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Possible hydrogen transitions in the UK: critical uncertainties and possible decision points

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Abstract

Many energy system optimization studies show that hydrogen may be an important part of an optimal decarbonisation mix, but such analyses are unable to examine the uncertainties associated with breaking the 'locked-in' nature of incumbent systems. Uncertainties around technical learning rates; consumer behaviour; and the strategic interactions of governments, automakers and fuel providers are particularly acute. System dynamics and agent-based models, and studies of historical alternative fuel transitions, have furthered our understanding of possible transition dynamics, but these types of analysis exclude broader systemic issues concerning energy system evolution (e.g. supplies and prices of low-carbon energy) and the politics of transitions.

This paper presents a hybrid approach to assessing hydrogen transitions in the UK, by linking qualitative scenarios with quantitative energy systems modelling using the UK MARKAL model. Three possible transition pathways are explored, each exploring different uncertainties and possible decision points, with modelling used to inform and test key elements of each scenario. The scenarios draw on literature review and participatory input, and the scenario structure is based on archetypal transition dynamics drawn from historical energy system transitions, reflecting insights relating to innovation system development and resistance to change. Conclusions are drawn about appropriate policy responses.

*Keywords:*Scenarios; energy system models; technological transitions; hydrogen energy;

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1. Introduction

This paper uses a combination of scenario approaches and modelling to examine the following question: What are the major possibilities and uncertainties that will shape the future for hydrogen energy technologies in the UK, and how might a transition unfold?

Both qualitative stakeholder-driven scenario processes and quantitative models are widely used to inform business and policy decisions in the energy domain, and this is certainly true for hydrogen. Both approaches are helpful, but both suffer from drawbacks in enabling systematic exploration of possible futures: models ignore the co-evolutionary nature of socio-technical change, since the decision-rules built into the model structure do not change along with the system; while the epistemological status of qualitative scenario storyline processes is typically opaque.

In order to capture the complementary strengths of both approaches, this paper presents a hybrid approach to assessing hydrogen transitions in the UK, by linking qualitative scenarios with quantitative energy systems modelling. The paper develops scenarios by drawing on literature review and participatory input, and the scenario structure is based on archetypal transition dynamics drawn from historical energy system transitions, reflecting insights relating to innovation system development and resistance to change. Section 2 describes the insights into possible hydrogen transitions for the UK derived from the literature and from stakeholder workshops and interviews. In Section 3, three possible transition scenarios are explored, each exploring different uncertainties and possible decision points, with modelling used to inform and test elements of each scenario. In section 4, conclusions are drawn about appropriate policy responses, highlighting those areas that appear to have been neglected in both analytic and policy domains. This paper devotes the focus of attention to section 2, the identification of key possibilities and uncertainties drawing from stakeholder opinion and the existing literature. Further detail on the approach, the scenario storylines and the modelling is the subject of a forthcoming journal article.

2. Characterising key uncertainties and possibilities in hydrogen transitions: insights from the literature and from stakeholders

In order to identify key uncertainties and possibilities for hydrogen energy in the UK, we reviewed the literature [1], ran a stakeholder workshop [2], and conducted stakeholder interviews and participant observation at hydrogen stakeholder events.

Having identified a long list of uncertainties and possibilities for a hydrogen transition, we then structured these in terms of an established theoretical framework, the multi-level perspective on socio-technical transitions. This perspective recognises events occurring at three levels of analysis: the overall background context or ‘landscape’ level, in which systems change takes place; the socio-technical system or regime, made up of technologies along with the actors, institutions and networks that together represent the incumbent technological system; and niches, within which innovations are fostered and from which some emerge to replace the regime. In the interests of brevity, the framework is not elaborated here, and the interested reader is referred to Geels [3,4].

Our literature review and stakeholder work has identified four key areas of possibility and uncertainty, mapped to the three ‘levels’ of the multi-level perspective in

Table 1.

Table 1. Key areas of uncertainty for hydrogen transitions

Level of analysis	Key areas of uncertainty
Uncertainties within niche developments	Technological uncertainties: relative performance and cost of hydrogen technologies and competitors (particularly Battery Electric Vehicles, or BEVs)
	Behavioural uncertainties: consumer responses to the introduction of new vehicle technologies
Interactions between niches and the regime	How do incumbent and new actors respond to landscape pressures, and to the opportunities and threats emerging from within niches?
Uncertainties at the landscape level	How will the overall energy system context for hydrogen evolve?

This section examines each of these uncertainties, and the evidence that helps to inform the degree to which the importance of 'known unknowns' has been characterised.

2.1. Technological uncertainties

Hydrogen energy systems currently come at a considerably higher cost than incumbent energy systems, even when one takes into account the social costs associated with emissions. Evidence from energy systems analysis suggests that the desirability of hydrogen as a decarbonisation option depends strongly on success in bringing down costs, for both fuel cell technologies and hydrogen production, delivery and storage systems [5,6,7]. Clearly, it is not only uncertainties for hydrogen technologies that are relevant here: successful developments within competing low carbon technologies (such as plug-in hybrid electric vehicles) may reduce the apparent desirability (or necessity) of deploying hydrogen systems.

Considerable progress has been made since 2000 in hydrogen technologies [8], but their future development remains uncertain. A wide variety of studies envisage opportunities for further cost reduction, through scale economies, volume manufacturing, and through further technological development (such as increasing the dispersion of catalysts in fuel cell membrane, resulting in a lower overall catalyst requirement).

Technological uncertainties have been studied using a wide range of tools, including energy system models [6,7], system dynamics and agent-based models [9, 10], and a number of techno-economic studies [11], and are relatively well characterized. We therefore do not review these in detail here.

2.2. Behavioural uncertainties

A large portion of previous analysis on the prospects for low-carbon vehicles has assumed that consumers will be willing to adopt vehicle types that require some behaviour changes (such as plugging-in to recharge), and that mobility patterns will remain unchanged by the introduction of new technologies. However, it is acknowledged that these assumptions are rather uncertain. Three issues in particular appear to be important, relating to both hydrogen vehicle technologies and potentially competing battery electric vehicles:

- First, to what extent will consumers be willing to adopt limited-range electric vehicles?
- Second, how will consumers charge their electric vehicles, and what implications does this have for the costs of charging infrastructure?
- Finally, how significant for the adoption of hydrogen-powered vehicles is the spatial density of fuel station availability – i.e. to what extent will initial consumers be inhibited by the fact that only a small portion of fuel stations will sell hydrogen?

There is little existing evidence on the range that consumers consider to be acceptable in automotive markets, since it is only very recently that battery electric vehicles have been placed on the market in significant numbers. Many studies examine the distribution of trips [12,13]), and find that the majority of trips are well within the range of a limited-range BEV (e.g. less than 160 km). Pearre et al [12] conduct a more sophisticated analysis of US trip data for a sample of 484 gasoline vehicles, relying on usage patterns by individuals rather than aggregated trip data. They found that 9% of these vehicles never travelled more than 160 km in a single day, implying that vehicles with this maximum range could capture a potential market of 9% of the total vehicle fleet. However, this conclusion excludes the possibility that many motorists will demand vehicles with greater range than they would actually use on a day-to-day basis.

Many analyses assume that consumers will charge electric vehicles at off-peak times, either by conscious choice or through smart-charging technologies. However, there is little evidence to support this supposition. Existing trials in the UK suggest that in the absence of appropriate pricing structures or smart controls, consumers are most likely to charge their vehicles at peak times [14,15], such as when returning from work in the evening. This has implications for distribution and transmission infrastructures, and for overall system generation capacity. Even if time-of-day pricing is in place, it is not clear what proportion of consumers will be concerned about leaving vehicles with depleted batteries for some hours in order to wait for cheaper power prices. Since the electricity cost is a small proportion of the total lifetime cost of ownership of electric vehicles, the financial incentive for consumers to do this may be small.

In terms of behavioural uncertainties associated with the adoption of hydrogen, the issues relate to consumer choice in the face of limited refuelling opportunities. Little is known about the relationships between the spatial density of supply and the resulting consumer willingness to adopt.

Underlying these specific issues about consumer vehicle choice is a broader uncertainty about the way in which private cars fit into a broader transportation regime. Individual ownership of cars has become an entrenched norm, with families owning one or perhaps two cars. Recent years, however, have seen the emergence of alternative models of cooperative ownership or car club ownership, in which consumers lease access to a wide range of vehicles across a city. Changes in patterns of vehicle ownership could be important in changing technology choice, since consumers with access to different types of vehicle may be more interested in including limited-range vehicles within their portfolio than single-car owners would to own one, since they do not have to rely on this vehicle alone. This is seen by automotive executives as one of the most important sources of change in car markets over the coming years [16] but has hardly been addressed in the research literature. Once again, the evidence base on which to judge the likelihood of changing ownership patterns is weak, and this set of uncertainties and possibilities must be regarded as less well characterized than those relating to technological issues.

2.3. Transition dynamics: strategies of actors

The infrastructure 'chicken-and-egg' barrier to hydrogen uptake is well known: there is no incentive to invest in infrastructure until there are vehicles, and vice versa. The dynamics that may enable this barrier to be overcome are a key uncertainty in whether and how a hydrogen transportation system might come about. UK stakeholders see it as unlikely that the UK government will lead a state-driven 'push' of hydrogen infrastructure development and vehicle sales. Rather, the way in which infrastructure is developed will depend on the strategic interactions of government and business actors.

- In addition to consumers, considered above, four groups of actors will be critical in determining how and whether a transition to a hydrogen energy system takes place:
- Governments. It is widely accepted that the adoption of hydrogen as a common transportation fuel will only take place in response to strong policy signals. However, the kind of policy instruments that governments adopt and their willingness to support particular technologies is highly uncertain, and will depend in part on the relative priorities assigned to policy drivers (climate change, air pollution, energy security, and industrial competitiveness). The way in which governments interact with national and multi-national automotive firms is also likely to play a strong role in influencing the development, deployment and adoption of hydrogen vehicles.
- Incumbent automotive firms. These firms are the technology leaders in developing fuel cell vehicles, but all of them maintain a portfolio of low-carbon vehicle options and none are likely to commit wholly to any one technology choice. Firms attempting to act as first movers may capture some first mover advantages if the attempt is successful, but they also take on significant first mover risks. Firms interact with governments in efforts to secure various kinds of support. This often takes the form of lobbying to reduce or water-down regulatory pressure, but leading firms may lobby for stricter regulations where this will grant their technical superiority an advantage†.
- Incumbent fuel providers (owners and operators of existing petrol stations). Even more than automotive firms, fuel companies investing in infrastructure take on very significant first mover risks. While industrial gas companies have been prominent in advocating hydrogen and providing support for hydrogen demonstration activities, few major incumbent fuel providers have played a strong role in hydrogen advocacy. No major fuel provider, for example, is a member of H2Mobility, the government-industry partnership aiming to foster the uptake of hydrogen in the UK.
- Hydrogen and fuel cell firms. The hydrogen innovation system contains a large number of firms whose survival and growth depends on the successful emergence of a hydrogen energy system. These firms may include challengers to incumbent automotive and fuel firms. What distinguishes them from the other categories is that they have a clear strategic interest in lobbying, attracting investment,

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† One interviewee suggested that hydrogen may benefit from incumbent automotive firms concerns over the potential for new, low-cost entrants from emerging economies to threaten their competitive position. Major firms may advocate very stringent emissions standards that secure the market for producers making very high-tech products such as FCVs against newcomers with more basic technology.

and building legitimacy, since their interests are large bound up in the successful realisation of a hydrogen energy system.

The major uncertainties concern the following questions:

- What are the business models and partnership approaches that may facilitate the diffusion of hydrogen vehicles?
- How will governments interact with business in facilitating a transition, and what is the importance of the governance paradigm (i.e. regulated markets; state corporatism; industrial policy activism, etc.).
- How successful will actors in the hydrogen innovation system be at 'system building' activities?

Two principal strands of evidence in the literature—historical analogies and model-based simulation—provide insights into the way in which the interactions of these may contribute to a hydrogen transition, and these are reviewed below. It is worth noting that neither of these provide significant insight into the possible *political* dynamics of a hydrogen transition, which have been of critical importance in previous energy transitions [17].

2.3.1. Historical analogies

An empirical literature examining the successes and failures of previous attempts to foster alternative-fuelled vehicles (particularly Liquid Petroleum Gas [LPG] and Compressed Natural Gas [CNG]) provides insights into the ways in which policymakers have attempted to initiate a transition, and how other actors have responded. Importantly, these examples demonstrate that chicken-and-egg dynamics are neither insuperable barriers to transitions nor are they unique to hydrogen.

The literature highlights an important role for local governments, frequently neglected in national-level analyses of possible hydrogen transitions. Yeh [18] shows that uptake of CNG and LPG has been significant in places with significant urban pollution problems, where local government regulatory decisions have been decisive. Local governments can be important both because they often have strong regulatory powers with respect to local air quality and public health, and second, because they often have strong powers with respect to local public transport and taxi fleets. National governments have played key roles in both successful and failed alternative vehicle and fuel programmes. In the US, the major policy drivers for alternative fuels have largely come from federal governments, with limited success [19]. National programmes have been successful elsewhere. Argentina's national programme to promote CNG vehicles relied on price controls on fuel, and has been relatively successful despite almost no government involvement in infrastructure provision [20].

The literature indicates that uptake can be rapid where the economics of alternative fuels are attractive, typically as a result of fuel or vehicle subsidies, leading to good payback times [21]. However, the cost of driving on natural gas is substantially below that of gasoline in many European countries, but this has not driven a transition in vehicle technology [22), perhaps because of the perceived inferiority of CNG vehicles or because of the lack of infrastructure.

The insights from this literature are that:

- Local and regional authorities can be powerful drivers of adoption, since they often have significant regulatory oversight of taxis and public transport, and may have legal duties with respect to public health, which has historically been a more important motivator than carbon emissions in driving strong policy.
- National-level policies, inspired by a desire to reduce dependence on oil, have tended to be less successful, except in countries in which there are domestic natural gas reserves and strong political reasons for relying on these rather than oil imports (Argentina, Iran, Pakistan).
- Uptake can be rapid where the costs of the alternative fuel and vehicle are low. Conversion of vehicles to run on CNG is low cost, and where gas costs are lower than petrol costs this has resulted in rapid uptake of CNG vehicles (e.g. Pakistan). Infrastructure barriers can be overcome where there is a strong consumer benefit to the new vehicle-fuel combination, even in the absence of government support for infrastructure (e.g. Argentina). However, cost of driving is not the only concern: natural gas has not become widely used as a vehicle fuel in Europe despite being a more economical option.
- Progress can be quickly reversed if the economics change. New Zealand fostered uptake of natural gas vehicles while oil prices were high in the 70s and 80s, but penetration of these vehicles reversed when oil prices fell and government subsidies were removed.

2.4. Modelling transition dynamics

There is a growing body of studies using models to assess the implications of different strategic choices by actors in the innovation system, using agent-based and system dynamics models. A review of these studies suggests some conclusions:

- The scale of early infrastructure provision can be very important, with initial infrastructure availability proving very important in several studies [23, 24, 25]. This suggests a strong role for government, since the private sector is unlikely to take on the full risk of initial infrastructure investment, since any first mover advantages are likely to be too small to compensate the risks of failure.
- If sufficient initial infrastructure is provided, and learning rates are sufficiently high, vehicle subsidies plus fuel tax exemptions can lead to a self-sustaining transition without the need for government to lead a massive infrastructure programme beyond the initial stages [25]. The literature also suggests that
- Learning-by-doing (the process by which costs fall as a function of cumulative deployment) is critical. Those studies that examine the sensitivity of findings to the learning rate suggest that a rate of higher than around 12% is essential if the transition is to be self-sustaining [9,10].

However, few of the studies included alternative low-emission vehicles. Studies that do include alternatives suggest that delayed introduction of FCVs could result in lock-in of the alternative low-emission vehicles, with hydrogen thus being excluded in the longer-term.

2.5. Energy system context: resources, infrastructures and pathways

It is clear that the broader energy system context will be critical for the development or otherwise of hydrogen. The relative costs of different resources, and the relative costs of decarbonisation in different sectors, will be important in determining whether there is a strong policy case to support the introduction of hydrogen in transport. Energy system modelling has provided some insights into the ways in which evolution of the broader energy system shapes the landscape for hydrogen.

A message emerging from many energy system modelling studies [26] is that low-carbon primary energy is typically best used to decarbonise the power sector first, enabling fuel switching to low-carbon electricity in other sectors. This suggests that there will be a shortage of low-carbon primary energy available for transport for some time, which will tend to limit the cost-effectiveness of fuel-switching in transportation in the near and medium term.

Further insights from modelling studies include the following:

- **Bioenergy**. The availability and perceived sustainability of bioenergy is a major uncertainty affecting hydrogen, because biofuels can compete directly in transport. Bioenergy can also compete indirectly, by reducing emissions sufficiently in other sectors that pressure to decarbonise transport is reduced and incremental technical change with petrol and diesel cars is sufficient to meet targets. [27]
- **Carbon capture and storage** (CCS). The availability and costs of key energy system technologies, particularly CCS, is important for both the viability of hydrogen, and for the relative importance of transport sector decarbonisation, as opposed to decarbonisation in other sectors.
- **Fossil fuel prices**. The availability and costs of fossil fuels – in particular oil and natural gas – are of critical importance. High oil prices will tend to promote a shift towards the adoption of hydrogen vehicles. An important uncertainty that has emerged in recent years is the discovery of large resources of shale gas. If this resource proves to be extractable in a sustainable manner, it has the potential to significantly lower natural gas prices, with implications for hydrogen.
- **Energy storage and intermittency**. An acknowledged weakness in many energy systems models is a lack of spatial and temporal resolution. Given that the critical selling point of hydrogen as a zero-carbon storable energy vector, this lack of temporal resolution may be important. Indeed, a number of studies with more explicit representation of temporal and spatial issues have suggested that there may be roles for hydrogen in balancing demand and supply in systems with significant intermittent renewables [28]. Using the ESME model, Haslett has suggested that there may be roles for hydrogen in inter-seasonal storage of renewable energy [29].
- **Future of gas**. Many long-term scenarios of decarbonisation envisage a very significant diminution in consumption of natural gas in the residential and service sectors. The political dynamics of energy transitions have been neglected in studies of transitions to low carbon energy systems [30,31], but it is clear that there will be losers. In particular, the owners and operators of natural gas infrastructure—who in the UK are currently investing many billions in new pipes—are unlikely to be passive politically in the course of a reference decarbonisation future. It is already clear that European, North American and Japanese gas companies are lobbying and investing in technologies to resist an 'all-electric' energy distribution future.

3. Transition scenarios for hydrogen in the UK

The possibilities and uncertainties examined in Section 2 have been combined to develop a set of transition scenarios, structured according to Geels and Schot's [32] typology of archetypal technological transition pathways. This section summarises the scenarios, and briefly comments on the findings from the modelling carried out to examine issues raised by the scenarios. The model framework used in this analysis is the UK MARKAL model [33]

There are common features of all scenarios, which define the 'state of the world' in which these futures are thought to exist. In this state of the world, there is continued global emphasis on achieving decarbonisation; continued global geopolitical stability; continued prosperity and growth.

The divergent features of the three scenarios are summarised in Table 2.

	'Car of the future'	'Horses for courses'	'Hybrid fuels'
Scenario overview	Conservative consumers lead to a failure of battery electric cars; automakers and governments align to drive the adoption of FCVs, with significant uptake by mid-century.	Successful introduction of BEVs into small vehicle segment results in shift in usage patterns, and goes hand-in-hand with new business models and social practices, with car clubs and multi-user ownership becoming more common. Hydrogen vehicles penetrate vehicle markets more slowly, and only in certain vehicle segments, so that by 2050 a portfolio of different vehicle types is on the road.	In this scenario, hydrogen vehicles make poor progress in the 2020s, with weak market adoption and slow infrastructure development. At the same time, changes within the broader energy system open up opportunities for hydrogen. The penetration of wind and nuclear results in a grid balancing problem, especially as attempts to improve energy efficiency are less successful than had been hoped. Hydrogen finds a role as a means of decarbonising natural gas, and avoiding curtailment of wind during demand troughs. By the late 2040s, interest in hydrogen as a vehicle fuel has resurfaced, as pressure to decarbonize switches to the transport sector.
Technological uncertainties	Continued strong progress for FCVs and other hydrogen technologies. Falling hydrogen compression costs in particular reduce the costs of refuelling infrastructure deployment.	Progress is steady but not revolutionary. Automotive batteries undergo improvements, and electric drive systems improve substantially as an increasing variety of electric-drive vehicles hits the road.	Slower technological progress for hydrogen fuel cell technologies; but more rapid progress in electrolysis, enabling better load-following without resulting in stack degradation.
Behavioural uncertainties	Conservative consumers prove unwilling to adopt BEVs, and many are reluctant to buy PHEVs.	Significant social innovation in ownership and user practices of vehicles, enabled by information technology.	Similar to car of the future: consumers remain conservative, and are less willing to adapt practices to accommodate technologies for which there is little direct personal consumer benefit.
Transition dynamics	Automakers work closely with governments and infrastructure providers. UK government takes a more activist role than has been the case in recent industrial policy history	Central governments less active in promoting a particular technological choice; but local government policy innovation important (e.g. Paris's Autolib system).	Actors fail to secure sufficient alignment to de-risk investment in vehicles and infrastructure, and there is insufficient confidence in consumer demand for hydrogen vehicles for any concerted attempt at introduction before 2035.
Energy system	Follows the anticipated decarbonisation trajectory: focus	Much like car of the future, the energy system undergoes a shift to	The energy system experiences a crisis, with significant penetration

landscape	through the 2020s on decarbonising power sector with nuclear, wind and by 2030 CCS. Gradual fuel switching to electricity of other sectors.	a low carbon power system, followed by significant fuel switching to electricity.	of intermittent renewables and inflexible base load, and less-than-expected success of conservation measures and smart meters. This scenario sees the emergence of niches for hydrogen to reduce curtailment of low carbon plant during demand troughs, with hydrogen then used to decarbonise delivered natural gas through blending.
Key branching points	Failure of consumers to respond to BEVs Governance paradigm shift enabling strong state action	Social innovation arising from new ownership and business models	Poor sales performance of hydrogen vehicles in 2020s Failure of policymakers to foster full shift to electrification, resulting in continued use of gas and pressure to decarbonise gas
Insights from interaction with MARKAL modelling	Under technologically optimistic assumptions, hydrogen becomes cost effective and plays a significant role in road transport [34]; However, achieving significant penetration (> 20% of the fleet) by 2050 implies very optimistic transition rates when compared with historical precedents [1]	Adapting the model to examine the assumption that technologies compete in different segments of the vehicle market does lead to changes in the models' technology choice. i.e. initial model results are sensitive to assumptions about social practices in vehicle markets.	We tested elements of this scenario by revising the models' representation of the gas network, and introducing the option of injecting hydrogen into the gas grid [35]. The modelling suggested that this could be a cost effective option, which highlights this as an issue worthy of further research and attention.

4. Conclusions

The paper has identified sets of major possibilities and uncertainties whose resolution will play a strong role in determining the future of hydrogen energy in the UK. Some of these uncertainties have been relatively well characterised in the existing literature. In particular, there is good evidence and agreement in terms of the development of technologies and their likely importance in enabling or hindering the deployment hydrogen. Much less analysis has addressed the uncertainties associated with consumer behaviour in the transport sector, or the ways in which the political and strategic choices of actors may enable or hinder a transition. The influence of the wider energy system context on hydrogen has been well characterised in terms of uncertainties associated with resource availability and cost, and stringency of carbon targets, but much less well in terms of changing system structures and the potential for hydrogen in mediating between heat, transport and power markets.

In combining these uncertainties and possibilities into three possible pathways, we have highlighted several issues neglected in the wider literature. First, we have highlighted the potential for social innovation to disrupt existing market paradigms, and noted that models of vehicle markets and energy systems generally do not account for this source of uncertainty. Second, we have highlighted the role of wider changes in the energy system to create opportunities for hydrogen outside the transport sector. Finally, we note that transitions to alternative fuelled vehicles are typically slow. Even under circumstances where governments and industry collaborate strongly to overcome transition barriers (as in the 'car of the future' scenario), the penetration of hydrogen vehicles into the vehicle fleet should be expected to take many decades. Nevertheless, both the scenario process and modeling highlight the strong potential for hydrogen energy systems, and the ongoing importance of fostering the development of hydrogen technologies.

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