility' with respect to scenarios. To say that something is possible, in his view, means that its occurrence is consistent with what we know (or alternatively, is not inconsistent with what we know[1]); in which case, a judgement on whether something is possible is dependent on a certain source of knowledge. In this context, historic analogies can be understood as providing knowledge about the nature of change in vehicle systems—these analogies represent 'what we know' about how fast such change can occur. This is not to say that this body of knowledge defines the limits of what is possible. Rather, it shows what range of futures is 'consistent with what we know', and what can thus be stated as 'realistic' or 'serious' possibility.

Though differently framed, this approach has some resonance with the work of Wiek et al. (2013), who have suggested that the "plausibility" of scenario elements can be to some extent validated by looking at whether similar things have happened in the past. Implicitly, their definition of plausibility is similar to the 'consistent with what we know' approach of Betz (2010) and it is that sense in which the term 'plausible' is used here.

This paper compares rates of diffusion of hydrogen fuel cell vehicles (FCVs) in scenarios with a set of historical alternative fuelled vehicle analogies. In doing so, it assesses future scenarios in terms of their consistency with our historical knowledge about technology diffusion. The paper also examines the socio-political and techno-economic characteristics that have been associated with rapid alternative vehicle adoption in the past, and uses this to reflect on the appropriateness of this historical knowledge for thinking about the future possibilities for hydrogen. Previous studies have drawn on historical examples of alternative fuelled vehicle transitions to inform the potential for hydrogen FCVs (Backhaus and Bunzeck, 2010; Hu and Green, 2011; Yeh, 2007). However, this paper is the first to draw on such examples to address the question of how fast alternative fuelled vehicles can be plausibly assumed to penetrate vehicle markets. The paper thus addresses the following two questions: *how fast have new types of vehicle achieved a given market share in the passenger car fleet? Are the rates of adoption in hydrogen futures in the literature consistent with these historic analogies?*

2. Methods: comparing rates of alternative vehicle adoption

The approach taken by this study was four-fold:

1 Identification of relevant analogies and collection of data;
2 Examination of key attributes of each analogy;

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[1] The distinction being between verificationist and falsificationist positions.

3 Identification and characterisation of scenarios of hydrogen fuel cell vehicle adoption;
4 Comparison of adoption rates between scenarios and historic analogies;

Each historical example took place in a different set of circumstances. The rates of adoption observed in the analogies can only be seen as an approximate guide for how alternative-fuelled vehicle substitutions might unfold. The paper therefore does not estimate precise quantitative differences in rates between the historical analogies and the scenarios in the literature. Instead, it brings together a body of knowledge that enables an assessment of whether such scenarios have been collectively optimistic.

2.1. Identifying appropriate analogies for hydrogen transitions

The purpose in selecting analogies is to identify past events that provide insight into the situation faced by hydrogen vehicles. With hydrogen fuel cell vehicles, a new fuel and new drivetrain are being introduced simultaneously. As with previous attempts to stimulate transitions to alternative fuel vehicles, hydrogen mobility does not offer significant benefits to the consumer in terms of new or different features. Analogies with shifts between transport modes – such as from horse to car – are not appropriate.

The following approach was taken to identifying appropriate analogies. Studies reporting barriers to the diffusion of alternative fuel vehicles (AFVs) were reviewed (Browne et al., 2012; Byrne and Polonsky, 2001; Leiby and Rubin, 2004; Melaina and Bremson, 2008; Petschnig et al., 2014; Struben and Sterman, 2008). From these, and from the wider literature on innovation diffusion (Rogers, 2003) and the literature specific to possible hydrogen transitions (McDowall and Eames, 2006) a set of factors inhibiting rapid adoption of AFVs was identified. These are:

- The well-known ‘chicken-and-egg’ problem (car makers cannot sell cars until the refuelling infrastructure is in place; infrastructure providers cannot recoup investment until there are cars using the fuel).
- The possibility that the attempted transition will fail generates significant investment risks, relevant for infrastructure providers, adopters and vehicle manufacturers (where new manufacturing investments are required).
- Low visibility/trialability for consumers. Lack of opportunities to test and get to know the technology will ensure it remains outside the choice set of potential consumers (Rogers 2003).
- Limited choice set for early adopters: a limited range of vehicle models on offer will mean that consumers who are seeking a particular category of vehicle (such as a small urban car or an SUV) may be completely excluded from the potential pool of adopters (Leiby and Rubin, 2004).

Historical analogies were then identified that also faced some or all of the four key challenges identified from the literature review. Several candidate analogies were identified directly from the review of barriers to adoption, since they were discussed in the literature referred to above. A further search for candidate analogies was made by searching for reports and papers discussing alternative fuel vehicles in general, and for specific fuels and vehicle types. Analogies were only included where they had reached a minimum of 5% share of the fleet; examples with less adoption than this are unhelpful for the comparison with the scenarios, which represent successful adoption with higher levels of penetration. The scenarios represent adoption of FCVs as passenger vehicles. As a result, data for the historical analogies have also been expressed in terms of the share of passenger vehicles[2].

From this process, several types of alternative vehicle were identified that clearly faced some of the barriers: compressed natural gas (CNG), liquefied petroleum gas (LPG, also known as autogas) and hybrid electric vehicles. Data was sought on transitions involving these vehicles, and where data was available, they were included.

Biofuels are frequently cited as an alternative fuel, and so attempts to foster transitions to biofuel powered vehicles were also considered for inclusion. However, biofuels generally require only very minor, or no, adjustment to the vehicle, and so were deemed to be an inappropriate analogy, since few of the barriers faced by hydrogen are common to biofuels. There is one exception: pure ethanol cars, which were introduced in Brazil during the late 1970s, require either major engine adjustments or the production of new cars. These were therefore included as an analogy.

Finally, the process of adoption of diesel as a fuel for cars in France has been included. Prior to the 1970s, diesel was almost exclusively a fuel for heavy duty vehicles. While automakers had offered a number of diesel taxi models during the 1950s, the first mass-market high-speed compact diesel car, the Peugeot 204BD, was introduced in 1967 in France. Countries following France’s lead faced lower barriers: whereas in the early years of the French diesel transition, only a few diesel passenger car models were available, the French market paved the way for others (this was both because of the increased range of vehicle models on sale via exports of French cars, and also the greater visibility to consumers of diesel as a fuel for cars rather than heavy duty vehicles). The analogy for hydrogen thus becomes much weaker in the follower markets.

The five types of alternative vehicle, and the countries in which their deployment has been attempted, is shown in Table 1, along with hydrogen and fuel cell vehicles. The table provides the author’s assessment of the extent to which each type of

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[2] The term ‘passenger vehicle’ and ‘car’ are used interchangeably in this paper, though it is worth noting that the definition of passenger vehicle includes light trucks (i.e., pick-ups).

Table 1
Historical analogies, and the strength of barriers faced in each of four categories.

Alternative vehicle type	Countries	Strength of barriers to rapid adoption			
		Chicken & egg	Investment risk	Low visibility/ trialability	Limited choice set
Liquefied Petroleum Gas (LPG) vehicles	Lithuania, Turkey, Poland and the Netherlands.	Medium	Weak	Medium	None
Compressed Natural Gas (CNG) vehicles	Argentina, New Zealand, Pakistan and Iran	Medium	Weak	Medium	None
Pure ethanol vehicles	Brazil	Strong	Medium	Medium	Weak
Diesel passenger cars	France	Weak	Weak	Weak	Strong
Hybrid electric vehicles	Japan	None	Weak	Strong	Strong
Hydrogen fuel cell vehicles		Strong	Strong	Strong	Strong

transition was confronted with each of the four key barriers identified earlier. A more detailed version of the table, with explanations as to how the relative strength of barriers was assessed, is available in Supplementary Online Material. As can be seen from the table, all of the selected barriers face some or all of the barriers faced by hydrogen, though to differing degrees.

Data was collected from industry associations representing the LPG and CNG vehicle markets, from national statistical agencies, and from report on vehicle statistics and road transport trends and markets. Data sources for each of the historical analogies included in the analysis are reported in the Supplementary Online Material I.

Some potential historical analogues are excluded. In Korea, LPG vehicles have reached a share of around 19% of the light duty vehicle fleet. The introduction of LPG vehicles started at the very beginnings of mass motorization in Korea, in the 1970s, and no good data from this early period has been identified. In 1982, the share of LPG in transport sector fuel consumption was the same as that of petrol, at 7%, and the sector was dominated by diesel for heavy goods vehicles, with very low motorization rates for passenger cars and other light duty vehicles; (Ishiguro and Akiyama, 1995; Sathaye, 1984). At the time Korea was highlighted as notable for experimenting with the fuel, and was seen as potentially leading down a non-petrol motorization route (Bharier, 1982). The introduction of LPG in the 1970s was thus not the introduction of a new fuel and vehicle type to replace an incumbent, it was rather the simultaneous development of two competing fuels and powertrains, petrol and LPG. In contrast, attempts to deploy hydrogen cars will take place in the presence of a very well-entrenched incumbent. LPG in Korea is thus a poor analogy for this process.

Two other exclusions have been made on the basis of insufficient data. There is a high proportion of LPG cars in Bulgaria (WLPGA, 2005), but insufficient time series data was identified to characterize their diffusion over time. Similarly, Armenia has a high proportion of CNG cars, but here too data was not identified to enable analysis of adoption rate.

Note that the sample of historical transitions is also skewed towards the inclusion of those that have had relatively rapid and successful transitions, in part since data is only available for vehicles that have had non-negligible deployment, and in part because slower transitions are of less interest for the analysis in this paper. The paper is aimed at exploring the plausible upper bound on rates of new vehicle adoption, rather than attempting to establish an estimate of what constitutes a 'normal' rate. However, the record of historical analogies, including those used here, includes many examples of attempts that ultimately failed, in the sense that the new vehicle type did not replace the incumbent technology. This includes those that were initially very fast (as in New Zealand and Brazil) and those that were much slower, as with the Dutch LPG experience. This suggests that there is no simple relationship between adoption rate and failure, and that the inclusion of historic failures does not undermine the relevance of the analogies for comparison with future scenarios.

2.2. Comparing rates of vehicle adoption: direct comparison of market share

Typically, analysts have found that the diffusion of innovations follows an s-shaped curve, with a three-parameter logistic curve often found to fit best (Grübler et al., 1999; Wilson, 2010). The logistic curve can be used to compare the rates at which technologies have historically diffused into markets and replaced an existing incumbent (Wilson, 2010). However, using the logistic model to compare rates of transition suffers from a number of weaknesses in the context of the present study. In order to use the logistic model, one either needs to have a sufficient time series to be able to identify the saturation point at which the alternative vehicle reaches 100% of its ultimate market share; or one needs to make assumptions about the ultimate market share. Unfortunately, many of the historic analogies have yet to reach their saturation point, and using a logistic curve to forecast the saturation point is well known to be highly inaccurate (Martino, 2003). One option would be to assume that any alternative fuel car is a direct substitute for all cars, and that the ultimate market potential for a new fuel is 100%. However, this would ignore the diversity of market segments that can be observed in real vehicle markets. The adoption of diesel as a fuel shows signs of saturating in European markets well below 100% of the car fleet. The weaknesses of the logistic approach preclude its use as the main metric for comparison of historic analogies and future scenarios.

This paper thus adopts an alternative approach. The question here is how one can best compare the rates at which new vehicle-fuel combinations have penetrated vehicle markets. Where good data exists on the year of introduction of a vehicle, it is possible to simply compare transitions directly by examining market shares at various years following introduction. Unlike

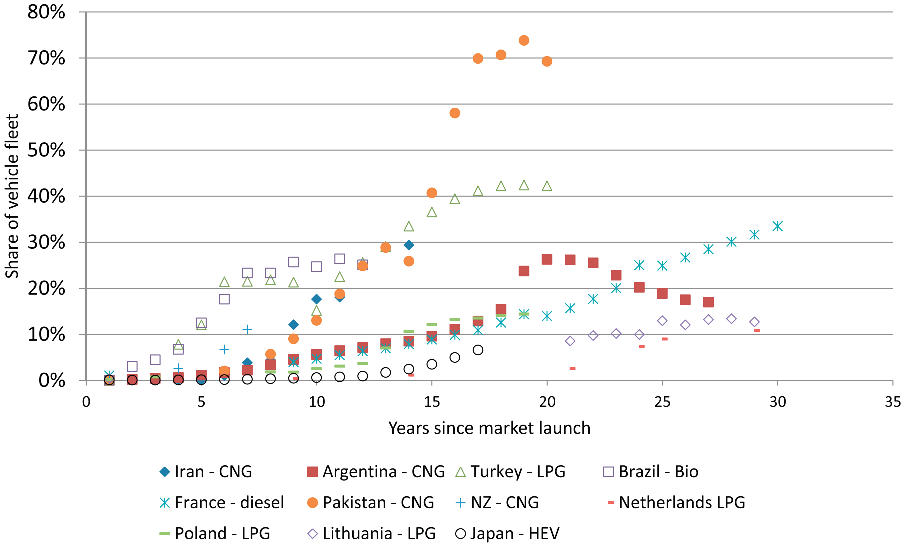

Fig. 1. Alternative vehicles as a share of the vehicle fleet: 11 historical analogies.

the approach based on the logistic model, this does not have the advantage of generating a neat metric of transition rate (such as the Δt metric discussed by Grübler et al. (1999) or Wilson (2010)). However, it does avoid the need for assumptions that may not be warranted on the basis of the heterogeneous transitions in the historical record and the projected future.

Identifying ‘market introduction’ is not always straightforward (nor indeed is the identification of any benchmark of technology diffusion, such as 1% market penetration). National vehicle statistics do not always record vehicle registrations of car types when very small numbers are concerned, and data on alternative vehicle numbers is often patchy, with data available in some years but not in others. In some cases, there is good data on the first refuelling station available for public use for a particular fuel, or the entry onto the market of the first mass-produced vehicle using a particular fuel (e.g., the pure-ethanol Fiat 147 introduced in Brazil in 1979). However, other cases make it more difficult to clearly identify the point of introduction. In Pakistan, a number of ‘pilot’ CNG refuelling stations and vehicles were deployed in the early 1980s, but it is not clear whether this represents the introduction of the vehicles, since news articles from that period clearly indicate that these were viewed as experimental more than commercial. Similarly, in Iran, plans to convert vehicles to CNG were adopted shortly before the revolution, in the late 1970s, with 2000 vehicles converted to run on CNG (Mohammadi et al., 2011). Subsequently some early fleet vehicles (numbering around 1200) were converted to CNG in the city of Mashad in the early 1980s (Kakaee and Paykani, 2013). However, these early activities do not appear to have been followed through during the 1990s, and thus these early experiments are ignored for the basis of estimating ‘market launch’.

It is typically more straightforward to identify market launch in projections of hydrogen vehicle futures than it is in the historical record. However, here too there are sources of error, particularly where data is only available by digitizing figures published in papers and reports. Most of the hydrogen futures studies against which historical transitions are compared are either explicitly or implicitly assuming that the transition begins at the point of mass market ‘launch’, rather than demonstration or pilot projects. In the data used here, the point at which introduction of the vehicle-fuel combination is aimed at the mass market has been identified, rather than using the establishment of pilot refuelling stations or the launch of prototype vehicles as a basis for comparison of the transition rates.

3. Historical transitions—insights from diffusion patterns

Having set out the rationale and method, this section reports on the historical analogies themselves. Each group of analogies is discussed in turn, with brief descriptions of the key techno-economic characteristics of the vehicles and fuels, as well as key socio-technical developments associated with the analogies. Note that only summaries are given here; more detailed versions of these histories are given in Supplementary Online Material II.

The socio-technical developments are described using the terminology and framework of the multi-level perspective on technological transitions (Geels, 2002), in particular the concepts of “regime” and “landscape” are used. The “landscape” level describes the background and long-term processes that lie outside the immediate influence of a socio-technical system. The “regime” refers to the actors, technologies, networks and institutions involved in the production, use and governance of cars.

Data on historic transitions were collected from a wide range of sources, and these are given in Supplementary Online Material III. The historic transitions are shown in Fig. 1, up to 30 years following market introduction of the new vehicle type. Transitions are also show against real time in Figs. 2, 3, 4, and 5.

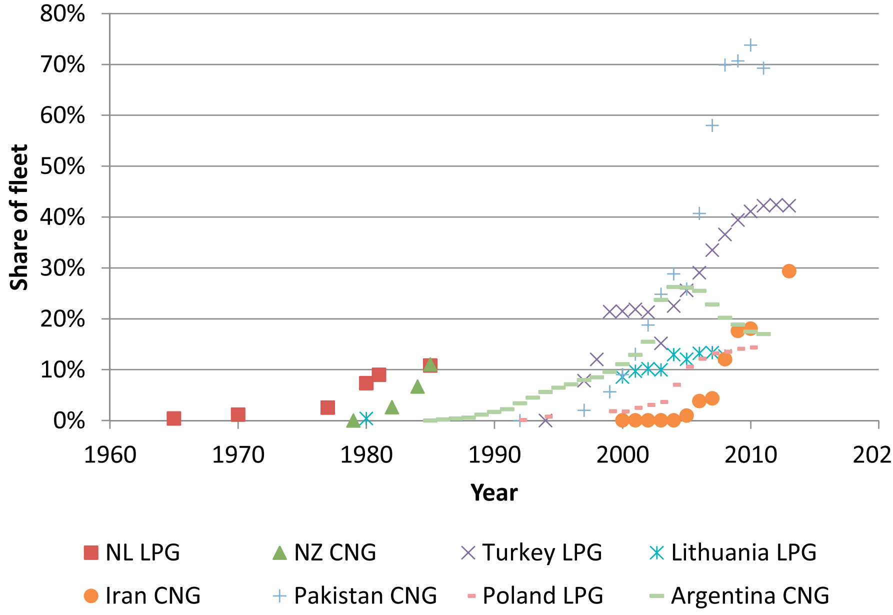

Fig. 2. LPG and CNG transitions.

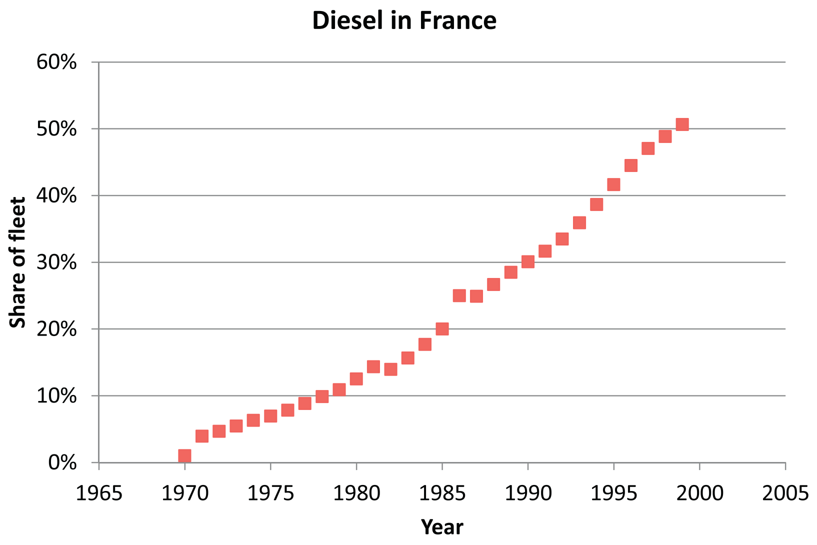

Fig. 3. Diesel car adoption in France.

3.1. LPG and CNG transitions

Both CNG and LPG have been used sporadically as a vehicle fuel for over a century. However, it is only since the 1970s that these fuels started to penetrate vehicle markets at significant market shares (adoption patterns show in Fig. 2).

3.1.1. Key techno-economic characteristics

As previously noted, both CNG and LPG are used in internal combustion engines, and can be retrofitted on existing petrol or diesel vehicles, significantly facilitating rapid adoption. Furthermore, both fuels are widely used for non-transport purposes, and there is thus a large existing network of production and distribution facilities. Construction of infrastructure for adoption of these fuels in the transport sector is thus much less challenging than it would be for fuels that have not been widely used.

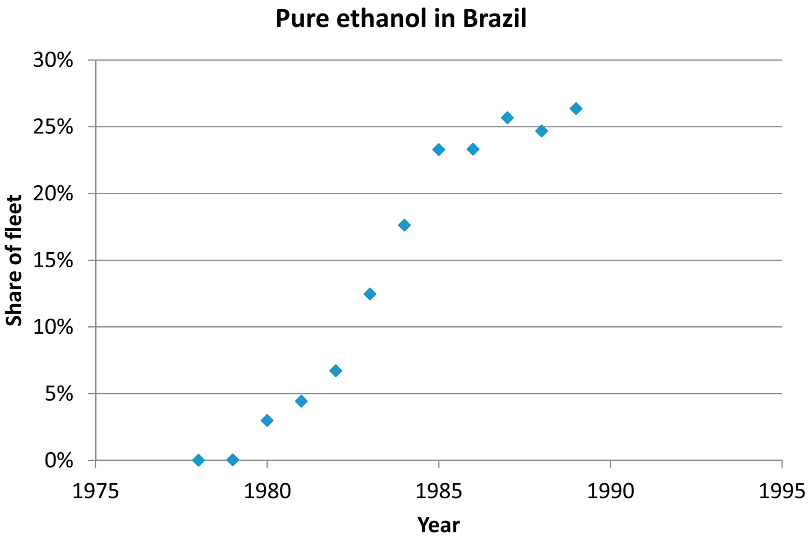

Fig. 4. Adoption of pure-ethanol cars in Brazil.

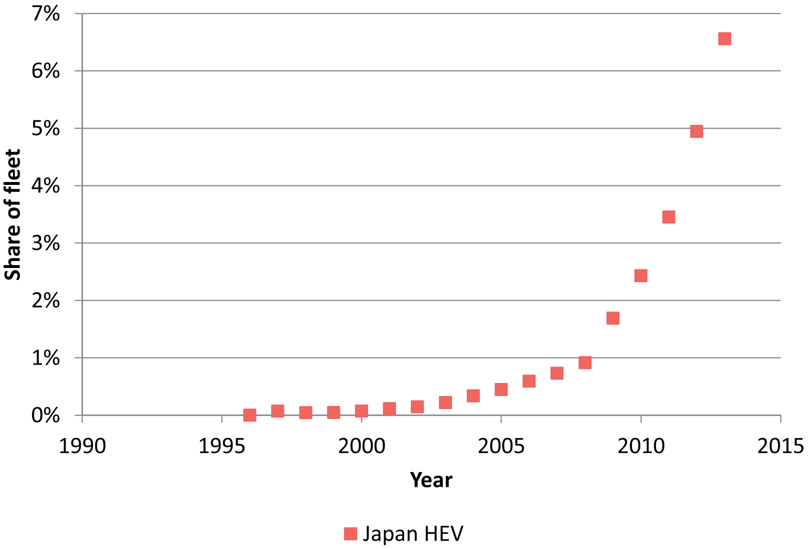

Fig. 5. Hybrid vehicle diffusion in Japan.

3.1.2. *Landscape and regime developments*

CNG and LPG have been promoted by national governments—often for reasons of energy security. In Argentina for example, domestic national gas reserves provided a strong rationale for public support for adoption of natural gas, particularly following the country's default and currency devaluation, which substantially raised the cost of oil imports. Similarly, New Zealand's attempt to manage a transition to natural gas vehicles in the 1980s was inspired by the oil crises of the 1970s, and achieved rapid conversion of cars reaching around 10% of the fleet within a decade. Local governments (e.g. Karachi) have also provided support, because of the reduced emissions of air pollutants from CNG and LPG as compared with petrol or diesel. A summary of the regime-level (including policy) and landscape conditions and developments underpinning each example is shown in Table 2.

3.2. *Diesel fuel for private cars*

Diesel as a fuel for passenger cars was launched in France in 1967, with the introduction of the Peugeot 204BD. The subsequent market growth of diesel cars is shown in Fig. 3.

Table 2
Summary of regime and landscape developments and conditions of each of the CNG and LPG historical analogies.

	Key policy and other regime-level developments	Key landscape developments and conditions
Argentina CNG	Significant policy support in the form of price controls; enacted in order to improve security of supply and reduce the import dependence	Financial crisis and devaluation of the Argentine Peso; discovery of domestic gas resources
Pakistan CNG	Significant policy support through preferential pricing and support for infrastructure; enacted in order to improve security of supply and reduce the import dependence. Urban air quality has also been an important policy driver	Pakistan has some domestic natural gas reserves, but is strongly dependent on imports for oil products.
Iran CNG	Strong policy support in the form of subsidised gas supply, and generous support for vehicle conversions. The policy has been justified on the basis of severe petrol shortages, fostered by high petrol subsidies, in the presence of limited refinery capacity; in addition to the unmanageable costs to government of petrol subsidies, and political difficulties of subsidy reform	Imposition of trade sanctions by the international community has exacerbated an existing constraint on domestic refinery capacity expansion, resulting in severe petrol shortages; enormous domestic gas resources
New Zealand CNG	Very strong policy support (subsidies for both fuel and conversion) was introduced in the wake of the oil crisis and discovery of domestic natural gas. Confidence in conversions fell as many were of low quality; policy support was removed as oil prices fell and costs to government mounted	Oil crises of the 1970s; discovery of domestic gas resources. Subsequent decline in oil price contributed to policy withdrawal
Netherlands LPG	Initiated as a result of price advantage of LPG, which was produced as a by-product from refineries. Later policy support, in the 1980s, was justified by the need to protect Dutch business investments in the LPG sector	Surplus LPG production from refineries and the natural gas industry; 1957 Suez crisis a major boost to LPG demand; later oil crises also stimulated LPG vehicle demand
Lithuania LPG	Reduced rates of fuel duty for LPG	No major landscape developments
Poland LPG	Tax exemptions for LPG have encouraged adoption	No major landscape developments
Turkey LPG	Turkey's LPG boom occurred as a result of the tax exemption for LPG, which was initiated for use of LPG as a domestic heating and cooking fuel, not initially for transport. Commentators suggest this does not stem from a co-ordinated effort to promote LPG as a vehicle fuel, but is instead a product of policy inconsistency across sectors	No major landscape developments

3.2.1. Techno-economic characteristics

Since diesel fuel is relatively widely available for heavy goods vehicles, the barriers posed from an infrastructure perspective are relatively low. Key barriers for early diesel adoption are: the limited range of vehicle models; the perception of consumers that diesel was a fuel not for cars but for heavy duty vehicles; and the investment risks for car manufacturers, in light of uncertainties about consumer acceptance of diesel cars. Diesel engine technology was well known, and the technological adaptations required for introducing diesel as a mass-market private car technology were relatively

low (particularly when compared with the technological challenges of introducing hydrogen fuel cells). Diesel vehicles are more expensive than their petrol counterparts of similar size and class, but they are more efficient, which typically results in lower running costs.

3.2.2. Landscape and regime developments

Preferential taxation of diesel fuel – introduced for a number of reasons (discussed in the Supplementary material) – played an important role in the promotion of diesel cars. Government support for diesel has arisen for a variety of reasons, including the higher efficiency of diesel cars, and the relative comparative advantage of French and European vehicle manufacturers in diesel technologies. It has also been suggested that landscape developments were important for the French promotion of diesel vehicles (particularly a surplus middle-distillates of oil, which emerged from the late 1960s as France began to switch away from oil as a heating and power generation fuel; see the Supplementary material for further details, and relevant references).

3.3. Pure bioethanol in Brazil

The late 1970s and early 1980s saw rapid adoption of pure ethanol cars in Brazil, alongside the development of considerable refuelling infrastructure (see Fig. 4).

3.3.1. Techno-economic characteristics

Pure ethanol cannot be used in a petrol engine without substantial adjustments, though such conversion is possible. The basic internal combustion engine technology is very similar, and few changes need to be made to manufacturing plant to produce pure-ethanol cars. This meant that substantial new investments in car production were not required. The costs of such vehicles are not significantly different than for petrol cars. Refuelling stations also need to be adapted to safely store and handle pure ethanol.

Table 3
Summary of the future scenarios included in the analysis.

Type of Study	Studies included
Stakeholder process	HyWays (2008); McKinsey (2010); NHA (2009)
Exogenous input into further analysis	Almansoori and Shah (2009); Ball et al. (2007); Lin et al. (2008)
Hydrogen transition model	Greene et al. (2007) Keles et al. (2008); Leaver et al. (2009)
Energy system optimisation model	Bahn et al. (2013); Contaldi et al. (2008); Endo (2007); Martens et al. (2006); McCollum et al. (2012); Rits et al. (2003); Strachan et al. (2009); Tseng et al. (2005); Winskel et al. (2008)

3.3.2. *Landscape and regime developments*

The landscape conditions for Brazil's push to adopt pure ethanol vehicles are striking: in the late 1970s, the oil price rose rapidly, creating severe pressure on the country's balance of payments. At the same time, global prices for one of Brazil's major exports (sugar) had crashed, further exacerbating the economic problem.

The Brazilian government, which at the time was a military dictatorship, initiated very strong support for conversion to pure ethanol vehicles. Ethanol was seen as a route to energy independence, and ultimately also export markets and industrial strength. Policy support included fuel price fixing and subsidies for ethanol production facilities. Fuel distribution was in the hands of a state-owned monopoly (Petrobras), which initiated construction of large numbers of ethanol refuelling stations. The costs to government of maintaining this programme were estimated at 17% of the Brazilian government's 1983 budget (Sathaye et al., 1989).

Subsequent landscape and regime developments led to the withdrawal of state support for pure ethanol cars, including: slower than anticipated technological improvements and cost reductions in ethanol technologies; ethanol shortages that damaged consumer confidence; global falls in oil prices.

3.4. *Hybrid electric vehicles in Japan*

Hybrid electric vehicles were launched by Toyota and Honda in the late 1990s. The pattern of growth is shown in Fig. 5.

3.4.1. *Techno-economic characteristics*

Hybrid electric vehicles are more expensive than their non-hybrid counterparts, but the running costs are lower, making them attractive when fuel prices are high, and for those motorists with high annual mileage. There is no additional infrastructure required for refuelling. However, hybrids represent significant changes to the vehicle powertrain, and the introduction of hybrids required substantial investments in manufacturing plant.

3.4.2. *Landscape and regime developments*

Hybrid electric vehicles entered the market at a time when concerns about climate change were rising rapidly; and subsequently, high oil prices resulted in consumers making substantial shifts away from 'gas guzzling' models. Automotive manufacturers globally were quick to follow the lead taken by Toyota and Honda, and the range of manufacturers producing hybrids, and the range of vehicle models, has risen. However, consumers still have a relatively narrow range of hybrid models from which to choose (US data show 32 models available in 2010, compared to many hundreds of non-hybrid models). Policymakers have also provided incentives for adoption of hybrids, including both purchase tax incentives, and preferential parking and road pricing policies.

4. **Rates of hydrogen transition in the literature**

Having discussed the historical analogies, this section now turns to the hydrogen FCV adoption scenarios. A wide variety of approaches have been used to construct descriptions of the future of hydrogen vehicles. Though all of these are described here as 'scenarios' – since they provide depictions of futures thought to be possible – they differ in their methodological underpinnings, and in the sources of knowledge on which they are based. None of the studies examined described itself as a forecast. However, such differences between scenario studies – in methodological approaches, levels of detail and motivating objective – are often lost outside the relevant research communities that produce them (Loftus et al., 2015). Despite the diverse methodological origins, examining this body of scenarios as a whole is useful because these scenarios represent the collective published view of the possibility space for hydrogen vehicle adoption.

Rates of hydrogen vehicle adoption from four types of futures study were examined (the studies included for each of the four types is shown in Table 3):

1 Studies in which a fuel cell vehicle penetration scenario is developed as a result of a stakeholder process. These draw on a wide and diverse body of knowledge and expectations, often backed up by some formal quantitative analysis. As such, they embody a diversity of sources of knowledge, including subjective beliefs built on personal and professional experiences alongside formal analytic processes. As contributions to the policy discourse, they are also emblematic of the

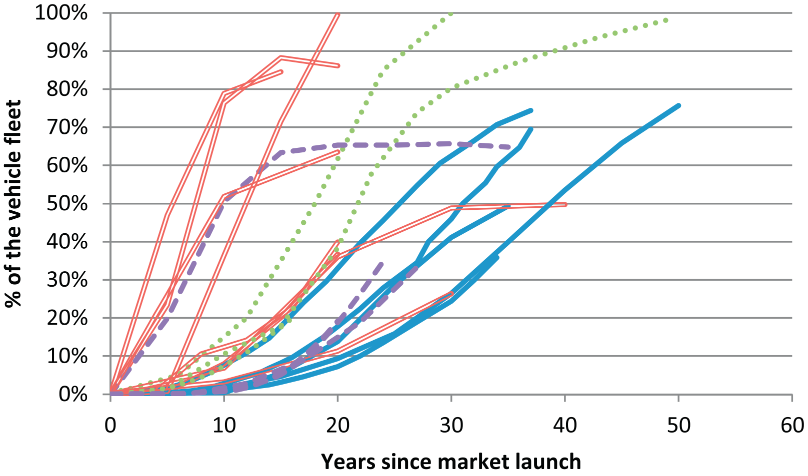

Fig. 6. Transitions in the literature: proportion of the vehicle stock that is hydrogen vehicles in the futures examined. The figure shows stakeholder based studies (solid blue), scenarios assumed as inputs into other analysis (green dots), dedicated hydrogen transition models (purple dashes) and energy system models (red tramlines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

'futures work' (McDowall, 2012; Pollock and Williams, 2010) of key innovation system actors, who have strong interests in articulating a credible and optimistic view of the future of hydrogen.

2 Studies in which an assumed trajectory of FCV adoption is used as an analytic input into further analysis, such as for analysis of the costs of hydrogen infrastructure development. One might expect that considerably less analytic thought has gone into such scenarios as compared with the first category, since these scenarios are simply starting assumptions for more detailed analysis. In the studies examined here, the assumed adoption scenarios are statements about the future that are presented as possible, but without any explicit justification for why they might be thought to be possible.
3 Studies in which the diffusion of hydrogen vehicles is projected through a dedicated hydrogen transition model. These scenarios have been developed by analysts seeking to represent the key processes driving a transition to a hydrogen-fuelled transportation system, using an agent-based model (Keles et al., 2008), a system-dynamics model (Leaver et al., 2009), and non-linear optimisation (Greene et al., 2007). They share a focus on modelling the processes by which increasing returns to adoption[3] enables a self-sustaining transition to emerge. They represent attempts to capture the most significant dynamics of AFV transitions within a formal modelling framework.
4 Studies in which the adoption of fuel cell vehicles is projected by an energy systems optimisation model (ESOM), such as MARKAL/TIMES. These models take the perspective of a single social planner, optimising the energy system (including the deployment of fuel cell vehicles, and hydrogen demand and supply) to meet policy targets.

The range of studies is shown in Fig. 6. From 20 studies, 24 scenarios are compared. Most are national-scale studies though two are from a US State (California (Lin et al., 2008; McCollum et al., 2012)) and two for the EU (HyWays, 2008; McKinsey, 2010) are included. Several studies contained more than one scenario, however in many cases only sufficient results were available from a single scenario for estimation of market penetration of hydrogen vehicles over time.

It is interesting to observe that scenarios produced by energy system optimisation models (ESOMs) tend to be the most rapid. This can partly be explained by the formulation of ESOMs, which tend to represent consumers as having homogenous preferences, operating under perfect foresight and with cost-optimisation as the sole decision criterion. This gives such models a tendency to rapidly deploy a cost-effective technology. In contrast, the scenarios developed through stakeholder processes reflect the accumulated experience and insights of a body of people some of whom have been involved in bringing new vehicle technologies to market. These tend to be among the more gradual transitions.

5. Results: comparison of transition rates in historical analogies and hydrogen futures

A comparison of the hydrogen futures and historic analogies is shown graphically in Fig. 7. The figure shows the historic analogies with the fastest diffusion, since it is this upper bound – the fastest historic examples – that are of principal interest in determining a plausible upper bound on alternative fuel futures. These upper bounds are compared with the minimum, maximum, and quartiles for the range of hydrogen futures, through the use of box-and-whisker plots.

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[3] As increasing numbers of users adopt a new vehicle technology, the attractiveness of that technology to others increases, because of increased visibility, growing infrastructure and greater provision of associated maintenance services, reduced capital costs associated with learning-by-doing, among other factors. These are forces are known collectively as resulting in 'increasing returns to adoption'.

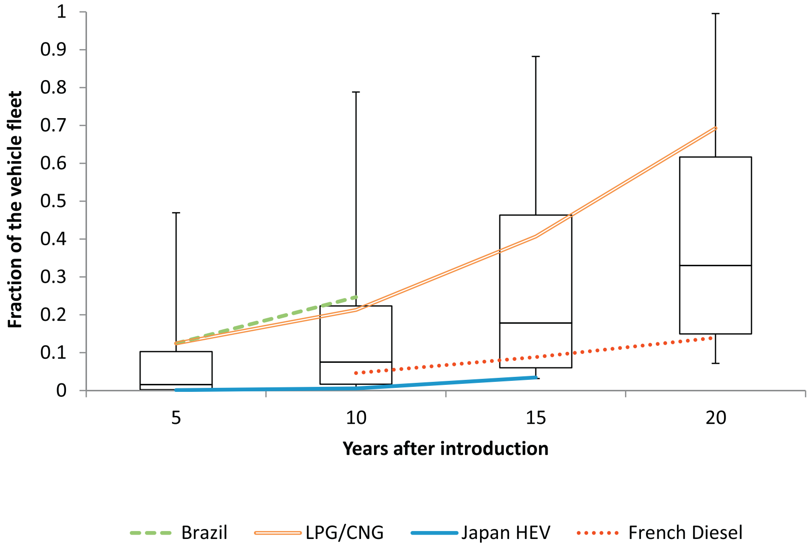

Fig. 7. Box-and-whisker plot showing the range of forecasts in the hydrogen futures literature. Boxes show the interquartile range, intersected by the median, while the whiskers show the minima and maxima. Lines show the fastest historical analogues in each group.

Several key points can be seen from this figure. First, the maximum penetration from historical examples is well below the maximum from the futures literature. Around a quarter of the hydrogen futures depict transitions that occur more rapidly than has previously been experienced for a switch to a new vehicle/fuel type. These very fast scenarios are largely derived from energy system optimisation models, which have a well-known tendency to rapid technology deployment (Jaccard et al., 2003).

The chart also shows the exceptional nature of Brazil's attempt to make a transition to pure-ethanol cars. Unlike the CNG/LPG transitions, all of which relied to some extent on after-market vehicle conversion and bi-fuel operation, the Brazilian case largely relied on new vehicles running only on ethanol.

The bulk of scenarios examined – and the median scenario – does fall within the range of historical precedents. However, with the notable exception of Brazil, all of the rapid transitions involved significant after-market conversion and bi-fuel operation.

Only one of the hydrogen futures examined (one of the HyWays scenarios, developed on the basis of stakeholder input as well as quantitative analysis) takes place more slowly than the adoption of hybrid electric vehicles in Japan, which is the most successful market for hybrids. Despite hybrid electric cars generally being seen as a commercial and technological success, and one for which no infrastructure adjustment was necessary, their uptake has been slower than almost all hydrogen futures examined.

6. Discussion and conclusions

6.1. Lessons for hydrogen from the past

The historical precedents for alternative fuel vehicle adoption suggest – as shown in Fig. 7 – that scenarios for the future of hydrogen have tended to be optimistic about the rate at which vehicle adoption might take place.

This optimism appears particularly acute when one considers that none of the historical transitions examined faced barriers as substantial as those facing the development of a hydrogen FCV system. In particular:

- Some existing distribution facilities existed before market entry for most of the examples. Diesel was available in a portion of filling stations in France before diesel engines became widespread in passenger cars, significantly reducing the infrastructure burden; countries adopting CNG vehicles had existing distribution infrastructures for natural gas for residential and service sector consumption; LPG is widely distributed as a fuel for cooking and heating in most of the countries in which LPG has become widely adopted. Ethanol blends had been promoted in Brazil prior to the introduction of pure ethanol vehicles, and as a result an existing ethanol production and distribution infrastructure was widespread (though new dedicated fuel pumps were required for pure ethanol cars). For hybrid electric vehicles, of course, no new fuel distribution facilities were required.
- In countries adopting CNG and LPG, a large portion of these vehicles are relatively cheap retrofits. This means that a wide variety of vehicle models was available to potential consumers. Furthermore, conversion means that rapid adoption can take place without retiring existing vehicles before they reach the end of their useful lives. Finally, the costs to consumers of

adoption are low (conversion costs much less than buying a new vehicle outright) and relatively low risk, since conversions need not be permanent.

- Many CNG and LPG vehicles are bi-fuelled, able to run on both petrol and the alternative fuel, considerably reducing the barriers to adoption in the face of limited alternative fuel filling stations.
- All of the transitions involved the use of internal combustion engine technology that was well understood and mass-produced at the time at which ‘market launch’ occurred. The changes implied by these transitions for upstream manufacturing capacity were limited in many of the cases, suggesting relatively low investment risks for automotive manufacturers. Diesel cars in France required the development of new manufacturing plants for diesel passenger cars, but the mass-production of diesel engines was well established. For ethanol vehicles in Brazil, existing manufacturing plants were used to produce pure-ethanol vehicles with minimal disruption. The exception is hybrid electric vehicles, for which new manufacturing capacity, involving new technology, was required to produce the new vehicles.

Only one transition – the Brazilian attempt to foster pure-ethanol vehicles – involved rapid adoption in the face of production of new vehicles and the necessary construction of distribution and filling station infrastructure for a new fuel. The particular nature of the governance arrangements (nationally owned fuel distribution company under a military government), the global economic circumstances (sugar market collapse, oil price crisis), and the scale of costs required to achieve such a rapid transition are striking. Ultimately, the scale of resources required to support this transition was judged unsustainable, and support was withdrawn.

6.2. Rapid technology transitions: what do scenarios need to explain?

The hydrogen futures examined emphasise the technical and economic dimensions of socio-technical change. Most are derived from formal quantitative simulation or optimisation models, and most others are at least informed by such models. These studies put in the foreground the techno-economics of vehicle adoption and choice: costs, stock turn-over rates, vehicle efficiencies and so on. However, the historic examples of the fastest transitions suggest that typically it is unusual political and social circumstances – often associated with landscape-level developments – that underpin rapid transitions. In the cases of Argentina and Iran, it was a sudden currency devaluation and severe economic sanctions, respectively, that enabled rapid adoption of CNG. In Brazil, it was the exposure to oil price shocks and sugar price volatility.

What becomes interesting in scenarios of rapid alternative fuel transitions is thus not only the techno-economics, but the politics and social dynamics: what kinds of political and social circumstances are required for, or implied by, scenarios of rapid hydrogen adoption? Under what circumstances might the political legitimacy of an attempt to transform road transport with advanced fuel cell vehicles be achieved? These questions are rarely asked in scenarios that depict quantitative projections of hydrogen transitions. However, they shift the burden of plausibility in such scenarios: how can scenarios of rapid transition explain themselves in socio-political terms? Clearly, radical scenarios are possible—but a failure to engage with and confront the socio-political dynamics of rapid change reduces the usefulness of a scenario exercise by obscuring critically important uncertainties. Rather than focus on whether a high carbon tax or infrastructure subsidy will catalyse a transition to a hydrogen-fuelled transport system, scenarios should perhaps also consider where and under what circumstances such sustained political support might come about.

The point here is that rapid transition scenarios do have a place in thinking about the possible future of alternative fuelled vehicles. But where such scenarios are used to inform policy, it should be clear that these scenarios are perhaps unlikely to occur in the absence of rather extreme social and political events. Scenarios that invoke only the application of policies with a positive cost-benefit ratio struggle to appear plausible if they depict such rapid change, and the developers of scenarios depicting alternative vehicle transitions could improve scenarios by reflecting on the social and political implications of (or requirements for) such rapid change.

6.3. Comparison with related work

Wilson et al. (2012) compare the rates of adoption of new energy technologies in two energy models (MESSAGE and REMIND) with past experience. They conclude that the models have been conservative in their depiction of technology diffusion, in contrast with the results found here. This may be in part because the historical analogues they explored focused on the full technology life-cycle, rather than the first decades after market introduction. Their work thus assessed rates over longer durations, using the Δt metric derived from a logistic diffusion model. The results here are more in line with those discussed by Höök et al. (2012), who find that scenarios from two studies (a set of Shell scenarios and the GET global energy systems optimisation model) significantly overstate the rate at which energy transitions can be expected to take place, given historical precedent.

6.4. Conclusions

The analysis presented here provides important insights into plausible rates of adoption for alternative fuelled vehicles. It should be clear that the analogies are limited in terms of their applicability to hydrogen, and the quantitative patterns identified are limited by data weaknesses. Furthermore, the diffusion of new technologies is not a deterministic process, but rather is one that is historically contingent, as has been illustrated in the overview of key aspects of each of the historic analogies. One should therefore be careful in drawing strong conclusions about likely future rates of technology diffusion from a set of particular, imperfect historical analogies.

Together the assembled analogies provide a coherent body of knowledge against which to assess whether the future scenarios are consistent with what we know about change in vehicle technology choice. In this comparison, the hydrogen futures appear to have been collectively optimistic. The historical analogies do show that rapid transitions are possible, but none of the transitions examined faced barriers as significant as those faced by hydrogen. The apparent optimism over transition rates in the literature is problematic, both because much subsequent analysis is informed by depicted transitions, and because over-optimistic expectations about transition rates can damage the chances of applying effective policy.

We conclude that those studying hydrogen futures should include more conservative projections about the rate at which a hydrogen fuelled transportation system might emerge, alongside analysis of more optimistic scenarios. It should be clear that this does not mean that optimistic rates have no place: rapid substitutions have happened in the past, and as Tseng et al. (2005) have noted, the scale of energy system change envisaged in most low-carbon scenarios is such that historical precedent cannot be used as an unequivocal guide to what is possible. Indeed, one could argue that the levels of marginal abatement cost (and hence carbon price) that are necessary to meet emissions targets would be hugely punitive to high-emissions vehicles, and that under such circumstances transitions to low-carbon alternatives could be as rapid as those experienced in Brazil (which was undergoing the oil crisis and which had massive government support) or in Iran, where it is economic sanctions that have stimulated conversions to CNG. Furthermore, current efforts to introduce hydrogen fuel cell vehicles are the product of intensive efforts to co-ordinate industrial and policy action across many countries simultaneously, for which no precedent appears to exist. The conclusion is therefore that optimistic and pessimistic assumptions should both be examined, and their implications understood.

A final conclusion relates to the focus of both innovative efforts and futures studies in hydrogen vehicle developments, which focus almost exclusively on fuel cell vehicles. Bi-fuel and after-market conversion technologies for hydrogen internal combustion vehicles are possible, and indeed a number of firms exist developing and promoting such technologies. These incremental technologies are typically given short shrift in futures analysis. None of the 20 studies examined for this paper included conversion of petrol cars to hydrogen, or explored bi-fuel vehicles that are powered by either hydrogen or petrol. Yet the analysis here suggests that such technologies could play an important role in enabling a rapid uptake of hydrogen fuelled vehicles. While internal combustion engines running on hydrogen are less efficient than their fuel cell counterparts, they offer a route for the fuel to be adopted more widely and more quickly. This kind of incremental technology may be essential in enabling profitability of early refuelling infrastructure and so enabling hydrogen fuel to gain a critical mass of market share.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.eist.2015.10.004.

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