Scenarios and futures in the governance of sustainable innovation pathways: the case of hydrogen energy

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Scenarios and futures in the governance of sustainable innovation pathways: the case of hydrogen energy

By

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A note on pagination

The published journal papers in the portfolio all have page numbers from the original journal versions. In this compiled thesis, I have added consistent page numbers throughout, to which the table of contents above refer. Consistent page numbers are found at the foot of each page, in addition to any pagination from the original journal layout, which is found at the top of the journal article pages.

Abstract

Global climate change and other sustainability challenges demand a transition to more sustainable systems. The long-term and complex nature of such transitions invites long-term planning, but it also suggests that the future is unpredictable and contested. Moreover, the act of envisioning, forecasting and planning for possible futures itself influences transitions, because visions and expectations form part of the institutional environment that shapes the behaviour of policymakers, innovators and others. Futures activities are thus part of the process of transition.

A key source of technological expectations and visions are published technology futures documents, and the processes that are used to develop them. How are such published futures created, and why are they produced? How can we assess the quality of published futures? What role do computer models play in shaping such futures, and how can computer models be used to open up futures to alternative framings and perspectives? How can published futures be improved in order to facilitate the governance of transitions to sustainability? These are the questions that motivate this PhD, and which are the subject of the portfolio of publications and this commentary. These questions are addressed through a case: hydrogen energy technologies.

A key theme that runs throughout the publications is that the future is a contested space in which actors bid for their preferred futures, express their interests and their perspectives, and attempt to influence the processes of both *appraisal of* and *commitment to* particular futures. The thesis presents a variety of ways in which participatory scenario development can be combined with other methods to ‘open up’ futures and enable consideration and representation of diverse perspectives, deep uncertainty, and plural pathways.

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I am grateful to the UCL Bartlett School of Environment, Energy and Resources both for providing a stimulating intellectual atmosphere and for part-funding the PhD itself as part of my continuing professional development. I am also grateful to the Policy Studies Institute at the University of Westminster. It was at PSI that I began this work, and I have enjoyed returning to PSI to finalise the work as a thesis.

The work set out in this thesis has been produced over the course of a decade. During that time, a great many individuals have contributed to my professional and intellectual development, by providing guidance, feedback, or intellectual inspiration. Of those, I’m particularly grateful to Paul Ekins, Jim Skea, Andy Stirling, Julia Tomei. I am particularly indebted to my supervisor Fred Steward, for guiding me through the production of the final thesis. I am also, of course, profoundly indebted to my wife, the wonderful Ashleigh Keall, for all the love and support over the years.

The greatest intellectual and personal thanks are due to Malcolm Eames, with whom I began the work set out in this thesis. Malcolm introduced me to the field and inspired both my interest and enthusiasm for research. Malcolm has continued to provide mentorship, intellectual guidance and friendship over the years, for which I will always be grateful.

Declaration

I declare that all the material contained in this thesis is my own work, noting that some of the material – the three journal papers jointly written with Malcolm Eames – is co-authored. The work was executed by us both jointly, and the co-authorship of papers reflects a deeply collaborative process in which both authors made substantive and original contributions in the writing, analysis and empirical work.

Part I: Commentary on the Portfolio of Publications

Scenarios and futures in the governance of sustainable innovation pathways: the case of hydrogen

1 Introduction, research questions and aims of the research

It has long been argued that innovation, and in particular the development and deployment of new technologies, can play a central role in overcoming environmental challenges. For many years, this debate focused on the development of ‘environmental technologies’ and ‘cleaner production’, with technological responses to environmental problems focused on abatement and dispersal of pollutants (Berkhout & Gouldson 2003). Today, many scholars and policy advocates think that promoting environmental technologies is insufficient to meeting the goals of sustainable development. Growing awareness of environmental limits—and particularly the challenges of avoiding dangerous climate change—have resulted in the emergence of a new and more ambitious perspective on the governance of innovation for sustainability. This new agenda, focused on enabling *transitions* to radically more sustainable futures, has become an increasingly important lens through which innovation for sustainability is understood (OECD 2015).

The transitions perspective argues that only systemic shifts in the way that “societal functions” (such as transport, housing, food, etc.) are fulfilled can achieve the degree of environmental improvement required. Such transitions are ‘systemic’ because they rely on a co-evolutionary dynamic between technologies, institutions, social practices and business models, which (together with other heterogeneous elements) constitute a ‘socio-technical regime’ (Geels 2004).

This evolution of the environmental technology debate—from a focus on abatement technologies to the increasingly prominent frame of transition—has involved both a broadening (in terms of the scope of issues understood to be relevant) and a longer time horizon. Both of these make demands on the way in which we envisage the future of technology.

The broadening from ‘environmental technology’ to ‘transitions’ demands consideration of not only technologies and their immediate economic or environmental attributes, but also of the heterogeneous assemblages of institutions, actors, networks and other elements that form a socio-technical regime. This pushes innovators and policymakers to go beyond consideration of technologies that will ameliorate environmental problems (but otherwise leave socio-technical systems unchanged), and instead suggests more radical and systemic options should be considered, involving social, political and institutional change alongside the introduction of new technologies. Furthermore, the long timescales required for technological transitions force consideration of a longer time horizon than is typically necessary for considering pollution abatement technologies.

Less obviously, a transition perspective embeds the act of envisioning the future within the process of change itself (Smith and Stirling 2007). Expectations, visions and beliefs shape transitions: they form part of the institutional environment that constitutes (and continually recreates) incumbent socio-technical regimes, and are a key part of the establishment of niches that incubate emerging alternatives.

It has always been acknowledged that expectations—about both demand and about possible scientific or technological possibilities—have been at the heart of innovation processes (Rosenberg 1976). Applied researchers expect to be able to solve problems; innovators expect to find a market for their novel products, processes, or business models and strategies. However, until recently the social processes through which expectations were shaped, and through which they shaped innovation itself, had been somewhat neglected.

More recently, a richer depiction of the role of expectations in science and technology has been developed, largely by sociologists and historians of technology. This literature makes clear that visions and expectations of the future help shape innovation processes (Borup et al. 2006), and that in particular shared expectations condition the way in which innovation system actors make judgements about market opportunities and technological possibilities (Bakker et al. 2011). In the context of long-term radical transitions, expectations are understood to be central to the creation of ‘niches’—protected spaces in which new technologies are developed (Geels and Raven 2006; Smith 2007). Such niches can be market niches, in which the cost, performance or some other attribute of a technology is particularly highly valued; or it can be a ‘technological niche’, in which actors foster the technology based on expectations about its social, environmental or future economic performance (Agnolucci and McDowall 2007).

On occasion, expectations are translated into 'promises', with innovators actively deploying expectations in order to win funding and support, and in doing so promising technological advances in return (van Lente 1993). Similarly, expectations shape patterns of support for emerging technologies, with funding and personnel directed towards areas with high expectations. Thus expectations can become self-fulfilling prophesies (van Lente 2012).

This has implications for innovation governance in the context of sustainability challenges: both in the straightforward sense that innovators must expect that markets will develop for products and services with lower environmental burdens (which typically requires them to have some faith in policy processes and political commitment); and also because if expectations and visions matter, the question of whose expectations and visions prevail becomes important.

An key source of such expectations are reports and other publications that aim to understand possibilities and implications of different futures (Weber 2002), as well as the processes through which these published futures are created. In this commentary, I refer to such documents as 'published technology futures' (or henceforth simply 'published futures', for brevity), in order to distinguish them from diffuse expectations or narratives which, while they may also be present in publications, are not set out as explicitly intended representations of the future of a specific technology or sector.

Published futures are thus important components of the governance of socio-technical change, and they are the focus of this PhD. In the next section, I set out the research questions that the portfolio of papers addresses, and provide a brief rationale for each.

1.1 Research questions and overall aims

The PhD addresses the role of published futures in the governance of socio-technical change. In doing so, I address the following four research questions.

1. **How are published technology futures created, and why are they produced?** This first research question explores the context for published futures, exploring the variety of futures exercises and their aims.

2. **How can we assess the quality of published futures?** Futures play a role in the governance of socio-technical change, and it is therefore important to be able to judge the quality of such exercises. This question addresses the need for critical reflection on key aspects of published futures if they are to inform public policy.

3. **What role do computer models play in shaping such futures, and how can computer models be used to open up futures to alternative framings and perspectives?** Many futures are produced using computer simulation tools. Such futures are often given privileged status in policy contexts, and there is thus a particular need for careful scrutiny of the processes through which they are produced, interpreted and communicated.

4. **How can published futures be improved in order to facilitate the governance of transitions to sustainability?** This final question explores some of the ways in which futures practitioners can respond to the quality criteria (explored in question 2) and the challenges of integrating simulation models in long-term futures (explored in question 3).

These questions reflect a pragmatic sequence of steps for achieving the overall aim of understanding, and contributing to improvements in, the use of futures in the governance of socio-technical change. That sequence first addresses the range of approaches and goals involved in current futures practice; it then asks whether existing practice is good enough given the high stakes involved in long-term governance of technology; and finally it addresses how can it be improved. The set of questions also reflects aspects of my personal research journey: my involvement with a community of energy system modellers has informed an understanding of both the value of and limits to computer modelling as a means of understanding and communicating possible futures.

1.2 Overview of the commentary

This commentary follows the sequence of questions raised above, expanding on the rationale for and importance of each of them, and providing both key context and the major findings of the associated papers. Table 1 shows the portfolio of publications, and the sections of the commentary to which they are most relevant.

Following a brief introduction to the case of hydrogen, the commentary discusses the diverse ways in which published futures are created, and the diverse purposes they serve (in Section 3, relating principally to *Paper No. 1* and research question 1). I then explore some dimensions of *quality* of published futures (responding to research question 2), in the context of their role in public policy for transitions (Section 4, relating to *Paper No. 2* and *Paper No. 3*). This section provides special discussion of the role of computer models in developing published futures, reflecting both their privileged status in policy debates (see, e.g. (Robinson 1988)) and my own personal research experience in applying energy system models (reflecting research question 3). In Section 5, the commentary then considers how futures approaches can respond to the challenges set out in the previous section, and it discusses my own attempts to produce such futures (in *Paper No. 4, 5* and *6*, responding to research question 4).

The commentary thus puts the portfolio of work in context, and it sets out some of the key results and insights from the work. The commentary also aims to show that the portfolio of publications presented sits within a wider body of my work around scenarios, modelling and technology governance. References to this wider body of work are provided throughout, and a full list of my relevant publications is provided in an appendix.

Table 1. The portfolio of publications and associated sections of the commentary

	Publication	Most relevant section of the commentary
1	McDowall and Eames (2006) Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature. *Energy Policy* 34: 1236-1250.	3
2	McDowall (2016) Are scenarios of hydrogen vehicle adoption optimistic? A comparison with historical analogies. *Environmental Innovation and Societal Transitions* 20: 48-61.	4
3	McDowall (2012) Technology roadmaps for transition management: The case of hydrogen energy. *Technological forecasting and social change* 79(3): 530-542.	4
4	McDowall and Eames (2007) Towards a sustainable hydrogen economy: A multi-criteria sustainability appraisal of competing hydrogen futures. *International Journal of Hydrogen Energy* 32(18): 4611-4626.	5
5	Eames and McDowall (2010). Sustainability, foresight and contested futures: exploring visions and pathways in the transition	5

	to a hydrogen economy. *Technology Analysis & Strategic Management* 22(6): 671-692.	
6	McDowall (2014). Exploring possible transition pathways for hydrogen energy: A hybrid approach using socio-technical scenarios and energy system modelling. *Futures* 63: 1-14.	5

2 Energy technology futures in action: the case of hydrogen

In this thesis, I explore the research questions above through a case: hydrogen energy. This section therefore provides some brief context for hydrogen, its potential role in a sustainable energy system, and its value as a case for addressing the research questions outlined above.

Hydrogen is a potentially sustainable fuel, and hydrogen technologies have received considerable funding support and policy attention in recent years. Hydrogen can be used as a fuel either through combustion or in fuel cells, which convert hydrogen into heat and power at high efficiencies. It can be produced from a wide array of primary energy sources, including fossil fuels and biomass, and also from electricity via the process of electrolysis. Thus a hydrogen energy system can capture and store energy generated by intermittent renewable technologies, and use that energy across a wide range of energy services, in transport, heat, power and a variety of industrial applications. The broad spectrum of possible applications of hydrogen energy, and its potential role as a complement to electricity as a zero-carbon energy vector, led to the idea of a “hydrogen economy”, a phrase that captures the potential for hydrogen to become a ubiquitous fuel used across the economy.

Hydrogen energy became a focus of energy innovation policy in industrialised countries towards the late 1990s, and as the technology matured it became increasingly possible to see hydrogen as an emerging system that would transform the production and consumption of energy. Interest in hydrogen has waxed and waned over the years, with various cycles of hydrogen or fuel cell ‘hype’ ((Schaeffer 1998; Bakker and Budde 2012; Ruef and Markard 2010)). Throughout these developments, it is expectations and visions—depictions of possible futures—that have sustained and shaped the activities of policymakers, investors, engineers and entrepreneurs (Sovacool and Brossmann 2010; Eames et al. 2006).

There is an abundance of published futures depicting, exploring and advocating different possible hydrogen futures. Such futures have applied a wide variety of methods and approaches. As will become clear, the future of hydrogen has been a contested space in which different interests have articulated radically different visions and expectations. Hydrogen's status as an emerging, uncertain, contested and potentially transformative technology ensured a great deal of attention from a wide variety of actors on the possibilities and implications of hydrogen. Governments, industry groups, campaigners and academics have all been involved in efforts to understand and shape the development of this emerging technology.

These characteristics make hydrogen a good case study for this project, both because it is of interest in itself (as a potentially transformative system innovation), and because the lessons learnt from studying hydrogen offer insights into the nature of published futures more generally.

3 Reviewing how published futures are developed

There is a wide variety of approaches to developing scenarios and related futures exercises, and reviews have emphasised various dimensions along which these differ (Börjeson et al. 2006; Chermack 2004). This literature highlights the different methods, purposes, types of futures exercises. A similar diversity is found in scenarios and futures specific to energy, including hydrogen.

Futures are often intended to be used directly in policymaking processes (Kunseler et al. 2015), either to directly inform decisions or to foster 'conceptual learning' (Hertin et al. 2009). Such futures are produced by a wide range of actors involved in policy debates, including businesses, government bodies, visionary individuals and civil society groups. McDowall et al. (2014) describe a variety of differing aims of such futures (these are not mutually exclusive: published futures may have several of these aims concurrently):

1. Producing a best estimate of what is expected. This may or may not come with a set of uncertainties elaborated around it. A weaker form of this might be an attempt to bound the range of possibilities.
2. Providing "what if" analysis. This is the creation of predictions given a known antecedent, or predictions of the impact of a given action or event (what will be the effects of policy x; what would happen if there was a rise in y). This might be framed in more or less 'predictive' language – i.e. "what might happen" – aiming to draw out a plausible but not certain implication of a particular event or parameter change. This can be combined with attempts

to elicit tacit beliefs and expectations from stakeholders, to draw out possible implications of different possible futures.

3. Illustrating or testing possibility/impossibility, difficulty/ease of reaching particular goals or particular futures. This may include providing a sequence of steps necessary to reach a goal.
4. Opening up thinking to options and/or issues that are thought to be 'hidden' by mainstream and/or dominant views; including attempts to open up thinking to possible 'shocks' (Van Notten et al. 2004; Volkery and Ribeiro 2009).
5. Improving thinking. A number of scenario and modelling exercises argue that they have a cognitive benefit, in that they improve the way that people think about the future (e.g. (Craig et al. 2002; Chermack 2004; DeCarolis et al. 2012).

3.1 Futures and governance: between appraisal and commitment

The aims above all related to futures that are intended to be 'substantive' inputs into business or policy decisions, either through informing specific decisions or fostering conceptual learning. Some futures are also developed to advance a particular goal, rather than inform decision-making. Roadmaps and visions are particularly good examples. They are explicitly designed to help bring about the futures that they depict.

The typology developed in *Paper 1* (McDowall & Eames 2006) made a distinction between normative vs. descriptive futures. Descriptive futures are typically seen as inputs into decision-making, i.e. they are descriptive of possibilities, and are used to help decision-makers make an informed appraisal of the options. Normative futures advocate particular choices. This distinction echoes Stirling's distinction (Stirling 2008) between 'appraisal' and 'commitment', in the context of public debate about technology choice. Appraisal relates to the evaluation of the relative benefits and risks associated with different technology pathways, while commitment describes the multiple ways in which commitments to particular technologies are pursued (including obvious commitment mechanisms such as direct subsidies). While purely descriptive futures are often seen as informing appraisal, normative futures advocate particular choices, and are thus an expression of emerging commitments to particular technological pathways.

Paper No. 1. (McDowall and Eames 2006). Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature. *Energy Policy* 34: 1236-1250.

The first paper of the portfolio (McDowall and Eames 2006) provides a review of 40 hydrogen futures studies, and explores the diversity of goals and approaches used.

However, published futures often blur these distinctions: while many are ostensibly neutral, and seek to inform appraisal and choice processes, they often embody implicit commitments to specific technology choices. Indeed, while *Paper 1* uses a 'normative/descriptive' distinction as part of the basis for a typology, all forms of futures work can be expected to be shaped by the norms and ideals of their creators. Normativity is pervasive in how people think about technology futures (Rip 2013).

It is thus unsurprising that many published futures that are self-described as impartial, or that avoid explicit endorsement of particular choices, carry clear preferences. In some cases, it is more obvious that futures are being used to advance a particular agenda, used to 'bid' (Berkhout 2006) for a particular future. In 2010, a study published by a coalition of businesses and NGOs presented itself as a neutral and descriptive piece of analysis: it was entitled "A portfolio of powertrains for Europe: a fact-based analysis", strongly signalling its descriptive rather than normative credentials. However, as a participant-observer in various hydrogen stakeholder forums, I observed the way in which the document was widely seen by stakeholders as a pitch by pro-hydrogen firms and interests to promote the role of hydrogen fuel cell vehicles alongside other low-carbon vehicle options.

That firms should seek to present analytic advocacy as pure analysis is to be expected. Less obviously, normativity can be seen to pervade attempts to produce objective analytic work. My own observations of energy system modelling practice (some of which is written up in (McDowall et al. 2014)) confirm that social norms about what constitutes reasonable living, driving, and heating practices become written into computer models, which then constrain and inform the way that people think about long-term future possibilities. This constitutes an often unconscious process that demonstrates prior commitments to specific forms of socio-technical arrangement. For example, the UK MARKAL/TIMES energy system models incorporate assumptions about the characteristics a vehicle must have in order for consumers to find it acceptable that are explicitly tied to current vehicle choice norms and preferences (see (McDowall and Dodds 2012)). Similarly, socially-shaped judgements about what forms of governance intervention are desirable and legitimate inform decisions about the plausibility of particular types of change. For example, judgements about the kinds of governance action that are legitimate and acceptable influence the choices that modellers make in parameterising scenarios. These normative dimensions to descriptive futures often remain hidden and unacknowledged, and may frequently be tacit even to modellers or scenario developers themselves (see, e.g. DeCarolis et al 2012).

So, while the distinction between ‘normative’ and ‘descriptive’ futures is useful in distinguishing between more or less explicit commitments in futures documents, it does not imply that ‘descriptive futures’ are a neutral space. Clearly, futures are developed not just to inform decisions, but can also be developed with more obviously political goals (this indeed reflects wider patterns in the use of evidence in policymaking, which recognises political uses (Hertin et al. 2009)). This is a key theme that runs through the portfolio of work associated with this commentary: futures are often used both for appraisal that informs technology choice, and are also used (explicitly, implicitly and even unconsciously) as part of the process of forming commitments to specific technology futures.

3.2 Engaging with futures: ontological divides

There are further, deeper, distinctions in the multiple ways in which diverse actors (scholars, activists, marketers, policymakers, visionaries, and so on) develop published futures. Those envisioning possible futures often differ in the underlying philosophies of science to which they adhere. Positivists focus on the presumed existence of general laws governing social and physical processes, and in examining possible futures they focus on predictive depictions of quantitative variables and their relative probabilities (Konrad et al. 2017). Such scholars have developed elaborate methodological repertoires for exploring quantifiable futures, yet pay relatively little attention to those aspects of socio-technical change that cannot be represented in system models, such as cultural meanings. The purpose of futures work here is often seen as decision-support, and the reduction of uncertainty about possible futures and outcomes. Since the obvious failures of long-term planning and forecasting in the mid- and late-20th centuries, it has become common for futures practitioners with a positivist inclination to express such predictive analysis in language that avoids explicit forecasting (McDowall et al. 2014). Instead, such studies tend to talk of ‘scenarios’, ‘outlooks’, ‘projections’, and so on. Nevertheless, what Robinson ((1990), p. 821) calls the “predictive flavour” of such studies remains clear.

In contrast, constructivists and interpretivists use futures to critique and open up dominant narratives (McDowall and Geels 2017). Sardar (2010) elaborates this perspective, arguing that futures should be understood as ‘futureless’, in the sense that the future is fundamentally unknowable. Futures work is therefore about uncovering the meanings, interests and social structures underpinning different representations of the future and their attendant policy implications. Such perspectives often have little interest in the likelihood or otherwise of specific aspects of envisaged futures. As Konrad et al. (2017) put it: “The broader task … is to …increase the process of critical thought about alternative trajectories of change without falling prey to the impossible task of predicting …the direction of technological advance…" (p. 481).

This PhD does not seek to resolve such debates. Rather, it adopts a practical and policy-oriented perspective that emphasises the value of revealing the deep assumptions and worldviews that underpin published futures, while also exploring the possible implications and plausibility of hydrogen futures.

3.3 Summary

This section of the commentary – and *Paper No. 1* of the portfolio – provide a response to the first research question motivating this thesis (*"How are published technology futures created, and why are they produced?"*). Published futures are produced using a range of methods and for a variety of purposes, which vary in the degree to which they explicitly endorse particular choices or beliefs about the future. A distinction between normative futures (advancing a particular goal) and descriptive futures (exploring future possibilities) is useful in understanding published futures, but it also clear that all futures exercises are shaped by the norms, beliefs and desires of their creators.

4 Evaluating the quality of published futures as evidence for policy

Since futures are used as tools of both appraisal and commitment in the governance of transitions, it is reasonable to ask how we can assess their quality. In McDowall 2012 (*Paper No. 3*) I articulate quality criteria for a specific form of published futures – technology roadmaps. The quality criteria developed in that paper are specific to roadmapping – an explicitly normative approach that aims to foster a particular future – and cannot be directly used for a wider body of futures work. Indeed, the diversity of types of technology futures used in public policy processes suggests that attempts to develop comprehensive quality criteria that would encompass the full range of futures work would be well beyond the scope of this thesis (see also Von Schomberg et al 2005). Rather than attempt to do this, in this section I address Research Question 2 by focusing on two quality criteria that *can* be applied to a wide range of diverse types of published futures. These two criteria are:

1. The plausibility of futures
2. The extent to which published futures contribute to 'opening up' futures to possible alternative perspectives, value judgements and uncertainties.

4.1 Assessing plausibility and possibility

There has been a lengthy debate between scenario developers interested in establishing relative probabilities of different futures, and those that reject the use of probabilities as irrelevant in scenario planning (Ramírez and Selin 2014; Morgan and Keith 2008). Much of this debate appears to rest on different conceptions of the primary purpose and roles of futures thinking, and I do not elaborate the arguments here. Rather, I draw attention to the point of agreement among these authors: regardless of the position taken with respect to the usefulness of assigning probabilities to futures, it is almost universally acknowledged that published futures must depict futures that are *possible*[1]. Thus the first quality criterion is "plausibility", i.e. showing that a given future is possible.

Unfortunately, it turns out that assessing the possibility status of complex socio-technical futures is not straightforward: while one can exclude futures that clearly violate well-established scientific principles, a great many imaginable futures cannot be easily shown to be possible or not possible. Betz (2010) discusses this issue, arguing that to say that something is 'possible' is to say that it is "consistent with what we know", and that it is thus justified with respect to a given body of knowledge.

In McDowall (2016; *Paper No. 2*) I make use of Betz' work to show how historical analogies can inform judgements about the plausibility of the rate of technological transition depicted in scenarios of hydrogen fuel cell vehicle adoption. This is similar to the argument from Wiek et al. (2013), which uses historical precedents as a basis for judging the plausibility of a scenario. In *Paper No. 2*, I compared a set of hydrogen futures scenarios with historical analogies – historical cases in which alternative fuel vehicles have diffused. The paper finds that as a whole, published studies setting out the future of hydrogen fuel cell vehicles have been optimistic about the rate at which hydrogen might be adopted. I also found that very rapid vehicle transitions *are* possible, but have occurred historically under rather extreme political and economic conditions. For example, very rapid adoption of pure-ethanol vehicles took place in Brazil in the late 1970s and early 1980s under a government programme – but this was in the context of a military government and national ownership of the energy and fuel distribution industries. The observation here is that any scenario

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[1] While it is recognised that science fiction has a role in stimulating socio-technical visions, such futures are self-consciously fictional, and are beyond the scope of this thesis.

depicting alternative fuel deployment as rapid as this begs questions about its plausibility in political terms.

Paper No. 2 suggests two conclusions of relevance here. First, the paper shows the direct value of historical analogies in clarifying what Betz calls the ‘possibility status’ of scenarios. Second, and perhaps more usefully, the paper shows that contrasting historical analogies with futures can generate insights into hidden assumptions and issues (for example, if a scenario asserts that rapid transitions are possible, what kinds of socio-political developments must be imagined in order to make this plausible?).

My work here is a contribution to an emerging body of literature that uses historical analogies to interrogate possible futures (see, for example, (Höök et al. 2012; Wilson et al. 2012; Sovacool and Geels 2016)). However, there are also risks with this approach. Kunseler et al. (2015) argue that using historical analogy to affirm the plausibility of futures can undermine creativity of futures thinking, and thus unnecessarily constrains futures to reproductions of historical patterns. My response to this argument is to use historical analogies not just as a “plausibility test”, but as a mechanism for revealing hidden assumptions and issues implicit in published futures.

4.2 Opening up, closing down

Many forms of technology futures are aimed at informing decision-making. In the context of the governance of innovation, such futures represent forms of, or contributions to, appraisal processes, in which alternative possible options are compared. Several of the publications in the portfolio draw on the distinction made by Stirling between “opening up” and “closing down” in the appraisal of technology options (Stirling 2008, 2006). Stirling’s work highlights the value of processes that open up appraisal, which includes attention to:

- The extent to which alternative possible perspectives are explored and represented
- The extent to which the degree of ignorance and uncertainty is made clear

Stirling’s emphasis on the need for opening up appraisal is based on the observation that wholly objective appraisal is impossible: in a plural society, it is not necessarily possible to identify a uniquely rational social preference ordering of a set of options (Arrow 1950). Any attempt to identify a ranking of options is thus likely to rest on framing assumptions (Stirling 1999). This suggests that futures should be interrogated to reveal and explore their framing assumptions, and how the apparent desirability of particular futures is informed by, and can change with, the particular perspective used. In other words, any attempt to explore the desirability and legitimacy of published futures should rest on an acknowledgement of the social nature of knowledge and evidence production. This is particularly important given our earlier recognition that the construction of possibilities is suffused with normative assumptions and goals. Rather than aiming to arrive at a neat social preference ordering across a range of possible futures, analysts should seek to ‘open up’ futures appraisal to examine relative desirability under different assumptions and perspectives. Hence, the second general quality criterion is the extent to which published futures (and the associated processes) enable ‘opening up’.

Clearly, this is particularly important where published futures are being developed in order to inform policy decisions. Do such futures enable understanding of how the performance of different futures might vary under divergent perspectives? Or do they present as universal and fact-based a narrow perspective that is representative of a particular interest group?

A further issue in opening up appraisal relates to the degree to which futures are transparent about the nature and scale of uncertainties and ignorance involved. Many commentators on published futures activities, particularly scenarios and modelling, have argued for clarity in the way in which uncertainties are described and communicated (Morgan and Keith 2008; Funtowicz and Saltelli 2014; Kloprogge et al. 2007; Mastrandrea et al. 2010). Yet despite such broad agreement on the importance of effectively communicating uncertainties, many futures exercises do not do this well. For example, I have explored the communication of uncertainties arising from futures work using the MARKAL energy system model in the UK, and documented weaknesses in the communication of uncertainties (Trutnevyte et al. 2016).

In *Paper No. 3*, I observed that roadmappers face something of a dilemma. On the one hand, an open, participatory process that fully acknowledges uncertainty and the contested and diverse set of possible futures has greater legitimacy as an input into decision-making; but on the other hand, a process that purports to have achieved consensus and that downplays uncertainty is more likely to motivate and catalyse the alignment and action of key actors, and thus achieve its goals. This echoes the observation of Hulme and Dessai (2008): “We therefore suggest that using … scenarios in a social learning process may actually require a degree of illusion about their predictive skill before expectations about what the scenarios offer decision-makers can be more appropriately calibrated.”

(p. 6). But while Hulme and Dessai's concerns are practical (relating to participant motivation), the concerns for roadmappers are more problematic, and relate to the way that roadmaps straddle both appraisal and commitment. The way out of this dilemma is for roadmaps to be part of a wider iterative and reflexive process, allowing for both ongoing revision of roadmaps as well as the pursuit of diverse possible pathways.

Paper No. 2. McDowall (2016) Are scenarios of hydrogen vehicle adoption optimistic? A comparison with historical analogies. *Environmental Innovation and Societal Transitions* 20: 48-61.

This is the most recent paper in the portfolio, having been published in September 2016. The paper discusses how historical analogies can be used to inform judgements about the plausibility of scenarios.

Paper No. 3. McDowall (2012) Technology roadmaps for transition management: The case of hydrogen energy. *Technological forecasting and social change* 79(3): 530-542.

This paper deals with a particular form of futures exercise, the roadmap, and develops an approach to evaluating the quality of roadmapping processes in the context of transition governance.

4.3 Modelled futures: assessing plausibility and openness

The research underpinning the portfolio of publications has been informed by my involvement in a number of modelling activities related to possible future hydrogen energy systems. Models are widely used in exploring possible energy futures, and often play a powerful role in shaping shared expectations.

In policy contexts, models are often given privileged status (Robinson 1992; Porter 1995) and are treated as having a different epistemic status than qualitative futures developed by groups of stakeholders. This is sometimes because modelling enables a scientific discourse to be evoked, which appeals to norms about the use of scientific and objective information in policy; It is also sometimes because the modelling often defies scrutiny: only those with appropriate training can question the results.

Furthermore, the attractiveness of models to policymakers itself generates strong instrumental pressures on those generating futures using models (McDowall and Geels 2017). Experience in a wide array of fields of relevance to sustainability transitions (e.g. (Schneider 1997), including my own work (McDowall et al. 2014), makes clear that those carrying out modelling are often influenced by instrumental pressures to emphasise the importance and reliability of their findings, and have incentives to downplay uncertainties.

In the above, I set out two broad areas against which the quality of published futures can be judged. I now explore how well modelled futures stack up against those criteria, and in doing so, I address Research Question 3.

4.3.1 Models and plausibility

First, we can ask about the extent to which models are useful for determining the ‘possibility status’ of futures. Again following Betz (2010), we can see that models can often show that particular futures are not possible, because consistent accounting and quantification can show when scenarios breach fundamental physical limits. Yet it is also clear that many well-established models can easily be used to produce highly implausible outcomes. As tools for establishing possibility, models can thus have a limited, though important role: they can help to eliminate some futures by showing them to be not possible, but futures produced with even a sophisticated model should not be assumed to be possible simply because they can be modelled.

4.3.2 Models and opening up

Optimisation models, such as the MARKAL/TIMES energy system models that I have worked with, are programmed to identify the ‘optimal’ energy system, subject to a set of constraints (optimal, in these models, is defined in purely techno-economic terms). They thus operate within a narrow framework, ignoring many aspects of possible futures that are clearly important (such as equity and justice issues) and making strong assumptions about the commensurability of costs that may be difficult in practice to justify (e.g. trading off costs of new technologies against costs associated with reduced delivery of energy services such as heating). Such models are typically used as tools for ‘closing down’ appraisal of possible future options, enabling policymakers to justify specific technology choices (e.g. (LCICG 2014)), and even as vehicles for the expression of prior commitments (e.g. (BERR 2008)).

However, it would be a mistake to assume that models of this kind are inevitably associated with closing down appraisal, in contrast to participatory processes that enable opening up. Stirling has highlighted that relatively opaque analytic processes, such as models, are not necessarily any more prone to acting as vehicles for 'closing down' appraisal than are participatory processes involving stakeholder engagement (Stirling 2008), since the latter may succumb to similar pressures to close down appraisal, expressed through choice of participants, framing of participatory processes, and so on.

Moreover, we can identify ways in which even highly closed technical methods can be used in a way that facilitates opening up. Betz discusses the role of models in the context of climate change scenarios. His work argues that it is often difficult to use models to definitively determine the 'possibilisitic status' of scenarios, since the validity of models in open systems is weak (Hodges and Dewar 1992; Windrum et al. 2007; Ormerod and Rosewell 2009; Oreskes et al. 1994). But he notes that models may play a different role: by uncovering possible scenarios that would otherwise not be imagined: "simulating complex systems based on their microdynamics might suggest possibilistic hypotheses we have not even thought about" (Betz 2010, p. 98).

In this case, a model can be seen as opening up decision contexts to new perspectives and possibilities, by bringing to light possibilities that had previously been overlooked. While a linear optimisation model such as MARKAL/TIMES is typically emblematic of relatively closed form of analysis, we can see here that sensitive use of such tools can contribute to opening up wider debate and dialogue about possibilities, options and choices. The question is then how to use models to inform futures exercises that enable opening up. I present one attempt to respond to this challenge in section 5.2 below.

4.4 Summary

This section has addressed Research Question 2 ("How can we assess the quality of published futures?"). In particular, the section has articulated the rationale for two key criteria: i) plausibility and ii) the degree to which appraisal can be 'opened up'; and it has explored some of the challenges in assessing futures against these criteria.

The section has also explored the particular role of computer models in shaping published futures, responding to Research Question 3 ("What role to computer models play in shaping such futures, and how can computer models be used to open up futures to alternative framings and perspectives?”). This work highlighted that models do not provide a simple ‘plausibility test’, and noted that models can provide a route to ‘opening up’ futures by highlighting possibilities that had previously been overlooked.

The next section turns to the challenges of improving the development of published futures.

5 Building and learning from futures for energy transitions

I have argued that published futures should facilitate opening-up in the appraisal of technology options. What practical steps can be taken to achieve this? The final three papers of the portfolio each address an alternative approach to building and using scenarios to inform sustainability transitions in the context of hydrogen energy, and they thus respond to Research Question 4 (“How can published futures be improved in order to facilitate the governance of transitions to sustainability?”). These different methods reflect different rationales for conducting scenario exercises, and attempt to respond to some of the quality criteria, and common weaknesses in scenario approaches, discussed in section 4. As a result, the approaches adopted are intended to respond to some of the concerns set out in the previous section.

5.1 Participatory backcasting and vision appraisal

The first two papers (both co-authored with Malcolm Eames) set out a process in which normative ‘visions’ of a hydrogen economy were developed drawing on a participatory workshop. These visions were then subjected to a process of multi-criteria mapping (MCM), which revealed the divergent value judgements and perspectives that conditioned beliefs about the relative sustainability of the different futures. This process is described in detail in *Paper No. 4* (McDowall & Eames 2007). The next stage in the process was a participatory backcasting exercise, which aimed to explore how such futures might be achieved. These processes aimed to a) use futures as a space for enabling dialogue and debate about socio-technical priorities and possibilities; b) develop pathways informed by different governance contexts and insights from the literature on long-term change in socio-technical systems.

This work thus directly responds to the requirements that foresight knowledge should:

- Be plausible, in 'socio-technical' terms, with the use of archetypal transition pathways derived from detailed case studies of historical technological transitions.
- Enable opening up to alternative perspectives, in both the sense that the process was developed through a participatory process, but also that the visions were subjected to a detailed participatory evaluation process using multi-criteria mapping (MCM).

The MCM work found that the sustainability of hydrogen was deeply contested. In assessing the relative sustainability of different hydrogen futures, stakeholders identified many issues familiar to techno-economic analysts concerned with energy systems: such as costs, feasibility, life-cycle CO_2 performance, uncertain oil prices and policies, and so on. Stakeholders with different perspectives also differed on fundamental issues of how technology futures should be judged, raising issues that went far beyond techno-economic concerns or uncertainties. These related to concerns about relevant scales of governance and the resulting distribution of political power and control of energy systems, and concerns relating to the relationship of certain technologies with particular power structures and interests (such as a perceived reliance of nuclear energy on a more heavily militarised state). These more fundamental differences in beliefs about the nature of society-technology relationships shaped participants' appraisals, and suggest that divergent assessments of sustainability in the context of hydrogen ultimately involve deeply political choices in the face of incommensurability of value judgements and social priorities.

Portfolio of publications: papers 4 and 5.

McDowall & Eames (2007) Towards a sustainable hydrogen economy: A multi-criteria sustainability appraisal of competing hydrogen futures. *International Journal of Hydrogen Energy* 32(18): 4611-4626.

This paper applies multi-criteria mapping (MCM) to a set of hydrogen visions, developed through a participatory process.

Eames and McDowall (2010). Sustainability, foresight and contested futures: exploring visions and pathways in the transition to a hydrogen economy. *Technology Analysis & Strategic Management* 22(6): 671-692.

This paper elaborates a participatory backcasting approach to building scenarios, informed by theoretical frameworks drawn from transitions studies.

5.2 Scenarios and interdisciplinary dialogue: integrating qualitative and quantitative dimensions

The exercises published in *Paper No. 4* and *Paper No. 5* (Eames and McDowall 2010) provided a valuable and novel approach to opening up appraisal, by combining participatory scenarios development with multi-criteria mapping. However, I also felt that the resulting scenarios lacked the techno-economic consistency that models are well placed to provide. This led me to develop an approach to linking quantitative modelling with qualitative and participatory scenario approaches.

The final paper in the portfolio (*Paper No. 6*; McDowall 2014) is the result of that effort. In *Paper No. 6*, I tackle the challenges associated with applying both qualitative and quantitative approaches to thinking about the future of hydrogen energy. Advocates of quantitative methods typically argue that these have greater usefulness, and also that they avoid material infeasibilities – such as techno-economic internal inconsistencies (see e.g. discussion in (Fontela 2000)). Yet as previously discussed, such tools are often used in a way that obscures both the partial and value-laden nature of the resulting scenarios, as well as the scale of the uncertainties and choices involved.

Several authors describe a need for 'integration' of different forms of knowledge across disciplines to enable modelling to more effectively support the pursuit of sustainable development objectives (e.g. (Harris 2002)). Others have described the necessity of transdisciplinarity and the *integration* of social and natural sciences in producing foresight knowledge.

In *Paper No. 6*, I describe an approach of creating 'dialogue' between narrative scenarios and models. The idea here is to use the strengths of both approaches, while highlighting where each may have shortcomings. This process generates additional learning into possibilities, and often generates insights into previously tacit assumptions or beliefs held about what constitutes likely or desirable outcomes – both those held by stakeholders and those built into models. Thus a dialogic process between narrative scenarios can help scenario approaches to be more effective in their roles as "learning machines" (Berkhout et al. 2002).

The emphasis on dialogue between different approaches has been partly inspired by the work of Cuppen (Cuppen 2010), who used the phrase 'constructive conflict' in the context of a participatory process of deliberation. It also has some resonance with Barry's work on interdisciplinarity (Barry et al. 2008), which highlights the possible value in an 'agonist-antagonist' mode of interdisciplinarity, rather than the typically assumed integration of disciplines.

Portfolio of publications: paper 6.

McDowall (2014). Exploring possible transition pathways for hydrogen energy: A hybrid approach using socio-technical scenarios and energy system modelling. *Futures* 63: 1-14.

While participatory scenarios are valuable, a consistent challenge for scenarios is the integration of qualitative approaches and quantitative modelling. This paper articulates a novel approach that puts these alternatives into 'dialogue'.

5.3 Summary

The papers discussed in this section of the commentary provide some answers to the fourth and final research question ("How can published futures be improved?"). The work in this section of the thesis has described how futures can be used to create opportunities for dialogue and deliberation over the direction of socio-technical change, and how modelled futures can be used in dialogue with future narratives derived from participatory processes. The work has thus demonstrated ways in which futures can be opened up to diverse perspectives.

6 Conclusions

The PhD has addressed each of the research questions: highlighting the range of aims and types of futures methods; developing and applying quality criteria for roadmaps in particular and for published futures in general; exploring the role that computer models can play in opening up futures; and it has suggested some ways in which technology futures can be improved. In this final section, I turn to the overall conclusions that can be drawn from across those research questions and the portfolio of publications as a whole. The PhD delivers two broad categories of conclusions – the first related to the specific case of hydrogen, and a second, broader set of conclusions on learning from technology futures.

6.1 The future of hydrogen

The work underpinning the portfolio of publications resulted in a set of conclusions specific to hydrogen. These are contributions to the debate around the possible role of hydrogen in future energy systems. Here, I provide a short summary of some of these conclusions.

1. The sustainability of hydrogen is contested: while hydrogen is often framed as 'sustainable', and is typically included in e.g. statistical measures of "clean energy" innovation (such as R&D funding or low carbon patents), people disagree considerably about whether and under what circumstances a hydrogen energy system is indeed sustainable. There are two important points here. First, hydrogen can be used in a wide variety of systems with very varied environmental performance, suggesting that any assertion of a hydrogen system as automatically sustainable is misleading. Second, people disagree about how best to judge which hydrogen systems are sustainable: there are contested values and different beliefs about key uncertainties that defy any attempt to overcome divergent opinions through analytic data gathering and research (*Paper No. 4*).
2. Hydrogen researchers and policy advocates may have overlooked the potential for hydrogen internal combustion engines to facilitate a more rapid transition than would otherwise be plausible (*Paper No. 2*).
3. Despite a proliferation of technology roadmaps for hydrogen, many of these have been of rather low-quality. There is potential for technology roadmapping to play a more constructive role in facilitating the development of hydrogen energy systems (*Paper No. 3*).
4. Model based analysis depicting hydrogen as an attractive option has tended to make implicit assumptions about strong co-ordination capabilities between groups of relevant actors, beyond that typically observed in emerging technology innovation systems. Scenarios that include significant business model innovation (such as through alternative modes of car ownership and use) may offer an important way of circumventing some of these co-ordination barriers (*Paper No. 6*).

6.2 Published technology futures and innovation governance

Looking beyond hydrogen, the insights and approaches developed in this thesis can be applied more generally to the governance of innovation for sustainability. As I made clear in the introduction, technological expectations and beliefs play a direct role in the development of socio-technical change: they actively influence the choices that innovators, researchers and governments make in developing new technologies. It is no wonder that the published technology futures that reflect and influence such expectations are increasingly seen as potential tools of governance of innovation (Konrad et al. 2017). Alongside governments, a wide variety of actors attempt to influence expectations, by promoting futures that correspond to their interests (Pollock and Williams 2010). One means by which they do this is formal, published futures: documents that depict, describe and explore possible futures.

The work in this thesis, addressing Research Question 1, has showed that actors employ a wide variety of techniques, and produce futures both to inform decision making and to assert a particular future. While they vary in the extent to which they explicitly endorse particular choices, they inevitably express the perspectives and concerns of their producers. The future is thus a contested space in which actors bid for their preferred futures, express their interests and their perspectives, and attempt to influence the processes of both *appraisal of* and *commitment to* particular futures.

In that context, I argued that it is important to examine the quality of published futures, since they are a part of the institutional context that shapes technological change. Critical examination of published futures in this way is important, both because it can help governments to direct innovative activities towards more sustainable outcomes, and because scrutiny of published futures can help to prevent powerful incumbent actors from dominating the way in which the future is understood and represented. I identified two quality criteria that can be applied to a wide range of published futures: first, they should be plausible, and second, they should enable consideration of alternative perspectives, and be open and honest about the scale of uncertainties involved.

My work devoted particular attention to computer models, since published futures produced using models are often seen as more ‘scientific’, and they carry greater influence in policy than futures produced using alternative forms of foresight knowledge. Yet it is clear that, despite their many strengths, models do not provide a simple ‘plausibility test’, nor do they necessarily enable opening up of futures to alternative perspectives. Subjecting modelled futures to greater scrutiny is thus important in avoiding a misleading sense of certainty about the likely or desirable direction of socio-technical change. A conclusion from the work is that a key benefit of models is often overlooked: modelling may reveal possible futures that had previously not been considered, and in doing so they can contribute to opening up consideration of a wider range of futures.

Finally, the thesis has explored some ways in which published technology futures can be improved. In particular, the set of papers provides three specific methodological contributions that facilitate both the construction and critique of published futures in the context of governance of long-term transitions. All of these mechanisms help to foster reflection on goals, possibilities, contingencies and options, and create opportunities for revealing tacit assumptions.

1. The irreducibly political nature of disagreements about the sustainability or desirability of different futures highlights the importance of opening up futures to multiple diverse perspectives. Participatory futures exercises can be usefully combined with multi-criteria participatory appraisal to facilitate the process of 'opening up' a policy area to divergent perspectives (as illustrated in *Paper No. 4*). Through combining participatory visioning and multi-criteria mapping, decision-makers and others can be informed about not only the apparent performance of possible hydrogen systems under different perspectives, but also the fault-lines and beliefs that preclude a simple analytic identification of a 'best' option.
2. The work recognises the value of models as tools that can help futures work by revealing where scenarios may contain material infeasibilities, and by revealing previously overlooked possibilities. However, models are also prone to misuse and misinterpretation. The work in this portfolio of publications (*Paper No. 6*) concludes that a 'constructive conflict' approach, in which models and model runs are confronted with stakeholder-based narrative scenario approaches, can be a successful way of harnessing the benefits of models in transition scenarios while reducing the risks that models then serve to unduly close down the futures generated.
3. The work has shown the benefits of using historical analogies to learn about the plausibility of particular futures (*Paper No. 2*). The 'constructive conflict' between narratives and models referred to above relates to a dialogue between two different approaches to thinking about the future. Similarly, the work with historical analogies shows that there is value in creating dialogue between specific elements of scenarios and historical analogies.

The overall conclusion is that technology futures are not a neutral space – they carry within them the values, perspectives and often tacit assumptions of their creators. Opening them up to scrutiny – through participatory processes, through engagement with formal modelling frameworks, and through comparison with historical analogies – can result in learning both about future possibilities, but also about the present-day perspectives and assumptions that are relevant for decision-making.

In doing so, opening up technology futures can help drive better public policy, and so facilitate the orientation of innovation towards more sustainable outcomes.

Finally, the PhD suggests a number of avenues for further research, some of which I am pursuing through ongoing projects. In particular, I am keen to further develop the ‘constructive conflict’ approach to integrating narrative scenarios and system modelling; and I am also working further on the use of historical analogies to reveal insights into the dynamics represented in future scenarios. Technology futures are an important part of the broader socio-technical environment in which new technologies develop – and they will remain an important arena for future research.

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Appendix: Full list of relevant publications

Those publications that are included in the portfolio are underlined.

Critical engagement with use of models and scenarios

1. McDowall and Geels (2017) Ten challenges for computer models in transitions research: Commentary on Holtz et al. *Environmental Innovation and Societal Transitions* 22: 41-49.
2. McDowall (2016) Are scenarios of hydrogen vehicle adoption optimistic? A comparison with historical analogies. *Environmental Innovation and Societal Transitions* 20: 48-61.
3. Trutnevyte, E., W. McDowall, J. Tomei and I. Keppo (2016). "Energy scenario choices: Insights from a retrospective review of UK energy futures." Renewable and Sustainable Energy Reviews 55: 326-337.
4. McDowall (2014) Exploring possible transition pathways for hydrogen energy: a hybrid approach using socio-technical scenarios and energy system modelling. *Futures, 63, 1-14.*
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Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature

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Abstract

Scenarios, roadmaps and similar foresight methods are used to cope with uncertainty in areas with long planning horizons, such as energy policy, and research into the future of hydrogen energy is no exception. Such studies can play an important role in the development of shared visions of the future: creating powerful expectations of the potential of emerging technologies and mobilising resources necessary for their realisation.

This paper reviews the hydrogen futures literature, using a six-fold typology to map the state of the art of scenario construction. The paper then explores the expectations embodied in the literature, through the 'answers' it provides to questions about the future of hydrogen. What are the drivers, barriers and challenges facing the development of a hydrogen economy? What are the key technological building blocks required? In what kinds of futures does hydrogen become important? What does a hydrogen economy look like, how and when does it evolve, and what does it achieve?

The literature describes a diverse range of possible futures, from decentralised systems based upon small-scale renewables, through to centralised systems reliant on nuclear energy or carbon-sequestration. There is a broad consensus that the hydrogen economy emerges only slowly, if at all, under 'Business as Usual' scenarios. Rapid transitions to hydrogen occur only under conditions of strong governmental support combined with, or as a result of, major 'discontinuities' such as shifts in society's environmental values, 'game changing' technological breakthroughs, or rapid increases in the oil price or speed and intensity of climate change.

Keywords: Scenario building; Hydrogen economy; Roadmapping

1. Introduction

Scenarios, roadmaps and similar foresight methods are increasingly used in academia, government and industry as a means of coping with uncertainty in areas with long planning horizons, such as energy or transport policy (Greeuw et al., 2000). Research into the future of hydrogen as an energy carrier and the putative 'hydrogen economy' has been no exception. There is a rich contemporary literature, spanning articles in academic peer reviewed journals and official or semi-official policy documents, through to works of popular advocacy, exploring the future potential of hydrogen energy.

Foresight methods and approaches can play an important role in the development and propagation of shared visions of the future, creating powerful expectations of the economic, social and environmental potential of emerging technologies; and mobilising the intellectual, financial, political and institutional resources necessary for their realisation (Weber, 2004).

This paper presents an extensive review of the current (English language) hydrogen futures literature, and maps the state of the art of scenario construction around hydrogen. The review undertaken for this work is not an exhaustive list of all hydrogen futures studies ever published. Rather, the aim has been to capture the diversity of the current hydrogen futures literature by identifying groups of studies, and characterising them by asking questions about their aims, how they were put together, what kinds of perspectives they have of the future and of technological change, and over what sort of time scales each type of study tends to operate.

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The paper is structured as follows. Section 2 briefly describes the search strategies used to identify and analyse the hydrogen futures literature. Section 3 presents a simple typology that characterises this diverse literature according to the objectives, methodology and narrative structure of the studies discussed. Six broadly distinct, although not entirely exclusive, types of study are identified. These are: (1) Forecasts; (2) Exploratory Scenarios; (3) Technical Scenarios; (4) Visions; (5) Backcasts/Pathways; and, (6) Roadmaps. Section 4 then provides a second analytical 'cut' on this literature by interrogating it for the answers it provides to a series of questions about the future of the hydrogen economy:

- What are the drivers of a hydrogen economy?
- What are the barriers and challenges facing the development of a hydrogen economy?
- In what kinds of future does hydrogen become important?
- Which technologies are important and what does a hydrogen economy look like?
- How does a hydrogen economy develop and evolve?
- When does a hydrogen economy emerge? and
- What does a hydrogen economy achieve?

Finally, Section 5 draws together some overarching conclusions and reflections.

2. Review methodology

Studies were identified by using electronic journal databases and internet searches to search for: 'Hydrogen or fuel cells' AND 'economy'; 'scenario'; 'futures'; 'roadmap'; 'pathway'; 'routemap'; 'forecast'; 'foresight'; 'backcast(ing)'; 'vision'. Some studies were also brought to the attention of the investigators by colleagues working in the field.

Studies were included that described a hydrogen or fuel cell future, or a strategy or 'route' by which a hydrogen or fuel cell future might develop. There was a focus on those studies which were most relevant to the UK, but studies specific to other countries were included (Andersen et al., 2004; Arnason and Sigfusson, 2000; Australian Government, 2003; Fuel Cells Canada, 2003; US Department of Energy, 2002).

A total of 40 studies, published between 1996 and 2004, were reviewed. Of these 11 focus on hydrogen or fuel cells in road transport, whilst a handful emphasised stationary fuel cell applications. Most studies considered hydrogen or fuel cells in more general contexts, including a variety of production routes and uses. All of the studies were analysed against a standard template to ensure that the same elements of each were captured and compared in a rigorous and efficient manner (McDowall and Eames, 2004).

3. A typology of hydrogen futures

Our analysis identified six distinct though overlapping types of hydrogen futures study.[1] These can be further grouped into 'descriptive' and 'normative' approaches. See Table 1 below.

3.1. Forecasts

Two 'roadmaps' also included market forecasts as part of the study (Fuel Cells Canada, 2003; HyNet, 2004) (Table 2).

Forecasts are characterised by the use of quantitative methods to predict futures based on current trends, or based on surveys of expert opinion (Kosugi et al., 2004). They tend to explore shorter time scales (up to 2030). Most used inputs such as technological learning curves, demand projections, fuel cost or oil price projections, and the characteristics of competing technologies to model market penetration of fuel cells or hydrogen (Christidis et al., 2003; Fukushima et al., 2004; Mima and Criqui, 2003; Thomas et al., 1998). Some used 'scenarios' (here meaning variations in the set of input assumptions) to explore the impact of different factors on shaping the future of hydrogen. The most basic forecast in the literature simply extrapolates sales figures from 1996 to 2003 to project stationary fuel cell market growth to 2020 (HyNet, 2004).

Rates of adoption of hydrogen technologies are considered to be largely a function of their relative costs compared to alternative technologies. However, several of the above studies also model the effects of policy interventions such as carbon taxes.

In assessing what necessary developments must occur in order for a hydrogen economy to develop, these studies focus on concrete technological challenges (e.g. price of fuel cell electricity per kWh). The central challenge to a hydrogen economy is seen as bringing down the costs of hydrogen technologies, along with creating the necessary market conditions for penetration, such as the establishment of a refuelling infrastructure (sometimes assumed for the purposes of the modelling exercise).

Significant strengths of forecasting approaches are that they can provide: quantitative targets for technology development (providing a sense of performance and cost necessary to compete successfully); a quantitative consistency check and basis for exploring the importance of different assumptions; and unlike many of the other studies reviewed, they tend to view hydrogen in the context of wider energy systems and competing technologies.

However, forecasts, particularly over long time-horizons, have been widely criticised for an overly deterministic view of the future (Berkhout and Hertin, 2002; Smil, 2000), and of technological change (Geels and Smit, 2000). Such

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[1] This typology has been developed post hoc: the individual studies do not necessarily identify themselves in the way in which they have been classified here.

Table 1
A typology of hydrogen futures

Descriptive	*Forecasts* use formal quantitative extrapolation and modelling to predict likely futures from current trends. *Exploratory scenarios* explore possible futures. They emphasise drivers, and do not specify a predetermined desirable end state towards which must storylines progress. *Technical scenarios* explore possible future technological systems based on hydrogen. They emphasise the technical feasibility and implications of different options, rather than explore how different futures might unfold.
Normative	*Visions* are elaborations of a desirable and (more or less) plausible future. They emphasise the benefits of hydrogen rather than the pathways through which a hydrogen future might be achieved. *Backcasts and pathways* start with a predetermined 'end' point—a desirable and plausible future. They then investigate possible pathways to that point. *Roadmaps* describe a sequence of measures designed to bring about a desirable future. Studies from the previous four groups, or elements of these groups, frequently form the basis for the identification of specific measures, but not always.

Table 2
Studies classified as 'Forecasts'

Forecasts

Study	Brief description
Christidis et al. (2003)	Study using the IPTS Transport Technologies model to explore fuel cell vehicle market penetration with business as usual projections, plus sensitivity to oil price, industry decisions, and carbon policies.
Fukushima et al. (2004)	Uses quantitative model to project diffusion of solid oxide fuel cells for power generation in Japan, exploring sensitivity to technological change, component availability and recycling, and fuel price.
Kosugi et al. (2004)	A survey of expert opinion used to provide predictions of fuel cell technological development.
Mima and Criqui (2003)	Uses New & Renewable Technologies module of the POLES world energy model to forecast penetration of fuel cells into both stationary and mobile applications, and explore the impacts of technology breakthroughs, cheaper natural gas, and carbon policies.
Thomas et al. (1998)	Uses a market penetration model to predict fuel cell vehicle uptake under the California Zero Emission Vehicle mandate, and calculates returns on investment, and social cost/benefit ratios.

criticisms challenge the assumption that new technologies simply replace old ones, without perturbing the technological 'regime' or 'paradigm' in which they operate: creating new markets, new institutions, and new user behaviours and patterns of consumption. By themselves, such forecasts may be of limited use in helping us to understand the complex processes by which large technological systems are transformed.

3.2. Exploratory scenarios

Rather than extrapolating from existing trends, exploratory scenarios seek to inform policy making by illuminating underlying drivers of change, often drawing upon tacit knowledge and expertise, to build internally consistent storylines describing a number of possible futures (Table 3).

The exploratory scenarios reviewed here explore longer-term (2030–2100) futures and include trend-breaking developments. However, whilst the possibility of including 'surprise' elements is thought to be a key strength of the exploratory approach (van Notten et al., 2004; Schwartz, 1996), this possibility was explicitly discussed in only two of the exploratory studies reviewed (Ohi, 2001; Shell, 2001), and not by others which nonetheless invoked trend-breaking changes such as sweeping shifts in social values (Barreto et al., 2003; Di Mario et al., 2003). Similarly, though some authors have emphasised the importance of participatory techniques in exploratory scenario building (e.g. Berkhout and Hertin, 2002), only the studies by Ohi (2001), Watson et al. (2004) and The Australian Government (2003) appear to have involved stakeholders in their development.

Table 3
Studies classified as 'Exploratory Scenarios'

Exploratory scenarios

Study	Brief description
Andersen et al. (2004)	Participatory exercise based on the development of qualitative scenarios to describe possible contexts for hydrogen development, followed by workshops to generate targets for hydrogen technologies.
Australian Government (2003)	Develops qualitative scenarios for high, medium and low hydrogen uptake. Explores the combinations of drivers that might push a hydrogen economy.
Barreto et al. (2003)	Elaborates on the SRES-B1 scenario developed by the IPCC. Hydrogen is introduced in a qualitative scenario, and this is then quantified using MESSAGE-MACRO
Di Mario et al. (2003)	Uses the SRES B1 scenario as a baseline around which two alternative hydrogen scenarios are explored, with low and high hydrogen uptake. Each of the scenarios are then quantified.
Kurani et al. (2003)	Explores the growth in three sets of infrastructure: transport, communications, and power grids, and uses these socio-technical trends to explore the future for FCVs as mobile communications and power platforms.
Ohi (2001)	Three qualitative scenarios, structured around rate of technological change and dominant social values, are used to explore possible futures for hydrogen and R&D strategies that are robust across scenarios.
Shell (2001)	Explores two scenario storylines, one of which describes a possible future for hydrogen arising from a radical innovation in hydrogen storage.
Watson et al. (2004)	Uses the UK DTI Foresight Futures framework to structure four qualitative scenarios. The prospects for hydrogen in each different 'world' are examined and quantified.

Unlike most of the other studies reviewed in this paper, several of the exploratory studies made explicit reference to theories of technological change, such as Geels' multi-level perspective of technological transitions (Geels, 2002a, b; used by Andersen et al., 2004; Watson et al., 2004).

Three of the exploratory studies reviewed develop existing scenario sets e.g. the UK Foresight Futures framework (Watson et al., 2004) and the IPCC SRES scenario B1 (Barreto et al., 2003; Di Mario et al., 2003). These studies explore the potential for hydrogen within their 'parent' scenarios, and use quantitative models (such as MESSAGE-MACRO, POLES, or the purpose-built THESIS) to enrich and help quantify the scenario outputs.

The other exploratory studies develop new scenarios and storylines to explore the conditions under which a hydrogen future might unfold (Andersen et al., 2004; Australian Government, 2003; Kurani et al., 2003; Ohi, 2001; Shell, 2001). This involves identifying sets of drivers that are likely to be important in the future development of hydrogen technologies and the transition to a 'hydrogen economy'. At least one study assumed the presence of strong pro-hydrogen policies, to investigate the implications of such policies in a variety of future worlds (Andersen et al., 2004).

The exploratory scenarios stand out as having more structured approaches to thinking about drivers, although they tend to emphasise those that operate at the 'landscape' level. This approach has been criticised as being overly 'top-down' (Geels, 2002b). However, when considering long time periods it arguably provides a useful means of capturing the broad dimensions of change. Table 2 outlines the dimensions chosen by the eight exploratory scenario studies, such as rate of technological change, or type of governance (Table 4).

An important feature of exploratory scenarios is that the storylines are not supposed to be driven by a preconceived desirable end-point. However, many of the exploratory scenario studies reviewed here include a 'happy ending' storyline, in which CO_2 is dramatically reduced and society is reasonably well off and secure. These scenarios tend to involve rapid technological change integrated with a socially responsible and globally co-ordinated society—with a significant role for hydrogen. This suggests a tendency for such exercises to come up with an unconscious 'favourite'—one that, in this case, is usually decidedly pro-hydrogen.

3.3. Technical scenarios

The approach of these studies is best summed by Hart et al. (2003):

> …the purpose is not to *predict* the uptake of alternative fuels or vehicles…, but to assess the implications of a large-scale move, *should it be attempted.*

These studies explore different possible hydrogen-based technological systems, and assess the implications of these against a range of criteria, such as carbon emissions, cost, and technical feasibility. Technical scenarios are much more specific about the systems envisaged for the future,

Table 4
Major drivers in exploratory scenarios

Study	Dimensions	Assumed correlations
Australian Government (2003)	Rate of economic growth Strength of social & environmental values Rate of technological change Conventional energy price	Economic growth defines energy price, and to a large extent technological change. Environmental values strongest in highest growth world, lowest in low growth world.
Ohi (2001)	Environmental & social activism Rate of technological change	Strong social values can make increased R&D funding politically acceptable, driving faster technological change
Andersen et al. (2004)	Not expressed as 'dimensions for change' in the study itself—these are inferred. Balance of power: market vs. state Severity of climate change impacts Security of oil supplies	Environmental concerns vary according to the market vs state relationship, with the most market-oriented scenario having least concern.
Watson et al. (2004)	Used the dimensions of the UK Foresight: Strength of social & environmental values Governance system: autonomy—globalisation	Assumes that technological change, rates of economic growth, etc are ultimately derived from these fundamental dimensions of change.
Shell (2001)	Resource scarcity Technological advance Social and personal priorities	Assumed correlations not clear
Di Mario et al. (2003)	Used the dimensions of the IPCC Special Report on Emissions Scenarios B1 world only (see above), rates of hydrogen penetration within this determined by government support.	Strong environmental values and globally co-ordinated decision-making allow steady and sustained economic growth.
Kurani et al. (2003)	Explored only one future—characterised by three driving dimensions Growth in mobility Growth in mobile energy demand Growth in mobile communications	Assumed correlation between the three dimensions.
Barreto et al. (2003)	Used the dimensions of the IPCC Special Report on Emissions Scenarios B1 world—high environmental values, strong globally co-ordinated decision-making.	Strong environmental values and globally co-ordinated decision-making allow steady and sustained economic growth.

Table 5
Studies classified as 'Technical Scenarios'

Technical Scenarios	
Study	Brief description
Eyre et al. (2002)	Uses qualitative scenarios to define energy demand conditions in 2050, and then examined the carbon emissions of alternative possible technological systems that would meet that demand.
Hart et al. (2003)	Examines implications of supplying transport energy demand with renewably produced hydrogen or biofuels, given estimates of 2050 transport demand. Models penetration of different combinations of vehicle and fuel technology, and examines the carbon impacts.
Ogden (1999)	Outlines five alternative possible systems that would meet projected transport demand for southern California in 2020, and calculates the investment costs associated with each.
Sørensen et al. (2004)	Describes two possible technological systems based on hydrogen and wind electricity, matching hour by hour electricity demand, and for each system calculates the total wind supply and hydrogen storage system needed to meet that demand.
Winebrake and Creswick (2003)	Uses the Analytic Hierarchy Process to explore the benefits and disadvantages of alternative fuel cell vehicle fuel configurations, and conducts a sensitivity analysis exploring how robust the findings are in the face of different dominant social values.

and how these might work in technological terms. Whilst such studies can make an important contribution to assessing the feasibility and desirability of alternative future systems, they often neglect the social and cultural dimensions of technological change (Table 5).

The future is viewed as a series of more or less static technological options, rather than storylines of technological change. Most of the studies (Eyre et al., 2002; Hart et al., 2003; Ogden, 1999; Sørensen et al., 2004) make assumptions about future demand for energy provided by hydrogen, and model possible systems that would meet that demand. Of the five studies, three investigate the potential for producing hydrogen entirely from renewable resources.

The drivers for change are considered at the macro level of carbon emissions and energy security, while the major barriers identified are the higher costs of hydrogen technologies, and the lack of renewable electricity supplies. However, these studies do not attempt to investigate the dynamics of the transitions to the modelled systems, and therefore do not explore the broader factors that would promote or inhibit particular futures developing, or how a hydrogen infrastructure might develop, as these issues are outside the scope of the analysis.

3.4. Visions

There are two broad types of 'vision' identified in the literature. The first, and the kind with which this section is concerned, are produced by individuals or small groups, outlining a desirable hydrogen future. The second is produced through stakeholder workshops to provide the basis for a 'road-mapping' exercise, and is an attempt to generate a shared picture of a desirable future and way forward. This latter type will be considered under 'Roadmaps' (Table 6).

Table 6
Studies classified as 'Visions'

Visions	
Study	Brief description
Arnason and Sigfusson (2000)	Describes a possible future for Iceland, based on hydrogen and renewably produced methanol.
Bockris (1999)	Describes a solar-hydrogen future for the US
Bossel et al. (2003)	Presents an argument against the use of hydrogen as a fuel, and provides a possible alternative —a synthetic liquid hydrocarbon economy.
Dunn (2001)	Presents hydrogen as the fuel of the future, and describes a vision of what a hydrogen economy will involve.
Goltsov and Veziroglu (2001)	Presents a vision of the 'hydrogen civilisation', a future world posed as the only alternative to continued dependence on fossil fuels.
Lovins and Williams (1999)	Describes a future hydrogen economy, and outlines some of the components of the transition, in the form of super-efficient vehicles and synergy between mobile and stationary power.
Rifkin (2002)	Outlines a decentralised and democratic vision of the future for hydrogen and energy, drawing parallels with the internet, and introducing the concept of the 'hydrogen energy web'.
Schwartz and Randall (2003)	Draws a parallel between the Apollo programme to put a man on the moon, and the challenge of energy independence and hydrogen; describes how hydrogen could become the dominant fuel within a decade.

Vision studies present, often rather utopian, narrative descriptions of a future hydrogen economy. In so doing they aim to show that a hydrogen economy is both plausible and desirable. These studies tend to be rhetorical rather than analytical. Their role is not to analyse or predict the future; the strength of the approach is that they expand the possibilities considered, and create a shared picture of what the future could be. Time scales are generally undefined, although visions are often set further into the future than more formal futures exercises. They also tend to include more 'surprise' elements that break with current trends (e.g. technological breakthroughs, shifts in social values). A notable misfit amongst these studies is a paper by Bossel et al. (2003), which presents a vision of an alternative to hydrogen, the 'liquid synthetic-hydrocarbon economy'.

Generally these visions depict a future where technological, infrastructural and institutional changes go hand-in-hand with a shift towards greener social values and a more egalitarian society. In the more radical examples, the hydrogen economy heralds no less than ‘the redistribution of power on earth’ (Rifkin, 2002). Some even frame a transition to a hydrogen economy as an inevitable development of human ‘progress’—e.g. Dunn (2001).

While some see technological transitions as manageable through R&D investment, demonstration projects, taxes, and strong government leadership (Dunn, 2001; Lovins and Williams, 1999), others invoke a need for major shifts in social values (Goltsov and Veziroglu, 2001), or revolutionary technological breakthroughs (Bockris, 1999). However, most visions do not directly address the dynamics of change or the development of infrastructure.

The macro drivers of the transition to a hydrogen economy are perceived to be its potential societal benefits particularly with respect to climate change, but also fossil fuel depletion, energy security, air pollution, and ‘geo-political dominance’. However, at a meso/micro level, government actions and policy measures, such as funding for demonstration projects, tax regimes, and education programs, are seen as critical to shaping the emergence of a hydrogen economy. Other ‘micro’ drivers include the development of renewable energy and hydrogen technologies, and potential synergies between building and vehicle energy use.

The degree of commonality amongst visions is striking, not least because they tend to gloss over potential areas of disagreement, such as the potential role of carbon sequestration or nuclear power. All the visions, with the exception of Bossel et al. (2003), see an eventual transition to a system in which hydrogen and electricity are predominant energy carriers, and are used more or less interchangeably. Vehicles will be fuelled by direct hydrogen, not synthetic or fossil hydrocarbons. Hydrogen provides the ‘missing link’ for intermittent renewables, allowing the entire world to move to a zero carbon economy. A weakness of the visions is that they tend to gloss over areas of disagreement (such as roles for carbon sequestration or nuclear power), and potential pitfalls or disadvantages associated with the development of a hydrogen economy.

3.5. *Backcasts & pathways*

These studies all start with the assumption that some form of hydrogen economy is desirable, and investigate possible paths by which the transition to that hydrogen future might be attained. Indeed, this attention transition issues is a key strength of these studies. This normative scenario process is in the spirit of backcasting, in which a future vision is elaborated, and storylines work back from that vision to the present (Robinson, 1982). However, none of these studies represent extensive backcasting studies, nor do any refer explicitly to the methodological literature on backcasting or scenario building more generally. For most, a clear picture of a future hydrogen economy remains undefined, though goals are sometimes expressed as targets (e.g. California Fuel Cell Partnership target for number of fuel cell vehicles (FCVs) on the road) (Table 7).

Table 7
Studies classified as ‘Backcasts & Pathways’

Backcasts & Pathways	
Study	Brief description
California Fuel Cell Partnership (2001)	Outlines criteria for defining successful commercialisation, and then explores specific barriers and threats to achieving that success, and four possible transition pathways based on four different fuels: hydrogen, methanol, gasoline, and ethanol.
Foley (2001)	Explores policies and pathways by which hydrogen might be introduced into transport.
Fuel Cells UK (2003)	Presents a vision of the future for fuel cells in the UK, and explores the important trends that will set the context for the transition towards that vision.
Mauro et al. (1996)	Presents two alternative transition routes to a hydrogen economy, a centralised route, and a decentralised ‘village path’, exploring the potential for off-grid and remote community applications.
Owen and Gordon (2002)	Technical analysis of two routes towards commercially viable fuel cell vehicles, and evaluation of the alternative routes in terms of well-to-wheels carbon emissions.
Wurster (2002)	Explores how a hydrogen refuelling infrastructure might develop.

Typical time scales range from 2020 to 2050. Only the California study considers the possible effects of ‘surprise’ and discontinuities. Despite the attention to transition issues, few appear to draw explicitly on theoretical literatures on change in large technological systems. Most rely on a simple technology push/market pull models of technological change. An exception is Farrell et al. (2001), which is heavily informed by the multi-level ‘technological transitions’ theory of Geels (2002a, b).

3.6. *Roadmaps*

Like backcasts, roadmaps assume the desirability of hydrogen, often defining a (usually vague) vision, and outlining a series of steps to get there. The difference with backcasts/pathways is in the way that roadmaps view the future, as explained below (Table 8).

In general, assumptions about the future are not made explicit or explored, leaving ‘business as usual’, or the continuation of current trends as a default perspective. Unlike in other futures studies, the future is described only in terms of the actions to be taken and the targets to be met, rather than elaborating broader aspects of a future world, or describing storylines. The future is treated instrumentally, as a ‘policy problem’, with the emphasis placed on what is to be achieved.

Most of these roadmaps combine three important aims. Firstly, to identify barriers to the emergence of a hydrogen future and the measures needed to overcome them. They explore and, often graphically, communicate the relationships between future markets, technologies and policies (Phaal et al., 2003). Secondly, most fulfil an advocacy function. As a result it has been suggested that many roadmaps create unrealistically rosy expectations of a

Table 8
Studies classified as 'Roadmaps'

Roadmaps	
Study	Brief description
DTI (2004)	Outlines the actions and decision points for the development of hydrogen technologies
EST (2002)	Outlines steps that need to be taken in 2005, 2010, and 2020 in order to achieve low carbon transport in the UK.
Fuel Cells Canada (2003)	Stakeholder workshop process used to generate targets and milestones in key areas for fuel cell development, and to develop a strategic action plan outlining specific measures.
Greater London Authority (2002)	Describes a series of actions for the Greater London Authority to promote the development of hydrogen in London.
Hynet (2004)	Builds on a hydrogen vision for Europe, and outlines timelines and necessary action for the visions to be realised.
US NHA (2004)	A study based on workshops to identify key goals for hydrogen commercialisation, and barriers and solutions to those goals, in order to produce a realistic and plausible roadmap for hydrogen development.
Toshiaki (2003)	Presentation outlining Japan's strategic targets for fuel cell and hydrogen development.
US Department of Energy (2002)	Roadmap developed through stakeholder workshop process, outlining key targets and milestones in the development of a US hydrogen economy.

technology's future (Geels and Smit, 2000). Lastly, the roadmapping process seeks to bring together key stakeholders to develop a shared vision of the future: a common 'script', defining agreed roles and cues for action. Whilst this may also be an implicit function of other types of scenario studies, it is an explicit aim of many roadmapping initiatives.

The great strength of the roadmapping approach is the identification of barriers and solutions to them, and generation of shared targets. While the process itself is often important in terms of bringing together stakeholders in a common strategic forum, the final roadmap itself also provides a measure against which progress can be measured.

Building a roadmap usually involves groups of stakeholders identifying the drivers, barriers, targets, and wider threats and opportunities. Some roadmaps are less inclusive, and are produced by advocates of particular policy routes. The approach is very pragmatic. Policies are usually identified for the short term (5–10 years), with targets mapped out over the longer term (up to 2050 and beyond). Such studies are often dominated by rather linear market pull/technology push perspectives.

4. What does the literature say about a hydrogen future?

Having outlined the main types of hydrogen futures studies, the following section examines what this literature tells us by examining the answers it provides to a series of specific questions about the future of the hydrogen economy.

4.1. What are the drivers of a hydrogen economy?

The literature revealed divergent views on the factors that will shape the future of hydrogen energy. In many of the visions and exploratory scenarios, for example, the development of a hydrogen future is explicitly seen as being driven by shifting social values, particularly the emergence of stronger environmental values, but also greater concern for social equity: the latter being perceived to underpin a shift away from centralised energy production and distribution towards more distributed forms of generation.

Many of the visions suggest that the major technological barriers have been overcome, or are readily solvable, as long as the political will is there to provide funding and support (e.g. Dunn, 2001; Lovins and Williams, 1999; Goltsov and Veziroglu, 2001; Rifkin, 2002). These studies frame the hydrogen economy as an issue of politics—held back only by the inability of governments to take a lead.

In contrast, many other studies focus on technological drivers (Bockris, 1999; Bossel et al., 2003; Kosugi et al., 2004; Owen and Gordon, 2002). Some of these make the implicit assumption that 'if it works', the hydrogen economy will be realised, while others focus on costs, working on the principle that it has to 'work' at a price that is competitive with conventional technologies (Mima and Criqui, 2003; Thomas et al., 1998).

The literature also includes divergent views on the level at which driving factors should be considered. This means that the term 'drivers' has many interpretations, just as the terms 'scenario', 'vision' and 'roadmap' are used in a variety of different contexts. Exploratory scenarios consider drivers to be broader societal changes (social values, rate of technological change etc), while other studies defined government intervention and investment in R&D as a driver, or specific market demands, such as that for backup power.

However, four overarching problems or policy objectives consistently stand out in the literature as providing the underlying drivers of a transition to a hydrogen future. These are:

Climate change: Reducing carbon dioxide emissions is clearly considered to be the most important of these. Climate change is cited by all of the studies reviewed. Indeed, seven of the studies refer only to climate change as a reason for a transition to a hydrogen economy.

Energy security: This encompasses a range of concerns over the finite nature of oil and gas reserves, their geopolitical sensitivity and location, energy prices, and vulnerability of centralised energy systems to attack. No studies focused exclusively on this aspect, and 18 made no mention of energy security at all. Of the studies that emphasise energy security (Arnason and Sigfusson, 2000; Australian Government, 2003; DTI, 2004; Dunn, 2001; US

NHA, 2004; Rifkin, 2002; US Department of Energy, 2002), most are roadmaps or visions.

Local air quality: Many studies cited reductions in local air pollution as a significant benefit of a transition to a hydrogen economy, though only regionally focused studies, such as those from London and California (California Fuel Cell Partnership, 2001; London Hydrogen Action Plan, 2002; Ogden, 1999; Thomas et al., 1998) gave this factor particular emphasis.

Competitiveness: Seven studies refer to international competitiveness as an important driver in the transition towards a hydrogen economy (Australian Government, 2003; Fuel Cells Canada, 2003; Fuel Cells UK, 2003; Greater London Authority, 2002; HyNet, 2004; Owen and Gordon, 2002; US Department of Energy, 2002).

A final less frequently cited objective is the potential of FCVs to reduce noise pollution in urban areas.

4.2. *Barriers & challenges*

The literature recognises a diverse range of barriers to the development a hydrogen economy. The three most prominent are:

- The absence of a hydrogen refuelling infrastructure—the difficulty of establishing a market for FCVs in the absence of a refuelling infrastructure—and vice versa.
- High costs: particularly of fuel cells and of low-carbon hydrogen production.
- Technological immaturity: hydrogen on-board storage and consequent limited current driving range of hydrogen vehicles; limited life-time of fuel cells. Several other technological challenges are specific to particular hydrogen futures, and will be discussed in the context of the differing technological architectures envisaged for hydrogen in Section 4.4.

Other frequently cited barriers include safety, public acceptability, and the absence of codes and standards.

There are also many barriers that are picked up by only a few studies, including: the absence of surplus renewable electricity; social values that disregard the environment; a regulatory framework that currently supports fossil fuels; ability of incumbent technologies to adapt in the face of competition from hydrogen; limited skills base; absence of global co-operation or plan of action; limited availability of fuel cell components, particularly platinum; difficulty of technological developers in accessing capital; lack of demand for hydrogen products; and, social opposition, uncertainty over viability and costs of carbon sequestration.

4.3. *In what kinds of future does hydrogen become important?*

The exploratory scenarios are rather consistent. Hydrogen emerges in future worlds where there is medium-strong economic growth, associated with rapid technological development; and when

(a) concerns about the environment are strong, especially when climate change becomes obvious;
or,
(b) when traditional energy supplies are expensive or vulnerable.

Hydrogen does not emerge in worlds dominated by market rather than social values; where climate change impacts are small; where technological development is slow; and when economic growth stagnates. The development of hydrogen is patchy in worlds of strong regional autonomy, with strong uptake locally only in areas without significant oil or gas reserves.

4.3.1. *Does a hydrogen future rely on 'step-changes'?*

It is noteworthy that hydrogen generally emerges slowly or not at all in 'Business as Usual' type scenarios (Andersen et al., 2004; Australian Government, 2003; Di Mario et al., 2003; Owen and Gordon, 2002; Mima and Criqui, 2003; Ohi, 2001).

In contrast, rapid penetration of hydrogen occurs only when there is strong government support (although typically even this is not seen as a sufficient condition: Andersen et al., 2004; Di Mario et al., 2003), or major 'discontinuities', such as shifts in social values (Di Mario et al., 2003; Ohi, 2001), technological breakthroughs that radically reduce costs (Ohi, 2001), shifts in the relative price of oil (Andersen et al., 2004), or increases in the speed and intensity of climate change.

4.4. *What does the hydrogen economy look like?*

The drivers, barriers and challenges outlined above shape a wide range of possible hydrogen economies, involving different technological trajectories and 'architectures', demonstrating very different conceptions of what is meant by a 'hydrogen economy'. Only some (19) of the studies provide detail about the sources, uses and modes of distribution of energy in a hydrogen future. Of those that do, most fall into one of two broad technological architectures: decentralised or centralised, as illustrated below (Fig. 1).

4.4.1. *Decentralised architectures*

These architectures are based on local production of hydrogen, from electrolysis, biomass processes, or steam reforming of natural gas. Some decentralised systems envisage hydrogen production from local energy sources (such as small-scale biomass conversion, or 'micro' renewables) while others see *energy* production as remaining centralised, with energy transferred to hydrogen production units (in homes or on forecourts) either as electricity or natural gas. Decentralised hydrogen production overcomes

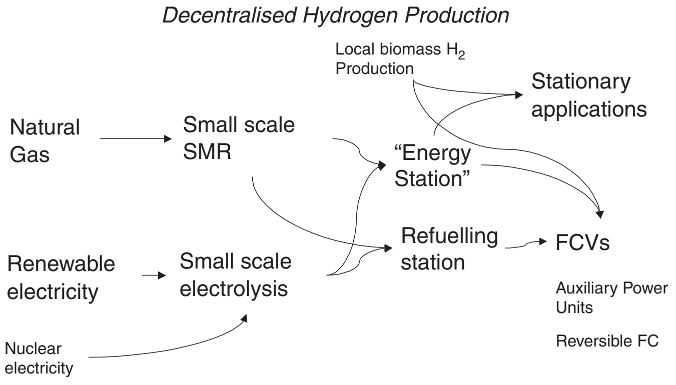

Fig. 1. Shows common building blocks of decentralised hydrogen production systems. Text size of each building block indicates the number of studies that envisage a role for it. Key technologies: small-scale electrolysis and steam methane reforming of natural gas (SMR), renewables, 'energy station' stationary systems, FCVs.

many of the infrastructural barriers facing a transition to hydrogen.

Some studies (Foley, 2001; US NHA, 2004), particularly those with a focus on road transport, see on-site hydrogen production as a transitional phase (for discussion of how these technological architectures change, see below). For others, decentralisation is a key feature of the hydrogen economy, allowing the benefits of distributed generation, home refuelling, and even the 'democratisation of energy'—empowering people by giving them control of energy (Rifkin, 2002). Some of the decentralised systems involve synergy between the transport and heat & power sectors, with FCVs both providing mobile power and selling power to the grid at times of peak demand (Australian Government, 2003; Barreto et al., 2003; Dunn, 2001; Lovins and Williams, 1999).

4.4.2. Centralised architectures

A centralised system can draw on a wider variety of energy sources than decentralised systems (coal gasification and nuclear thermal hydrogen generation, for example, are largely incompatible with decentralised systems) but it depends on the development of a dedicated hydrogen distribution infrastructure. Many of the centralised systems focus on hydrogen use in road transport, and envisage local hydrogen pipeline grids linking early demonstration projects and fleet vehicle refuelling depots, creating 'hydrogen corridors' in areas of high demand (Fig. 2).

A third technological architecture, described by Bossel et al. (2003) and Arnason and Sigfusson (2000), involves the use of hydrogen and captured carbon to synthesise liquid hydrocarbon fuels, such as methanol. These liquid hydrocarbon fuels can then be used in FCVs with on-board reforming. It is argued that this can be compatible with a low-carbon hydrogen economy, since the carbon for the fuel is captured from other sources (such as industrial emissions from metals processing (Arnason and Sigfusson, 2000), or biomass (Bossel et al., 2003).

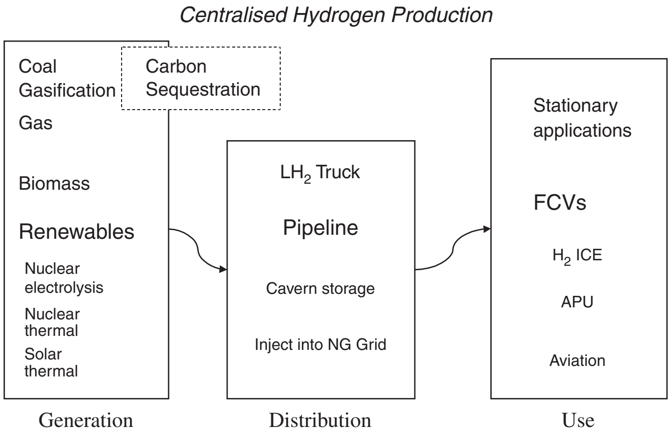

Fig. 2. Shows common building blocks of centralised hydrogen production systems. Text size of each building block indicates the number of studies that envisage a role for it. Key technologies: carbon sequestration, pipelines, renewables, biomass, FCVs, stationary fuel cells.

Other very different technological architectures are possible, e.g. the Shell scenarios, initially at least, envisage hydrogen sold 'in a box' as a fuel cartridge, which it is claimed breaks current distribution and infrastructure paradigms (Shell, 2001).

Many studies envisage a final mix of centralised and decentralised architectures, with pipelines in areas of strong demand, and with both centralised and decentralised production supplying the hydrogen market, or see one as a precursor to the other.

4.4.3. Each architecture is dependent on key technological building blocks

If government or industry support a particular architecture, or simply expect a particular architecture to emerge, R&D will prioritise particular technological challenges, which may be irrelevant for other possible architectures. This highlights the role that expectations and visions of the future can play in directing technological change—a vision of a future architecture defines the technological challenges in the present.

The corollary of this is that a technological 'breakthrough' may lead to a particular architecture becoming dominant. For example, the development of low-cost liquid hydrogen storage, or a (perceived) failure of solid storage and high-pressure tanks, could rule out decentralised systems, given the technological difficulties of small-scale liquefaction. Similarly, a breakthrough in on-board reforming could make the synthetic liquid hydrocarbon route more attractive, obviating the need for on-board hydrogen storage. Breakthroughs in key technologies could thus produce 'emerging irreversibilities', leading to 'lock-in' or 'path dependency' (see Arthur, 1989; David, 1985; Rip and Schot, 2003), a phenomenon cited by some authors as a reason to avoid R&D in particular technologies, such as on-board methanol refuelling (Lovins and Williams, 1999; US NHA, 2004).

For decentralised systems, the major technological challenge is the expense of hydrogen from small-scale natural gas reformers and electrolysers, while centralised systems rely on the viability of a large-scale hydrogen distribution infrastructure, and prospects for centralised systems are greatly enhanced by cost-effective coal gasification or nuclear–thermal water splitting.

Additional technological developments are necessary for the envisaged hydrogen economies to be low-carbon: plentiful and competitive renewable electricity, carbon sequestration, or nuclear power. While fossil fuels are seen by most studies as transitional, some envisage a long-term role for fossil fuels based on sequestration.

Key technologies for all pathways include improved fuel cell power density and longevity, improved fuel cell economics, and fuel storage. Compressed hydrogen is seen as the most likely option by most studies, though solid state storage is thought to be a possible long-term solution. Liquid hydrogen storage is considered to have a transitional role in some studies.

The basis on which studies reject particular building blocks varies, from the 'purely technological' rejection of liquid storage as hopelessly energetically inefficient, to the rejection of components that fail to meet policy goals. For example, studies with an emphasis on climate change reject carbon-emitting hydrogen technologies, while studies concerned with energy security focus on nationally abundant resources, such as coal in the United States and Australia, wind in Denmark, and hydroelectricity in Iceland.

In summary, the literature envisages a range of hydrogen economies, which are described in terms of alternative technological architectures. The future of hydrogen is thus contested. The roles of carbon sequestration, nuclear energy, renewable electricity, on-board reforming of hydrocarbons and the viability of pipelines and trucked hydrogen are all areas of particular debate and uncertainty. The basis on which different elements, or 'building blocks', are included or rejected varies, but there are also shared elements. Almost all include fuel cell vehicles, and most include strong roles for renewables. Steam methane reforming is widely expected to be the principal method of producing hydrogen over the short-to-medium term. Finally, it should be noted that crucial technological details are often omitted. For example, many studies suggest a role for fuel cells in distributed electricity generation, but do not specify the type of fuel cell, or fuel used.

4.5. Evolution of hydrogen economies

As noted above much of the literature seeks to illuminate pathways to a hydrogen future. Whilst there is considerable variation in the transition paths described, a number of patterns are apparent:

(1) From decentralised to centralised: Most studies see the decentralised route as the key to by-passing the infrastructural problem, but some (e.g. US Department of Energy, 2002) see centralised production as coming first, through the 'link-up' of demonstration projects and the creation of 'hydrogen highways' or 'corridors' fuelled with industrially produced hydrogen.

(2) From fossil fuels to renewables: Most studies see the ultimate hydrogen economy as fuelled entirely by renewables, with electricity and hydrogen as the dominant, and largely interchangeable energy carriers. Fossil fuels, and nuclear, are described, in some studies, as transitional technologies, or 'bridges'.

There are also disagreements about system evolution. There is broad agreement that fleet vehicles, refuelled at depots, will be the most likely entry point of hydrogen into road transport (despite evidence from other alternative fuels that fleets may be poor early markets; McNutt and Rodgers, 2004). However, there is marked disagreement about the types of fuel cell vehicles that will be first to enter the market. One line of argument is that the technology exists for small passenger cars to decrease greatly in weight, thus to some extent reducing the power and storage requirements of fuel cell systems, and that such 'hypercars' are the ideal strategy for a hydrogen transition (Lovins and Williams, 1999). Others argue that large heavy goods vehicles are more appropriate early adopters, since the space and weight requirements are less stringent—especially true for shipping (Arnason and Sigfusson, 2000; Farrell et al., 2001). The ability of fuel cells to provide auxiliary power for services (especially IT) inside luxury and large vehicles (such as SUVs), could provide convenience that will offset minor losses in driving range and performance (Kurani et al., 2003).

Another area of disagreement concerns the sequence of introduction of FCVs and stationary fuel cells, with views differing about which are likely to enter and dominate markets first.

4.6. Early learning: the importance of niche markets in technology development

A variety of early niche markets are either recognised or advocated as providing an important stage for the development of a hydrogen economy. Most of these early markets or technologies are described as overcoming cost barriers, by providing niche applications that allow learning and scale economies, as well as increasing public familiarity. The role of learning in niche applications is stressed in many approaches to technological change (e.g. Kemp et al., 1998).

(1) H_2 Internal Combustion Engine vehicles—hydrogen ICEs are far cheaper than FCVs, and are likely to remain so for some years. Their adoption could provide low pollution vehicles that help stimulate a market for hydrogen, and provide a means for public familiarity with hydrogen as a fuel.

(2) Portable electronics and consumer goods—widely seen as the most likely early fuel cell market, growth in micro and small fuel cell sales is thought likely to help drive down fuel cell prices, and push fuel cell acceptability and familiarity.
(3) Remote and off-grid power—would bring down FC system costs, allowing cheaper small-scale electrolysis or steam methane reforming.
(4) Premium/backup power—as above. It is argued that stationary fuel cells for backup or premium power, using the 'energy station' concept described above, could potentially become nodes for hydrogen refuelling.
(5) Injection of hydrogen into natural gas mix (up to 20%), and either using the mixture directly to lower emissions, or separate the gas and hydrogen, and using the natural gas network as a nascent hydrogen pipeline network (Andersen et al., 2004).
(6) Auxiliary power units (APUs) for vehicles—APUs would provide electricity in vehicles much more efficiently than current systems, and remain available when the engine is off, making them attractive to the military and long-haul trucks in particular (Lutsey et al., 2003). The cost challenges for APUs are much less daunting than for automotive cells.
(7) Ships—not constrained by size and weight as much as passenger cars, so storage is less of an issue. Can provide both reductions in fuel cell costs, and learning processes that will stimulate progress (Farrell et al., 2001).
(8) Demonstration projects—currently the largest market for fuel cells. Public authorities and companies eager to demonstrate commitment to high technology and green values are providing a niche demand for fuel cells, allowing cost improvements through scale economies and learning.

4.7. When does a hydrogen economy emerge?

Fig. 3 above sketches the estimates made for the transition to fuel cell vehicles, a 'building block' common to all but a few of the hydrogen futures studies. We have included estimates from two studies that were not included in the review, as their major focus is other than hydrogen (IEA, 2003; RAC, 2002). The chart is a graphical aid, rather than formal plotting of estimates (the *Y*-axis is not standardised and is inevitably somewhat subjective), but serves to illustrate both the diversity of views on a likely timetable for transition, and some common threads. The chart shows predictions of what is likely or possible, rather than proposed targets, which have not been plotted. Where studies straddle categories along the *Y*-axis, different possible futures were considered in the study with differing levels of FCV penetration, each assumed to be equally likely.

4.8. Policies

Many studies recommend particular policy paths, and a number of approaches are evident. At one extreme, one study advocates "the formation of a new environmental consciousness of the general public of all countries…based on scientific, highly reliable predictions" (Goltsov and Veziroglu, 2001). Other studies, rather more prosaically, propose the variety of specific measures outlined below.

The four most commonly advocated policy measures are:

- increased R&D funding (often targeted at specific problems, particularly storage);
- public education programmes;
- infrastructure development (sometimes through establishment and 'link up' of demonstration projects);
- tax incentives for hydrogen fuel and vehicles.

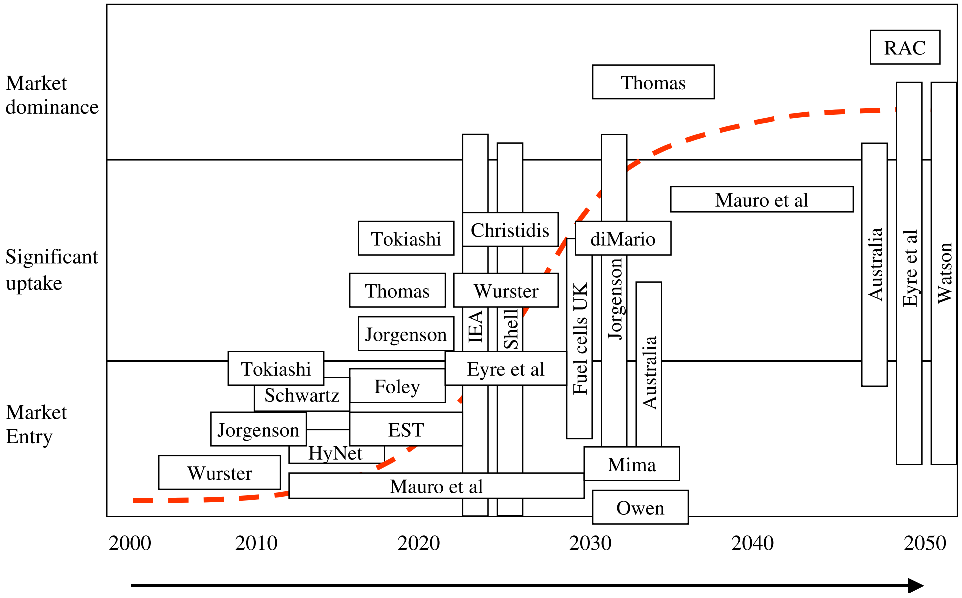

Fig. 3. Shows estimated dates for a transition to a fuel cell based transport system.

Other commonly recommended policies include: the development of codes & standards; mandates for zero emission vehicles; promotion of hydrogen through government and industry champions; clear government support to stimulate confidence and attract investment. Other recommendations include support for renewables; development and dissemination of a clear 'transition strategy' to provide confidence and reduce uncertainty; targets for low carbon vehicles; and improving the fuel cells skills base.

In the policy recommendations proposed, there is a tension between the risks of 'winner-picking', and of 'lock-in'. A winner picking strategy, involving definition of the technologies of the future, is high risk and arguably unrealistic—we can never know the best technology in advance. Conversely, an incremental approach, avoiding picking winners by providing a goal-oriented policy framework (e.g. incentives for low carbon vehicles), may be subject to 'lock-in' to current technological trajectories, which only winner-picking policies can break.

4.9. What does a hydrogen economy achieve?

Six studies address the extent to which a transition to a hydrogen future will ameliorate CO_2 emissions (Barreto et al., 2003; Di Mario et al., 2003; Eyre et al., 2002; Hart et al., 2003; Owen and Gordon, 2002; Watson et al., 2004). All conclude that hydrogen, and in particular fuel cell vehicles, can make a significant impact on reducing carbon emissions in the long term. However, three of these (Eyre et al., 2002; Hart et al., 2003; Owen and Gordon, 2002) suggested that the benefits from a transfer to hydrogen will only occur after 2030–2050, and that moving to a hydrogen-based road transport system before this is likely to increase total carbon emissions (either on a wells-to-wheels basis, or through the displacement of carbon gains from renewable electricity).

5. Discussion and conclusions

5.1. Futures in hydrogen: the state of the art

The literature reveals a range of sophisticated models, exploratory narrative techniques, simplistic trend extrapolations, rhetorical arguments, and strategic plans. Very few used participatory techniques, with the notable exception of many roadmaps, and two of the exploratory studies. None of the backcast studies represented a major and theoretically grounded backcasting exercise. Of all the studies describing hydrogen futures, only four made any reference to theoretical literatures of technological change.

The six types of study reveal five ways of considering and understanding the future of hydrogen energy and hydrogen technologies:

(i) as a product competing in a largely context-free market place (forecasts);
(ii) as a possibility among many as broader changes in society unfold (exploratory scenarios);
(iii) as a sequence of possible technological systems or architectures. (technical scenarios);
(iv) as a normative vision of a future world, in which hydrogen saves society (visions);
(v) as a solution to specific problems, and thus a policy goal (backcasts and roadmaps).

5.1.1. What is wrong with the hydrogen futurist's toolbox?

- The general lack of theory leads to several of the common futures 'pitfalls' identified by Geels and Smit (2000): for example, determinism and a pre-occupation with new, 'exotic' technologies. Furthermore, many of the studies that lack a theoretical background model the effects of technology policies in their depiction of a hydrogen transition, making assumptions about the effects of policies on innovation and diffusion of new technologies, but without making the basis for these assumptions explicit.
- Lack of transparency and participation.
- Lack of distinctness or clarity in the roadmaps.
- Predictions, forecasts and targets are recycled in the literature, deployed as arguments to confirm particular views of the future, rather than treated as best guesses under uncertainty, and targets tend to be recycled as predictions (e.g. the London Hydrogen Action Plan picks up targets from the Japanese Vision).
- The literature tends to provide a rather top down view, emphasising global and national drivers whilst paying little attention to the local challenges and opportunities associated with particular geographical areas.
- Few studies seek to systematically assess the broader sustainability impacts of a large-scale transition to a hydrogen economy. So for example there is little attempt to deal with product life-cycle and waste/de-commissioning issues—such as the possible toxicity of fuel cell components or hydrogen storage materials.
- Many of the studies reviewed tend to treat prospective developments in hydrogen in relative isolation, rather than as embedded features of overarching energy and transport systems. As a result they tend to give insufficient attention to the broader systems changes required for the envisaged hydrogen futures to be achieved, for example with respect to the primary energy basis of particular Hydrogen routes.

Moreover, many of the descriptive futures appear to display a pro-hydrogen bias, as is clear from the way that barriers to a hydrogen transition are considered. For example, the difficulty of storing hydrogen, a function of its low mass, is framed not as a disadvantage, but as a technological 'challenge'.

On the basis of the above one could argue that there is a need for more critical theoretically informed studies, explicitly addressing the sustainability, energy and transport policy implications, and socio-technological dynamics of the transition hydrogen. However, this criticism needs to be set against the broader function of much of this literature in stimulating imaginative thinking and so 'opening up' different possible socio-economic and technological futures, rather than 'closing down' possible options on the basis of inevitably incomplete knowledge. Furthermore, whilst this review has drawn attention to the lack of rigour in the treatment of technological change and socio-technical transitions found in much of the hydrogen futures literature, one needs to balance this against the limited predictive utility of current theoretical approaches to these issues.

5.1.2. What can we learn from the hydrogen futures literature?

The literature represents a rich resource describing the diversity of opinions about possible and desirable hydrogen futures, demonstrating that the hydrogen economy is not a simple, single idea. Moreover, this diversity of opinions extends beyond possible hydrogen systems, and includes the criteria on which those systems are understood and evaluated, implying that purely technological understandings alone will be unable to define a single 'sustainable hydrogen economy'.

More specifically, the questions explored in Section 4 provide insights into specific areas:

- Amidst a range of opinions about the types of factor that will shape the future of hydrogen, four major policy drivers are evident in the literature: climate change, energy security, air pollution, and perceived competitive advantage in developing hydrogen technologies.
- Three major barriers are also clear: infrastructure, technological immaturity, and cost.
- In 'business as usual' scenarios, hydrogen emerges slowly or not at all. In this literature, hydrogen only emerges quickly where governments take strong action in the face of climate change or security fears, or radical technological or social change occur.
- There is no agreement on what a 'hydrogen economy' might look like.
- Despite uncertainty about how a hydrogen economy will emerge and evolve, a series of 'promising niches' were identified as playing important roles in a transition. Widely divergent views exist on the likely dates of 'market entry' for fuel cell vehicles.
- There is considerable uncertainty over what, in terms of greenhouse gas emissions, a transition to hydrogen energy would achieve in the short to medium term.

5.2. Conclusion: no hydrogen economy, but many hydrogen economies

Shared visions and expectations of the future can be powerful forces in the shaping of technology, directing and constraining research efforts by providing a mental map of future 'possibility space'; recruiting support; mobilising resources; and providing a 'protected space' for new and emergent technologies, whose future promise can do much to offset their present poor performance (Geels and Smit, 2000; van Lente, 1993). The Hydrogen Economy is one such vision, yet the range of possible hydrogen economies depicted in this review demonstrate that the shape of a future hydrogen economy is contested rather than shared. Key disagreements focus on the sources of hydrogen, with disputes over the roles of nuclear power and carbon sequestration, while another set of disagreements focus on the configuration of infrastructure.

It may be that the indistinctness of the 'hydrogen economy' is part of the key to its rhetorical power. Berkhout (2004), borrowing a phrase from Bijker's work on the Social Construction of Technology (Bijker, 1995), claims that visions with greater '*interpretive flexibility*' have a greater ability to compete among multiple possible images of the future. This could help explain why many of the roadmaps fail to specify what is meant by a hydrogen economy—their very vagueness allows hydrogen to become 'all things to all men'.

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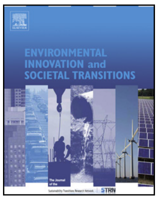

Are scenarios of hydrogen vehicle adoption optimistic? A comparison with historical analogies

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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

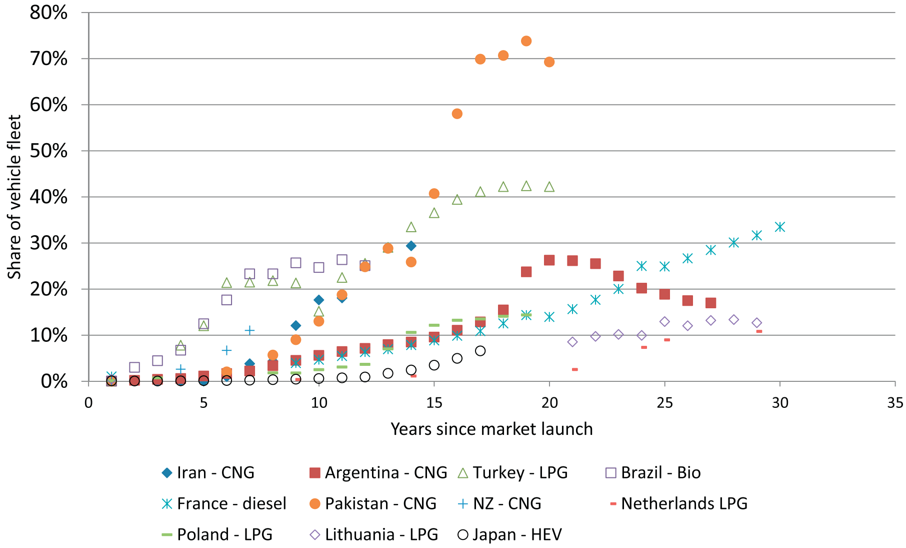

Fig. 1. Alternative vehicles as a share of the vehicle fleet: 11 historical analogies.

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.

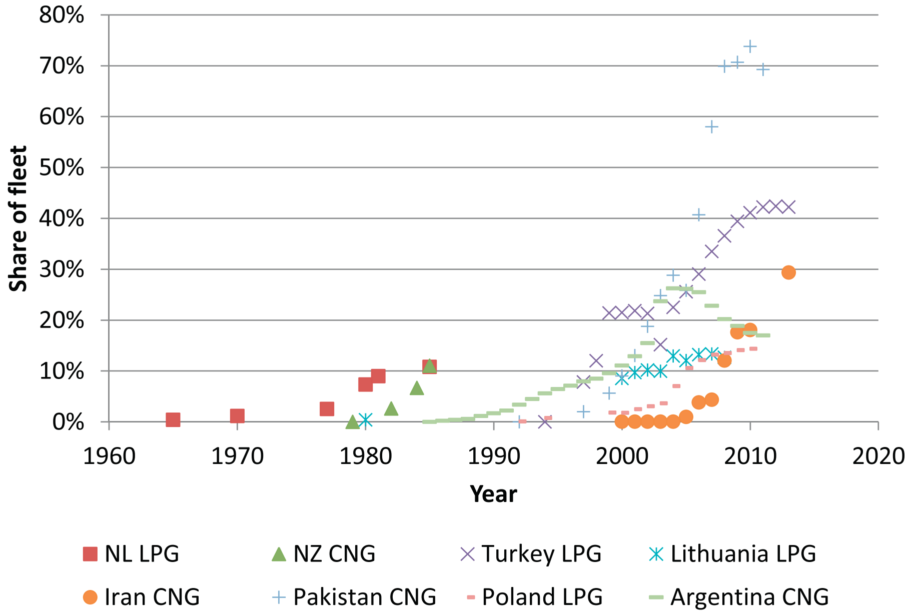

Fig. 2. LPG and CNG transitions.

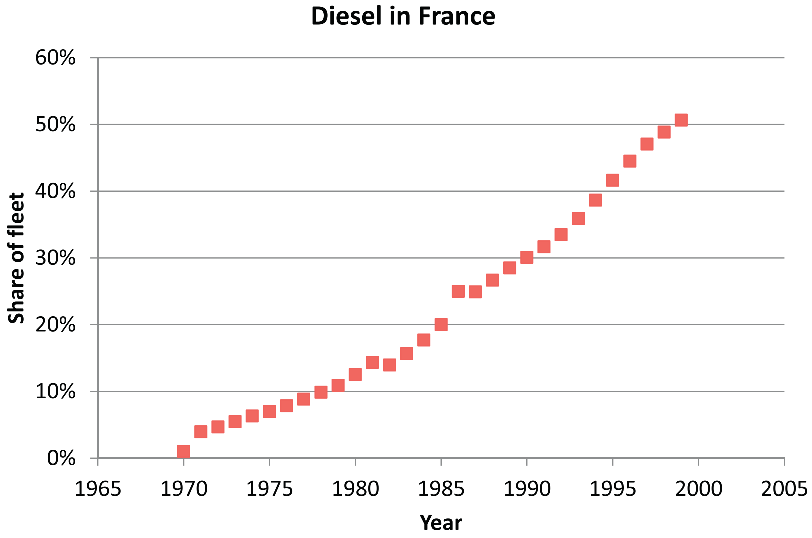

Fig. 3. Diesel car adoption in France.

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.

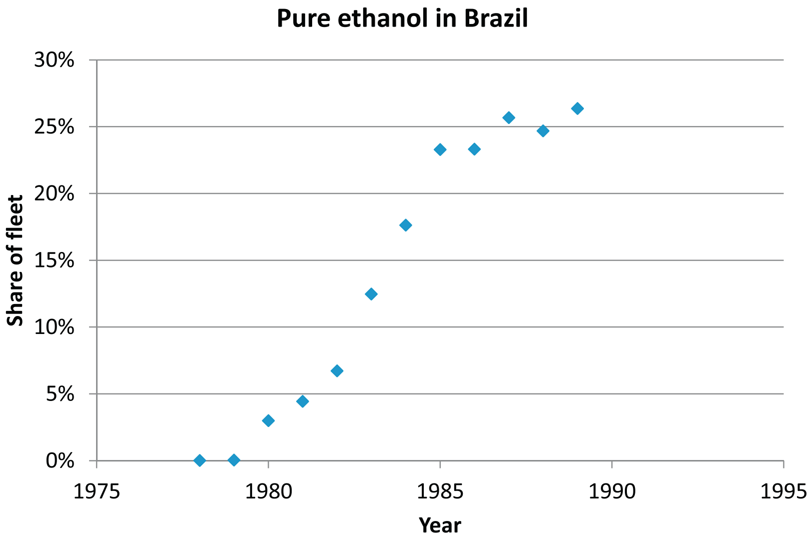

Fig. 4. Adoption of pure-ethanol cars in Brazil.

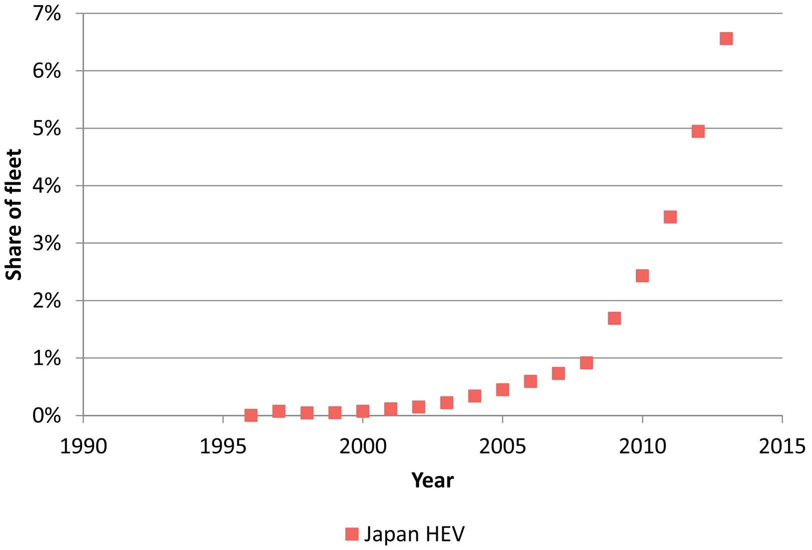

Fig. 5. Hybrid vehicle diffusion in Japan.

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

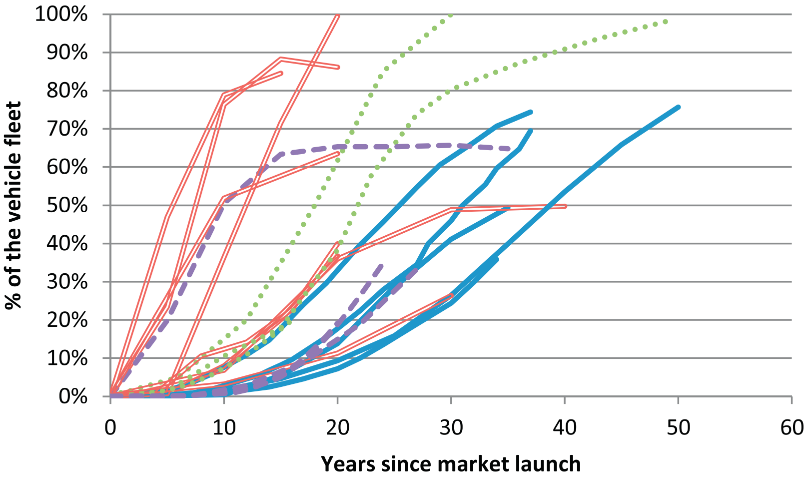

Fig. 6. Transitions in the literature: proportion of the vehicle stock that is hydrogen vehicles in the futures examined. The figure shows stakeholder based studies (solid blue), scenarios assumed as inputs into other analysis (green dots), dedicated hydrogen transition models (purple dashes) and energy 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'.

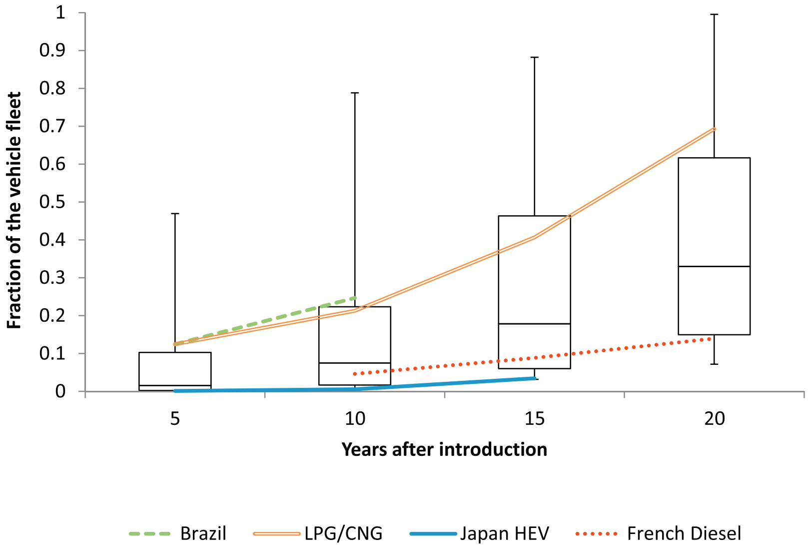

Fig. 7. Box-and-whisker plot showing the range of forecasts in the hydrogen futures literature. Boxes show the interquartile range, intersected by the median, while the whiskers show the minima and maxima. Lines show the fastest historical analogues in each group.

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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Technology roadmaps for transition management: The case of hydrogen energy

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ABSTRACT

Technology roadmaps are increasingly used by governments to inform and promote technological transitions, such as a transition to a hydrogen energy system. This paper develops a framework for understanding how current roadmapping practice relates to emerging theories of the governance of systems innovation. In applying this framework to a case study of hydrogen roadmaps, the paper finds that roadmapping for transitions needs to place greater emphasis on ensuring good quality and transparent analytic and participatory procedures. To be most useful, roadmaps should be embedded within institutional structures that enable the incorporation of learning and re-evaluation, but in practice most transition roadmaps are one-off exercises.

1. Introduction: roadmaps, transitions and hydrogen

Technology roadmaps have become ubiquitous in discussions of long term energy technology policy. Indeed, technology roadmapping has found a place at the heart of global policy efforts for a low-carbon future: In 2008, the G8 and Major Economies declared "We also note the value of technology roadmaps as tools to promote continuous investment and cooperation in clean energy research, development, demonstration, and deployment." [1].

Increasingly, technology roadmaps are developed for major socio-technical systems changes, or technological transitions. This paper examines the role of technology roadmaps as instruments in the governance of such long-term transitions. To do this, it draws on a large literature on socio-technical change that has developed over recent years, but that has done so largely independently of the literature on roadmapping. This paper seeks to bring together these separate but related strands of research, and make recommendations for the practice of roadmapping in transition policy.

To illustrate and inform the theoretical discussion, the paper draws on a case study of hydrogen roadmaps. Hydrogen energy – a long-term and highly uncertain option for enabling deep decarbonisation of the energy system – has been a particular focus for government-directed roadmapping activities. This paper draws on a review of hydrogen roadmaps to present a critical analysis of the use of technology roadmapping as part of the 'toolbox' of policy-makers tasked with steering society towards a low-carbon future.

The paper is structured as follows. Section 1 introduces technology roadmapping, and describes the way in which roadmaps have been adopted by policymakers seeking to facilitate transitions towards alternative, more sustainable, technological systems. Section 2 draws on insights from socio-technical theory to illustrate how roadmaps can be used as tools in governance of transitions, and uses this literature to develop a framework for evaluating roadmaps in Section 3. Section 4 introduces the case study, hydrogen energy. Section 5 evaluates hydrogen energy roadmaps against the framework developed in Section 3, and Section 6 draws conclusions.

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2. Technology roadmapping

2.1. Technology roadmapping: origins and use in industry

Technology roadmapping as a technique was brought to prominence in the academic literature by Galvin [2], in an editorial in *Science* that highlighted the successful use of roadmapping at Motorola and in the semi-conductor industry. Since then, a large literature has developed dealing with technology roadmapping in industry and within firms [3–7]. The approach has become widespread, and can be seen as part of the ongoing trend for technology futures to be more actively organized and managed both by private and public organisations [8].

Technology roadmaps allow technology developments to be integrated with business planning, and they allow assessment of the impacts of new technologies and market developments on the prospects for a firm [5]. Roadmaps are developed in a number of ways, and various scholars have produced outlines of the key stages of developing technology roadmaps (for excellent overviews, see [4,5]). From this variety of approaches, a set of core practices can be identified:

- Roadmaps identify the major players in the innovation system, and provide an outline of the industry or emerging innovation network.
- They describe the current status of a technology.
- They set out a view of the future of a technology, including the possibilities for its development and deployment.
- They identify needs and priorities—including R&D needs, and sometimes market and regulatory needs, such as codes and standards.
- Those produced at the sectoral level (rather than by individual firms) aim to offer a consensus view of the way forward. As a result, they are almost always collaborative, or at least consultative, in the sense that they include the views of different teams, groups and stakeholders.
- They are frequently – but not always – depicted graphically [9].
- Many roadmaps – but by no means all – involve regular updates and monitoring of progress against milestones and targets. The roadmap developed by the semi-conductor industry is re-issued every 2 years, with 'updates' issued in the interim. It, and roadmaps like it, is continually redrawn to reflect new knowledge and developments.

Roadmaps should not be understood as projections or forecasts. Rather, roadmaps conflate and combine three different ways of understanding the future: expectations (what is thought likely to happen), desires (what is hoped will happen) and promises (what will be made to happen). In combining and conflating these perspectives, roadmaps weave a picture of the future that attempts to galvanise actions in the present. In doing so, roadmapping processes often draw on other foresight approaches, including scenarios, Delphi surveys, and quantitative forecasts. In effect, we can understand roadmaps in the following ways:

- As the current 'state of the debate'. A roadmap embodies a view of the status of a technology in terms of its development, and an inventory of possibilities, barriers and opportunities. This is usually presented as a consensus view, at least of those who have participated in the process.
- As an attempt to create a *realistic and pragmatic projection* of what is both feasible and desirable. Roadmaps are informed by analysis, and aim to set out a plausible view of what the future could hold. A successful roadmap must be seen as at least credible or plausible, even if they are not always seen as setting out a likely or inevitable future.
- As *a guide to innovators*. A roadmap maps the key areas in which progress is required (what Hughes [10] memorably described as 'reverse salients'), including the barriers and the opportunities, allowing scientists and engineers to get a clearer sense of where resources need to be focused to move the innovation system forwards.
- As a 'bid' for a particular future in a competitive market in which only some futures will attract resources and support. Roadmaps articulate a particular view of what the future can and should be like – i.e. they set out a normative vision of the future – and they demand resources and support accordingly [11]. As a result, we should expect roadmaps to be optimistic, and sometimes even hyperbolic.
- As a *promise* of what will be done, and how the future will unfold.
- As a *process* that facilitates the development of networks and the alignment of actors within an innovation system.
- As a *tool* in the ongoing management of innovation. Many roadmaps are periodically updated, and provide an institutional structure through which actors in the innovation system can monitor progress, consider changing priorities and identify opportunities.

2.2. Roadmapping in public policy: from products to systems

Technology roadmapping was first applied at the level of individual products and technologies. Over time, the scope of roadmaps has expanded to encompass product or technology groups, and whole industry sectors [12]. As the scope of roadmapping has expanded, governments have become more involved in using roadmaps in public policy. Early examples of governments supporting technology roadmap initiatives emerged from industry and trade departments, keen to foster the competitiveness of their industries [13,14]. In these exercises, the role of government was limited to providing support for the roadmapping process, and government was not necessarily interested in the direction taken by the technological developments discussed. The interest of government in promoting roadmaps was to facilitate the development of competitive industries, and to push science and technology forward, wherever forward might be.

More recently, roadmaps have become a tool by which governments foster not only the development of competitive industries, but also the development of new and emerging technological systems that meet social goals, such as low-carbon technologies. Roadmaps are developed as part of the process of setting directions for the socio-technical development of society. The last decade in particular has seen increasing use of roadmapping approaches in technology policy by governments, particularly in the context of energy policy and the transition to a low-carbon energy system [15].

In making this shift from industry to public policy, the nature of technology roadmapping activities has adapted to include a broader set of concerns. Technology roadmapping in industry tends to focus on relatively short term and quite technical developments (see, for example, the roadmaps produced by the semi-conductor industry [16], which are often cited as an archetype of successful roadmapping). In contrast, governments and policy advocates have tended to use the tools, approaches and language of technology roadmapping to address issues that are considerably longer-term in nature [15], and that involve substantial social and political as well as technical elements.

This broadening of the scope of roadmapping activities echoes a shift in technology policy for the environment, from the promotion of individual 'environmental' technologies (such as end-of-pipe scrubbers), to the transformation of entire socio-technical systems [17,18]. Roadmaps, once used to map out the development path for new products, are now developed to articulate pathways for long-term sustainable "systems innovations" or "technological transitions" (these terms are used as described by e.g. [19,20]). In other words, they are used to articulate a vision of the development of an entire system, including the infrastructural, market, policy, educational and regulatory developments as well as technological issues.

The potential development of a 'hydrogen economy' is one such example—the development of a hydrogen energy system requires substantial shifts in institutions, physical infrastructure, user behaviour, supply chains, industry structure and so on. It is not simply the development of a set of new technologies, but rather it is a socio-technical transition [21]. Roadmaps for a hydrogen economy encompass a much broader array of concerns than is typical in technology roadmaps in industry.

In short, technology policy makers and advocates interested in the governance of technological transitions have adopted an analytical and management tool that was developed for use within industry (technology roadmapping), and transferred it into a new context (socio-technical transitions). Governments are using roadmapping as one of a number of tools (along with fiscal structures, technology funds, trading schemes and traditional regulations) for managing – or attempting to manage – long term transitions in the socio-technical arrangements of society.

This shift raises questions about the way in which the tools of technology roadmapping can be applied to these broader, more systemic shifts in socio-technical arrangements.

3. Technology roadmaps as instruments of transition policy

Policy-makers are already using roadmaps as part of the policy architecture through which they attempt to steer transitions towards more sustainable socio-technical arrangements. However, the practice and literature on roadmapping, and the literature on the governance of transitions, have developed largely separately. In this section, the paper seeks position 'transition roadmaps' within the broader theoretical literature on the governance of transitions.

3.1. Governing transitions: insights from socio-technical theory and transition management

Within the socio-technical literature, technologies are understood to be embedded within broad configurations – 'seamless webs' – of social and technical arrangements [10,20,22]. These arrangements include patterns of behaviour, social norms, regulatory rules, and so on. These structures in which technologies are embedded are termed a socio-technical 'regime', or 'technology-specific innovation system' [23]. Regimes are dynamically stable and resist change, resulting in inertia and what is often called 'lock-in' [24,25].

Change in such systems can be best understood through an evolutionary perspective [20,26]. Emerging technologies are developed and nurtured in niches, by 'proto' innovation systems. In the early stages of development, the actors involved in the emerging innovation system are less closely aligned than those in mature systems. To develop, networks of actors must align and coordinate action, and fulfil a series of key activities or 'functions' of a successful innovation system, including: development of knowledge, entrepreneurship, mobilization of resources, legitimation, guidance of the search, and diffusion of knowledge through networks [27,28].

This model of technological change as a quasi-evolutionary process, in which action is constrained by regimes, provides an explanation for the frequently observed failure of technology policies that are based on classic market failure approaches [27,29]. The economics of innovation (see, e.g. [30]), on which such policies are based, can be seen as only a partial account of the dynamics of innovation, because it does not take into account the 'embeddedness' of technologies within complex social structures that constrain action.

Advocates of market-based approaches to innovation policy frequently contrast market-based policies with the perceived alternative: top-down planning and control, characterised by a strong role for the state in attempting to 'pick technological winners' [31]. Quite rightly, attempts to plan technological progress are seen with considerable scepticism: we do not and cannot know which frontiers of scientific and technical advance will lead to the most rapid progress. Technological developments are inherently unpredictable and indeterminate. Furthermore, given the nature of innovation systems as networks of actors, practices and institutions, it is clear that no-one actor is 'in charge' to do the top-down planning [32]. The power required to steer the socio-technical development is diffused through networks of actors, rather than held by the state or by any one actor. As a result, attempts to 'plan' a successful transition are likely to fail [33], as are attempts to re-make socio-technical arrangements entirely through price signals.

How, then, can governments guide the emergence of more sustainable socio-technical systems? Various approaches have been suggested that emphasise a 'reflexive' and adaptive approach, focusing on learning, reappraisal and experimentation. These echo adaptive management approaches adopted in natural resource management [34,35], and include transition management [36,37], strategic niche management [38], and time strategies [39,40]. The literature on network governance is also useful here, describing governance strategies when power is diffused through actors in heterogeneous networks [41], of which emerging innovation systems are an example.

Of greatest relevance to our understanding of roadmaps as governance tools for transitions is the attention that the socio-technical literature in general, and transition management in particular, has placed on the role of expectations and futures in guiding socio-technical change. In order to more fully clarify how this relates to roadmaps, the paper now turns to a specific area of the socio-technical literature, that deals with technological expectations.

3.2. Technology futures in innovation policy: governance of and by expectations

A growing literature on the sociology of technological expectations has emphasised that expectations and social visions play an active role in shaping innovative activities and influencing the technological developments that ultimately occur [42–45]. Scholars in this field describe technological expectations as 'performative', meaning that expectations play a role in shaping the way in which technologies develop.

Expectations lead actors within an innovation system to focus their activities, investment and resources on options that are thought most likely to succeed, with the result that these options become increasingly likely to succeed as further resources are focused on them. Furthermore, expectations are important in the process of aligning actors around common goals. Shared expectations help to establish a common agenda, thus strengthening innovation networks. As a result, expectations can – to some extent – be self-fulfilling [43]. When expectations become widely shared, they shape even the actions of those who *do not* share in the widely held beliefs, since such sceptics know that most others in the innovation system will act on the basis of these shared expectations [46]. Simply put, it is easier to operate within the innovation system when you appear to be in agreement with what everyone else agrees is 'the way things are going'. Shared expectations thus become part of the 'rule set' that constrains and enables particular kinds of activities within the innovation system. Within an evolutionary perspective on technological change, expectations can be understood as important factors in both the generation of variation and in the selection environment [47].

Technological expectations thus help to promote several core functions of an emerging technological innovation system outlined earlier: the mobilization of resources, the development of legitimacy, networking, and establishing clear guidance of the search[1] [27,28,48]. Expectations are also critical in the establishment of niches, or 'protected spaces', in which new technologies can develop [38,49].

The fact that expectations help to shape the direction of innovative activity means that technology futures – scenarios and visions of the future – become a contested space in which various actors compete to establish dominance of expectations that match their interests [11,42]. Thus hydrogen enthusiasts envisage, anticipate and promote a hydrogen future; while many deep green environmentalists predict and describe futures in which social and cultural changes, rather than new technologies, reduce the pressures humankind exerts on our natural environment. This offers an opportunity for governments to attempt to engineer the 'expectations landscape', and hence influence the direction of socio-technical development. Konrad [50] has succinctly summed up this approach by speaking of 'governance of and by expectations'.

Several strands of research have built on the idea that futures can be performative, and have articulated approaches to the use of expectations and futures in the governance of transitions (e.g. [51–53]). Vergragt and others [53–55] have focused on the process of vision articulation and participatory backcasting as a means to foster learning about what is possible in terms of systems innovation, and to build the emerging innovation networks through alignment around a common vision. Their work focuses on the importance of activities within radical niches, arguing that environmental imperatives such as climate change require transitions to systems with radically improved sustainability performance, and that following business-as-usual assumptions and trajectories is insufficient. Participatory backcasting processes are advocated as providing people with a space to rethink cultural practices, and (ideally) to experiment with these in the context of 'bounded socio-technical experiments' [56].

Sondeijker et al. [51] have also focused on the role of visions and futures in transition management, advocating the use of 'transition scenarios'. These are seen as serving many of the same functions as technology roadmaps. "Scenarios provide long-term images of sustainable futures on a strategical level. In this sense, they serve as a framework for short-term actions at an operational level. They ensure the enrolment of actors into coalitions for change and strategic conversation within and between these coalitions. This is supposed to result in alignment and mobilization of collective action necessary to initiate and maintain sustainable system innovations." [51] pp. 20.

There has been little cross-over between 'transition scenarios' theory and those working with technology roadmaps, but the similarities are clear. Indeed, as de Laat has noted, the practice of technology roadmapping has in many ways adopted – perhaps unconsciously – some of the messages from socio-technical theory [57]. In particular, the idea that technical expectations and

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[1] Following Hekkert et al. [28], "guidance of the search refers to those activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users".

visions have a performative role, and that they therefore can be 'deployed' as a strategic action in their own right, is clearly embodied in the practice of roadmapping.

Roadmaps, alongside transition scenarios and participatory backcasting, can thus be seen as 'purposefully performative' futures exercises, in which the explicit aim of the process is not just to inform decision making, but to actively shape the behaviour of actors in the innovation system through the development and deployment of a view of the future. This is in contrast to many other foresight approaches, such as exploratory scenarios or Delphi surveys, and suggests that a different set of issues are relevant for evaluating roadmapping processes.

3.3. The roadmapper's dilemma: between opening up and closing down

The use of futures as tools with which to shape transition paths is not without its critics. In particular, the role of a consensus guiding vision in transitions has been questioned on both normative and practical grounds [58]. These critiques are of direct relevance to the use of roadmapping in informing and enacting transitions policy.

At the heart of these critiques lie questions about the extent to which it is desirable and useful to attempt to articulate and champion a *single* coherent view of the future, which 'closes down' the relevant set of perspectives and discourses, as opposed to processes that focus on 'opening up' the articulation of alternative possible futures to encompass a pluralist perspective and more diverse pathways [59].

Of particular concern are issues of politics, power and democratic accountability: if expectations can be deployed as tools with which to shape the direction of socio-technical change, the question of who is involved in informing the development of prospective transition paths becomes central. Shove and Walker have noted that "…[D]espite extensive debate and rhetoric about the construction and democratic choice of visions and images of the future, the depth of the politics involved is frequently underplayed." [60].p. 766. And while several authors writing on roadmaps have argued for the establishment of consensus pathways, it is important to recognise that achieving consensus often entails the exclusion of minority perspectives [61].

Researchers developing transition scenarios and participatory backcasting have acknowledged these difficulties. Indeed, some authors have suggested that the unique value of constructing normative technological visions and roadmaps is neither that they provide a clear set of 'signposts', nor their role in aligning actors and expectations – though these are both acknowledged to be important – but rather that they provide a space for debate and deliberation about technological options and the preferences, values and perspectives of different social groups [21,62,63]. In this view, the articulation of visions and pathways is part of what Stirling calls 'precautionary foresight' [64]—it is a means to open up appraisal of options to wider views, perspectives and framings, rather than a means to develop a consensus plan.

Second, and quite separately from concerns about accountability, the articulation of a single and exclusive transition path appears to ignore the inescapable truth that the future is neither wholly predictable nor wholly malleable. While shared expectations clearly play a role in determining the path of socio-technical development, it is obviously not possible to simply talk ourselves into a sustainable future [65]. In the face of such fundamental uncertainty, attempts to choose and pursue a single transition path are unlikely to be fruitful. Again, researchers involved in participatory backcasting and transition scenarios emphasise the multiple and contingent routes towards a 'guiding visions'. In doing so, they attempt to develop transition pathways that are more robust in the face of uncertainties, and that enable the inclusion of diverse and plural perspectives. Yet experience suggests that actors in the innovation system are unwilling to subscribe to overly diverse, pluralist and contested pathways. The language of inclusivity, diversity and 'opening up' does not breed the kind of confidence and shared sense of purpose on specific investments, projects and technologies that are required for aligning the innovation network.

Roadmaps must articulate a shared view of where things are going – a coherent and reasonably concrete shared direction of search – if they are to provide a basis for action. The roadmapper is thus trapped between two possibilities. On the one hand, a confident, prescriptive roadmap developed on the basis of a consensus of a subset of relevant (and powerful) actors will have most influence. Yet on the other hand, this is likely to reflect incumbent interests—who are often precisely those interests tied up with a less-sustainable socio-technical system and, by focusing on a narrow view of what can and will be done, it can downplay uncertainties and alternative pathways.

The following section develops a set of criteria to address how roadmapping for system innovations can balance these objectives.

4. Criteria for evaluating roadmaps for systems innovation

In this section, I draw on the preceding theoretical discussion to develop a framework through which 'transition roadmaps' may be developed and evaluated. The framework articulates the key attributes that must be addressed if a roadmap is to provide a useful component of transition policy. It is based on a process evaluation, in which the process used to develop the roadmap is assessed, as opposed to an outcome evaluation, since the latter would be impractical given the severe difficulties of attribution in a context as complex as an innovation system [66]. The framework is derived from the preceding theoretical discussion. In particular, the framework aims to assess the extent to which roadmaps are successful at balancing the need to 'close down' the direction to a single, prescriptive view, while remaining responsive and sensitive to the normative and practical critiques set out above.

Given the special character of roadmaps as 'purposefully performative' futures, the evaluation framework differs somewhat from others found in the foresight evaluation literature (e.g. [66]). Despite these differences, there are also clear parallels with the foresight evaluation framework developed by Georghiou and Keenan [66], for example in assessing the quality and type of analysis underpinning the exercise, and in gauging the appropriateness of the roadmapping process.

4.1. Credibility: is the future pathway plausible?

Roadmaps must articulate a view of the future that is credible and persuasive. Without being seen as a plausible view of the future, roadmaps lose their power to direct and shape the behaviour of actors involved in the innovation system.

This has a number of implications for how roadmapping is carried out:

- First, it demands that any analysis on which the roadmap is constructed is sound, and based on reasonable assumptions and methods.
- Second, it requires that the relevant expertise has taken part in shaping the analysis and the roadmap. In the context of a system innovation, such as hydrogen, this implies that a broad range of expertise must be involved, suggesting some form of participatory or consultative exercise with a broad range of expert stakeholders.
- Third, credibility demands that the actors with greatest ability to influence achievement of the envisaged futures are involved, and are – at least to some extent – committed to that future. The roadmapping process must secure the commitment of key actors to the process, and must communicate that these key actors believe in the roadmap.
- Finally, credibility requires that the roadmap engages adequately with the social, political, market and cultural aspects of the envisaged transition, as well as the 'purely' technological elements. A roadmap that fails to set out a plausible view of market and social contexts, but envisages profound technological systems change, will be less credible than one that embeds a vision of technological change within a broader context of anticipated market and socio-political evolution.

4.2. Desirability: is the future pathway defensible as a good choice for society?

Those developing roadmaps within a public policy context have a responsibility to articulate a future pathway that is desirable from a societal perspective. This begs the question of who gets to decide what kind of future is in the interests of society, and on what basis such decisions are made.

Clearly, the desirability of the envisaged future can be based on goals and directions established through existing democratic institutions. For example, analysis might show that hydrogen technologies can enable emissions reductions to meet legislated carbon targets. However, guidance from legislatures typically provides insufficient clarity in making choices about which technological pathways to pursue.

Those developing transition roadmaps must make choices about how to determine a desirable direction for socio-technical development. The roadmapping literature emphasises the desirability of establishing consensus amongst the stakeholders involved [3,67]. Yet in a pluralist democratic society, it is not always straightforward – or even necessarily possible – to establish a clear consensus view of the desirability of a given future pathway [68,69]. To overcome this challenge, the framework in this paper adopts a deliberative democratic perspective, which demands that public policy decisions are accountable, in the very literal sense that a clear 'account' is given of why a decision was made in that way [68]. Rather than demand that roadmaps set out a future for which there is a broad social consensus, evaluation of the roadmap should instead focus on the degree to which roadmaps can justify the choices made in deliberative terms. In other words, roadmaps should be explicit and transparent in their aims, the process used, and who took part.

Finally roadmaps that are developed through processes that are broadly inclusive and participatory will have a greater claim to setting out a legitimately desirable future pathway. Work on network governance (an appropriate theoretical frame for innovation system governance) has emphasised the importance of inclusivity [70]; and, as discussed, many theorists of technology argue persuasively that broad participation is important in both appraising and committing to particular technological futures [71]. This is not to say that participation is a clear route to democratic legitimacy, but rather that roadmapping processes that exclude opportunities for participation are less able to claim legitimacy.

4.3. Utility: does the roadmap help advance the innovation system?

The third criterion relates to utility: does the roadmap and roadmapping process facilitate the further development of the innovation system? In other words, does it help the innovation system to perform core functions of innovation systems, as described by Bergek et al. [27]?

Where roadmaps meet criteria 1 (credibility) and 2 (desirability), they automatically help foster legitimacy for the technology in question, which is a core function of a successful innovation system. Beyond this, to be useful the roadmap must provide a coherent direction of search for scientists, engineers, entrepreneurs and other innovation system actors. A shared research agenda enables alignment of enactors and selectors, and a roadmap is one of the ways in which this function can be facilitated. Any roadmap provides the broad direction of search, in the sense that it articulates a place for the technology in the world. Beyond this, a roadmap should identify specific research needs and priorities, highlighting what Hughes referred to as 'reverse salients' [10]. Depending on the degree of maturity of the innovation system, this may involve setting detailed, technically-defined 'targets'. Alternatively, it may only highlight areas that are of particular concern.

Roadmaps must navigate a careful balance between setting out a confident view of a plausible and desirable future, and over-promising and 'hype', which can damage the prospects of the innovation system [72].

Finally, the roadmapping process must be appropriate for the stage of the innovation system [66]. For innovation systems in an early, formative stage, for example, setting very long-term technical targets may not be helpful if the capacity to work towards meeting them does not exist. In such a situation, a roadmap that sets out a broad framing vision of the path forward is likely to be more useful.

4.4. Adaptability: is the roadmap process consistent with reflexive, adaptive management?

The literature on transition management emphasises the need for continual adjustment and re-evaluation of policies and programmes, and the literature on roadmaps in industry has emphasised that roadmaps are more effective where they are developed as an ongoing process rather than a one-off document (e.g. [5]). As Propp and Rip [73] have argued "Roadmaps need to be maintained and updated to become effective. Where an actor to fulfil that function exists… roadmaps become a powerful tool for creating alignment around technological and product options and to help accelerating their development" (p. 11). This argues for roadmaps to be developed and maintained within an institutional context – such as a partnership between government and industry groups – that is able to learn, and to produce updates to the roadmap as time goes by.

Ideally, the actor(s) responsible for producing and maintaining the roadmap will do so in a reflexive manner, one that emphasises learning and evaluation, and is open to reflection on the role and value of the roadmapping process and its framing. In the context of transition management, Shove and Walker [60] highlight that the question of 'what is to be transitioned' is frequently not a matter for debate. In the same way, roadmapping lacks obvious mechanisms through which to adequately justify how transition questions are framed and determined. As with the substance of the roadmap itself, the institutional structures through which roadmaps are identified and framed should be transparent, and able to reflect critically on the framing of the exercise overall. In effect, this requires that roadmapping processes sponsored by government should be conducted within a broader context of technology foresight and strategy governance processes.

4.5. Summary: evaluation criteria for transition roadmaps

Table 1 summarises the criteria, and highlights the key questions addressed by each criterion.

5. The case of hydrogen

Hydrogen, like electricity, is an energy carrier that can be produced and used in a variety of different ways. Like electricity, the environmental attributes of hydrogen depend largely on how it is produced and used, since it is not a significant pollutant in itself [74]. While there has been a decline in excitement in policy circles about hydrogen since around 2005 [72,75], it remains an important option for deep decarbonisation of the transport sector and for diversification of energy sources for transport, and potentially as a widespread carrier of energy for heat and power demands.

Hydrogen has been a vibrant arena for the development of roadmaps [67,76]. National and regional governments, US States (e.g. Ohio, California, Connecticut, New York, Florida, Indiana, Minnesota and others), and a number of cities across the globe have undertaken roadmapping activities concerning hydrogen, alongside numerous firms and industry associations.

A sample of hydrogen roadmaps produced in the last 10 years was reviewed, with a focus on those produced as part of policy processes by national governments (or supra-national, in the case of the EU). Roadmaps were identified by searching online databases and through stakeholder interviews. The review focused on those addressing hydrogen directly, aiming to identify those that have been used as part of a broader policy process that aims to address the transition to a hydrogen energy system. However, hydrogen technologies are developed and managed within the context of a broader portfolio of innovative energy technologies, and so the review identified the following types of relevant roadmaps:

- Hydrogen energy and fuel cell roadmaps
- Low carbon vehicle roadmaps (that include hydrogen)
- Low-carbon energy technology roadmaps (that include hydrogen)

Table 1
Summary table of criteria for transition roadmap evaluation.

Criteria	Key questions
Credibility	Is the roadmap based on sound analysis?
	Does the roadmap draw on the right breadth of expertise?
	Has the roadmap secured the participation and commitment of key actors in the innovation system?
	Does the roadmap adequately address the political, social and economic aspects of the transition?
Desirability	Does the transition meet social goals established through democratic institutions?
	Does the roadmap give a clear account of the justification for the proposed pathway, with transparency in aims, process and who took part?
	Is the roadmap process inclusive and participatory?
Utility	Does the roadmap effectively articulate a path forwards that can enable alignment around common goals?
	Is the roadmapping approach appropriate for the stage of innovation system maturity?
Adaptability	Does the roadmapping process involve periodic reviews, updates and learning?
	Is the roadmapping process embedded in a broader institutional structure that enables reflexivity and learning?

Table 2
Roadmaps included in the review.

Roadmapping initiative/document(s)	Abbreviation	Country/region and year	Core sponsors; reference
Hydrogen technology roadmap	AUS	Australia 2008	Government of Australia [77]
Canadian fuel cell commercialization roadmap; Canadian fuel cell commercialization roadmap update	CAN03, CAN08	Canada 2003, 2008	Government of Canada [78], Hydrogen and Fuel Cells Canada [79]
Hydrogen energy vision and technology roadmap report for China	CN	China 2004	Ministry of Science and Technology, China [80]
HyWays: the European hydrogen roadmap	HyWays	EU 2008	European Commission [81]
Hydrogen energy and fuel cells: a vision of our future	EUHLG	EU 2003	European Commission High Level Group on Hydrogen and Fuel Cells [82]
European Hydrogen and Fuel Cell Technology Platform: deployment strategy, strategic research agenda and implementation plan	EUHFTP	EU 2005, 2006 and 2007	European Commission Hydrogen and Fuel Cell Technology Platform [83–85]
The GermanHy roadmap	DE	Germany 2008	German federal government and the German National Organisation for Hydrogen and Fuel Cell Technology [86]
The Icelandic hydrogen energy roadmap	IC	Iceland 2008	Icelandic Ministry of Industry and Commerce [87]
National hydrogen energy roadmap: pathway for transition to hydrogen energy in India	IN	India 2007	Indian Ministry for New and Renewable Energy [88]
Strategic technology roadmap (energy sector)	JPSTR	Japan 2005	Japanese Ministry of Economy, Trade and Industry [89]
Cool earth innovative energy technology program: technology development roadmap	JPCE	Japan 2008	Japanese Ministry of Economy, Trade and Industry [90]
Fuel cell vision for the UK; and UK fuel cell development and deployment roadmap	UKFC	UK 2003, 2005	Fuel cells UK and Department for Trade and Industry [91,92]
Roadmap for hydrogen energy in the UK	UKH2	UK 2009	Technology Strategy Board, Department for Energy and Climate Change, UK Hydrogen Association [93]
A national vision of America's transition to a hydrogen economy — to 2030 and beyond; national hydrogen energy roadmap	USH2	US 2002	US Department of Energy [94,95]
Fuel cell technologies roadmap; hydrogen production roadmap; hydrogen delivery roadmap; hydrogen manufacturing R&D roadmap	USFCAR	US 2005, 2009, 2007, 2005	US FreedomCAR and Fuel Partnership [96–99]

The review included roadmaps from: the US, Australia, India, the UK, Japan, China, the EU, Iceland, Germany and Canada. In some countries/jurisdictions, more than one roadmap was examined. In total, 15 roadmapping initiatives were included in the review (see Table 2). Abbreviations, listed in Table 2, are used to ease the referencing and readability of the paper.

The review was conducted using a standard template to extract a consistent set of information from each document. While the review focused on the documents themselves, the review also examined further documentary evidence to inform the institutional context behind the roadmaps (i.e. how were they produced, how are they being used).

6. Evaluation of hydrogen roadmaps: a socio-technical perspective

Governments have used roadmaps to inform and promote the development of hydrogen energy in a variety of ways. The style and approach include roadmaps built on intensive, multi-year and analytically rich processes (e.g. HyWays), short overview roadmaps built on the basis of a single workshop (UKH2), and ongoing roadmapping processes that are embedded within broader energy technology strategy (JPCE). This section applies the framework developed in Section 3 to the literature, to examine how governments are using roadmaps for a transition to hydrogen energy.

6.1. Credibility

6.1.1. Are roadmaps informed by good quality analysis and broad expert participation?

The quality and depth of technical analysis underpinning roadmaps varies considerably. In many cases (e.g. USH2, UKFC, EUHLG, IC, CN03, IN), analysis focuses on mapping the actors and institutions involved in hydrogen and fuel cells, and market opportunity assessment. Rather fewer roadmaps explicitly include technological forecasting of future cost/performance or technology needs assessment (e.g. HyWays, AUS). Analytic modes include both forecasting (identification, examination and projection of market and technology trends) and backcasting (identification of steps that need to be taken in order to reach an established goal).

Some of the roadmaps are informed by detailed modelling exercises, sometimes involving multiple modelling approaches. The German, HyWays, and Australian roadmaps included detailed modelling studies of hydrogen costs and competitiveness. Other roadmaps were informed by relatively simplistic analysis, including simple extrapolation of historical sales figures many years into the future (e.g. CAN03). Across the studies, analysis of technological goals and needs appears to be more robust than analysis of future markets and opportunities. This is perhaps not surprising: the former is concerned with providing clear, informed direction to innovators; while the latter is subject to the inherent tension within roadmaps: providing confidence in the future of the technology, without contributing to potentially damaging 'hype' cycles. In retrospect, the market analysis that contributed to some of the earlier roadmaps reviewed (such as CAN03) can be seen as has having contributed to early hype about hydrogen. All the roadmaps involved some form of participatory or consultative process through which to engage expert stakeholders.

6.1.2. Participation and commitment of key stakeholders

Roadmap credibility depends on the participation and commitment of key stakeholders whose actions are critical in the further development of the system, such as major firms involved in automotive and fuel supply markets. All the roadmaps reviewed attempted to secure the participation or commitment of stakeholders through consultations or participatory processes. In several cases, participatory workshops were the main input into roadmap development (UKH2, CN, USH2).

Governments are central players in the development of a hydrogen energy system, since policy support is necessary to overcome the barriers associated with an infrastructure transition [76]. While all the roadmaps were either produced or sponsored by governments, there are obvious differences among roadmaps in the degree of commitment from government and from other major stakeholders. Some are endorsed at the highest levels of government, and are associated with the participation and engagement of major industries (e.g. USH2, USFCAR, JPSTR, JPCE, EUHLG, IN). Others are published or sponsored by governments, but without obvious high-level political endorsement, such as a preface by a senior minister (e.g. UKH2, UKFC, CN, HyWays). Several of the more technically-detailed roadmapping exercises were sponsored by government, and produced through formal collaborative partnerships made up of industry, government and research organisations, with working groups addressing particular issues (e.g. EUHFTP, USFCAR). These partnerships involve a degree of commitment from all participants to the process, and may be seen as producing more credible views of future pathways.

6.1.3. Adequate engagement with social, political and economic aspects

Most of the roadmaps engage to some extent with broader social, political and economic aspects of a transition, in the form of addressing future market needs, energy and transport demands, and the policy drivers that are informing the broader social context for hydrogen energy. In some cases, future consumer requirements (such as acceptable vehicle range) or market conditions (such as carbon constraints) are set out in specific details.

In all the roadmaps, the future is much like the present in terms of consumer behaviour, cultural practices and transportation patterns. This is in strong contrast to many hydrogen futures developed by NGOs, academics and visionaries, many of which describe futures that associate the establishment of a hydrogen energy system with widespread shifts in social values or structures. Discursive themes around ‘ecotopia’ or radical decentralization and democratization, present in many hydrogen futures [100,101], are entirely absent from the roadmaps. As a body of visions of the future, the roadmaps are strikingly conservative in their representation of how future people and societies will meet their needs. This can be viewed as a failure to engage with broader uncertainties around socio-technical change, or simply as a tacit set of assumptions about the durability of social structures and practices.

However, many of the roadmaps do depart from current social norms in their depiction of the governance mechanisms that might accompany the transition to a hydrogen energy system. Several of the roadmaps envisage a future in which a transition is effected through corporatist collaborative governance models involving partnerships of major industries (principally automotive and oil companies) with governments. This view envisages government–industry partnerships making major investment decisions in infrastructure and manufacturing capacity in a co-ordinated way, enabling a hydrogen system to overcome the enormous challenge of establishing an entirely new vehicle refuelling infrastructure solely because of the benefits of the new fuel to society. In other words, while the roadmaps reviewed tend to be rather conservative in their views of social practices and consumer behaviour, they envisage new governance models for purposive socio-technical transitions.

6.2. Desirability

Very few of the roadmaps incorporate a detailed analytic case for pursuing a hydrogen future (exceptions are HyWays and DE). Rather, most build an argument based on the key public policy drivers (climate change, energy security, air pollution, and international competitiveness). Where there is detailed analysis of hydrogen energy systems, these are not compared with alternatives (such as transport systems based on battery electric vehicles) on a like-for-like basis. The analytic work underpinning roadmaps, while often sophisticated, can thus be seen as providing justification, rather than supporting decision-making and deliberation.

All of the roadmaps are based on some form of participatory or consultative process, involving a range of stakeholders. Roadmaps differ in the degree of transparency about who was involved, with many not making clear who participants were. None of the roadmaps identified how participants were selected. Similarly, the roadmaps do not make clear how or whether consensus was reached. Few of the roadmapping processes appear to have directly included broader voices from consumer or citizen perspectives, such as elected officials, participants from civil society groups or NGOs, or simply interested or concerned citizens. In other words, the participatory processes through which roadmaps were developed were tightly framed and constrained in their modes of participation and representation, and cannot be seen as providing a strong basis for social legitimacy to the hydrogen futures envisaged.

6.3. Utility

All the roadmaps provide a broad, high-level vision. They frame hydrogen energy as a major area for future development, and as a priority for R&D and investment activities. In this sense, roadmaps are all useful in endorsing the legitimacy of hydrogen technologies as a focus for innovative activity.

Some roadmaps are limited to this broad, generic view. Examples of these roadmaps include CAN03, USH2, CN, IN, UKFC, UKH2, and AUS. These roadmaps project a sense of vision and the pathway of development, but with limited technical detail or specific targets. These 'framing roadmaps' are typically produced as an initial attempt to clarify the state of the emerging innovation system and its prospects. They deploy a coherent 'technology story', deploying generic expectations (in the sense used by van Lente and Bakker [44]) about the promise of the field in general, rather than expectations about specific technological details. Their purpose can be understood as primarily political, doing the work of establishing and legitimating a frame through which to understand and relate to hydrogen technologies. Many of these roadmaps lack substantial technical detail, and while they typically provide an overview of the relevant technologies, they provide only limited guidance to innovators in terms of focusing on research challenges. These roadmaps may describe the technologies in detail, but they are typically empty of the forward-looking technology analysis that is usually seen as a defining characteristic of technology roadmapping activities. They are most appropriate for the formative phases of an innovation system.

Other roadmaps combine this generic vision with specific technical detail. In these technically-detailed roadmaps, governments work with academia and industry to establish R&D targets and detailed technological milestones against which progress can be assessed. Examples of this mode of roadmapping include the USFCAR, HyWays, EUHFTP, JPSTR, and JPCE. Some of the roadmaps establish milestones and decision-points. For example, the US roadmapping processes highlight a decision point in 2015 on full-scale commercialization of fuel cell vehicles.

Both of these modes ('framing' and 'technically-detailed') can be understood as providing a coherent direction of search, but for different stages of innovation system maturity. For an emerging innovation system, in which alignment of actors is poor and shared expectations are weak, it is necessary to first provide an overarching framing roadmap through which to facilitate the coalescing of the innovation system. Only once this broader framework has become accepted is it possible to provide more specific direction.

6.4. Adaptability

Most of the roadmaps reviewed appear to be one-off exercises, rather than ongoing management processes. This is particularly true for the 'framing' roadmaps, which tend to set out a strategic view rather than a detailed structure for monitoring progress (e.g. CN, IN, AUS, UKH2).

A minority of the hydrogen roadmapping processes reviewed have been subject to updates and reviews. The development of sequential US roadmaps has been taken forward by the FreedomCAR and Fuel Partnership, a joint initiative of government, automotive firms and energy companies. In Japan, the Ministry for Economy, Trade and Industry (METI) has developed hydrogen roadmaps as part of its broader process of Strategic Technology Roadmapping, which includes reviews of roadmaps every 2 to 3 years [102]. The Canadian hydrogen roadmap has been updated, and radically revised, by the industry body Hydrogen and Fuel Cells Canada. The roadmaps developed by the European Commission have not explicitly been reviewed and updated, but they have formed a sequence of related roadmapping initiatives, managed through an evolving institutional structure (first the High Level Group on hydrogen and fuel cells, followed by the Hydrogen and Fuel Cell Technology Platform, and now the Joint Undertaking on Hydrogen and Fuel Cells).

7. Conclusions

This paper has described the way in which governments have increasingly been using the practices of technology roadmapping to inform and shape long-term systems innovations, or technological transitions. In reviewing hydrogen roadmaps, and evaluating them from a socio-technical perspective, the following conclusions can be drawn:

- The theoretic literature on transition management and the role of expectations suggests that roadmaps can be a valuable complement to transition management policy. Their use in such contexts reflects a rise in the use of 'systemic instruments' [103] in innovation for sustainability, and this is to be welcomed. However, none of the roadmaps reviewed fully met all the criteria, and there appears to be considerable scope for improvement in roadmapping practice for long-term transitions.
- The roadmaps reviewed vary in the quality of analysis on which they are based. Some draw on strong analysis, with well-established methods and transparent assumptions. However, there are also many roadmaps that appear to be based on weak analysis or that lack sufficient transparency to judge the robustness of the conclusions on which the roadmaps are based. This is potentially damaging: poor quality and opaque analysis results in unrealistic expectations, and can exacerbate hype-cycles, undermining the development of the innovation system.
- All of the roadmaps involved some form of consultative or participatory process involving key stakeholders. However, some of the roadmapping initiatives appear to have been conducted without ensuring participation and buy-in from key players in the innovation system, which limits the credibility – and therefore the utility – of the resulting futures. Those initiating roadmapping processes should ensure that they have sufficient resources and credibility to attract key participants to commit to the process.
- Few of the roadmaps set out an adequately argued case for the desirability of hydrogen futures. Most roadmaps clearly identify the drivers and motivations for developing a hydrogen energy system (climate change, energy security, air pollution and the development of new industries), but few adequately demonstrate that hydrogen is a likely or preferable means to achieving those ends.

- Roadmapping processes are often insufficiently transparent and are often closed to broader participation. Technology roadmaps, when used to address systems innovations, are attempts to engineer a landscape of expectations that is conducive to the development of a new socio-technical system. They can and should be a site of democratic engagement and debate about the direction of socio-technical change. Broader consultation and public input is common practice in many other fields of policy development and should be more common in roadmapping.
- Many roadmaps are conducted as one-off exercises. This is unfortunate, as roadmapping should enable a structure for learning about a transition as it unfolds. Those developing roadmaps should, where possible, institutionalize the updating and ongoing evaluation of roadmaps. In other words, roadmappers should allow roadmapping processes to operate in a reflexive, learning mode, through an established institutional arrangement.

The work has highlighted the potential of transition roadmaps as one type of 'systemic instrument' in the governance of transitions. Two priorities for further research can be identified from this initial study.

1. The relationship of transition roadmaps to other foresight approaches. This paper has suggested a distinction between roadmaps, as 'purposefully performative' futures, and most other kinds of foresight activity. However, many of the issues raised in the paper also apply to other foresight approaches when considered in the broader context of transition management. In particular, there is a need for clearer insight into the way in which different foresight activities can be used to enable either "opening up" or "closing down" of appraisal and commitments within the innovation system.
2. The institutional structure and design of transition roadmapping processes requires further development. This paper has highlighted ways in which the tools of technology roadmapping can be used to inform and shape socio-technical transitions, and it has provided a broad framework for the application of this approach. Further study on the dynamics of roadmapping processes, and the impact of roadmaps on innovation system development, would be valuable in shaping recommendations about the detailed design and structure of roadmapping processes as part of innovation and transition management policy.

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Towards a sustainable hydrogen economy: A multi-criteria sustainability appraisal of competing hydrogen futures

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Abstract

The ‘hydrogen economy’ has the potential to provide a sustainable and secure energy system, and there is a wide and growing literature promoting and exploring different possible hydrogen futures. However, despite broad agreement that hydrogen could make a significant contribution to energy policy goals, the literature exhibits strong disagreements about the form that a future hydrogen economy should take. Visions of the future select, combine and reconfigure individual hydrogen generation, storage, transport and end-use technologies into more or less mutually compatible energy and transportation systems, which embody deeply contested and conflicting views of sustainability.

This paper describes the application of a novel foresight methodology, which combined participatory scenario development, using a backcasting approach, with an expert-stakeholder multi-criteria mapping (MCM) process, in order to provide an integrated, transparent assessment of the environmental, social and economic sustainability of six possible future hydrogen energy systems for the UK. The findings suggest that: hydrogen has the potential to deliver substantial sustainability benefits over the status quo, or, business as usual, futures, but that hydrogen is not automatically a sustainable option; carbon emissions are the single most important dimension of sustainability, but that issues other than carbon and cost need to be considered if hydrogen is truly to deliver greater sustainability. Furthermore, there was significant disagreement about which visions were considered more or less sustainable. These findings reflect two important sources of divergence in the final sustainability rankings: uncertainties and contested views of sustainability.

Keywords: Multi-criteria appraisal; Backcasting scenarios; Sustainable hydrogen economy

1. Introduction

In recent years the concept the ‘hydrogen economy’ has received considerable attention, with the emergence of a broad based ‘advocacy coalition’ [28], comprising a diverse range of academic researchers, politicians, business and civil society organisations, promoting hydrogen as a means of delivering a sustainable and secure energy system. As a result there is a wide and growing literature promoting and exploring different possible hydrogen futures. However, despite broad agreement that hydrogen could make a significant long-term contribution to energy policy goals, the literature exhibits strong disagreements about the form that a future hydrogen economy should take. Visions of a hydrogen future select, combine and reconfigure individual hydrogen generation, distribution and end-use technologies into more or less mutually compatible energy and transportation systems, which embody deeply contested and conflicting views of sustainability [1].

In short, there is no single, shared vision of a ‘sustainable hydrogen economy’. Rather, different organisations and individuals produce visions and expectations of possible hydrogen economies that reflect their own interests and values [2]. For some, hydrogen is a means of maintaining current systems, structures and ways of life; for others, it has the potential to reorder energy in ways that may facilitate broader social change.

Despite the range of different possible hydrogen systems that the literature embodies, the few studies that attempt to appraise the relative sustainability of different hydrogen futures tend to do so on the basis of a rather limited set of criteria (typically carbon emissions, cost, and air pollutants, for example, [3]),

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or with no attempt to engage different legitimate perspectives on problem framings, weightings, and criteria definition (see, for example, [4,5]). More commonly research has focussed on comparing hydrogen energy systems with other prospective low-carbon transport options, usually biofuels and hybrid-electric or battery electric vehicles (for example, [6]). While such studies clearly provide important insights, they often fail to reflect the diversity of possible future hydrogen energy and transport systems.

This paper describes the visioning and sustainability appraisal phases of a novel foresight study conducted under the auspices of the UK Sustainable Hydrogen Energy Consortium (UKSHEC) over the period from March 2005 to September 2006.[1] Technology foresight is not forecasting. Foresight techniques use both quantitative and qualitative approaches to explore and communicate understandings of the long-term future of science, technology, the economy and society, in order to draw conclusions for the present. Foresight seeks to improve society's capacity to manage uncertainty and actively shape the direction of socio-technological change. As Cuhls notes often '*The communication effect of pre-assessing future options or decisions as well as mobilizing and bringing together the different stakeholders of the innovation system…seems to be as important as the empirical results*' [8].

This study engaged a broad range of expert stakeholders in an integrated appraisal of the environmental, economic and social sustainability and energy security implications of six visions, encompassing an indicative range of prospective hydrogen futures. The aim of the study was not to identify or predict the most sustainable hydrogen system, but to open-up debate about the relative sustainability of different options by exploring the technological uncertainties, divergent values and social priorities that shape competing expectations of the future of hydrogen.

What follows is not a technical analysis of the economic or environmental performance of a narrowly defined set of engineering systems. Rather, it is a systematic exploration of the way in which the expert stakeholders understand and value the various attributes of a range of prospective hydrogen futures, under the normative framework of sustainability. Experts and policy makers have a central role in shaping the advocacy coalitions that build behind particular socio-technical systems. This study therefore complements the technical literature on hydrogen by asking: what are the different ways of prioritising different elements of sustainability with respect to hydrogen? What are the implications of uncertainty for the prioritisation of different systems? And, how do experts translate analysis into judgement? By exploring these issues, the multi-criteria approach used identifies questions and uncertainties typically ignored within purely technical appraisals.

This paper is structured as follows. Section 2 briefly describes the novel backcasting and appraisal methodology used. The UKSHEC visions are presented in Section 3, and the appraisal results in Section 4. Section 5 reflects on these findings, and explores what the appraisal tells us. Finally, Section 6 draws out some conclusions and insights for policy.

2. Methodology: participatory backcasting and multi-criteria analysis

The methodology developed for this study comprised the following stages: (i) scoping and stakeholder identification; (ii) vision development; (iii) multi-criteria sustainability appraisal. A full account of the methodology is provided in the relevant project report [9].

2.1. Scoping and stakeholder identification

The scoping stage of the project sought to map the relevant stakeholders and expectations on the future of hydrogen, through a literature review [1] and a series of scoping interviews. Stakeholders were identified through an analysis of the membership of UK hydrogen-related organisations (such as H2Net, London Hydrogen Partnership and the Low Carbon Vehicle Partnership) and through a stakeholder mapping exercise ensuring representation from hydrogen production, distribution and end-use industries as well as relevant policy and civil society stakeholders. Finally a 'snow-balling' technique was used at the scoping interviews, in which interviewees were asked to identify other key stakeholders to ensure that no major interests were missed.

2.2. Vision development

The aim of vision development was to create a small number of credible, transparent and internally consistent end points that strike a balance between the specificity of the visions and the coverage of hydrogen 'possibility space'.

The UKSHEC visions were developed through a participatory workshop and consultation [10], involving over 40 expert stakeholders from the UK hydrogen and energy policy communities: from academia, business, government and civil society (NGOs).

The visions each comprise: (i) narrative descriptions of archetypal configurations of hydrogen production, infrastructure (storage and distribution) and end-use technologies; (ii) indicative quantitative indicators to provide a sense of the scale of technological deployment implied; and (iii) system diagrams providing pictorial representations of each vision.

The visions are not intended as predictions, nor should they be seen as mutually exclusive. Indeed, the technologies they comprise could be configured into a wide range of possible future hydrogen systems, and hybrid systems. Instead, the visions are intended to cover the broad range of possibilities in a manageable number of visions. This means that the results cannot be seen as advocating or endorsing any one of the visions alone, but they are rather to be thought of as tools for learning about important perspectives, issues and uncertainties surrounding the hydrogen debate. The full visions are presented in Section 3.

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[1] For details of the final phase of the study, which developed a set of detailed transitions scenarios exploring the dynamics of four possible socio-technical transitions or pathways to hydrogen economies see [7].

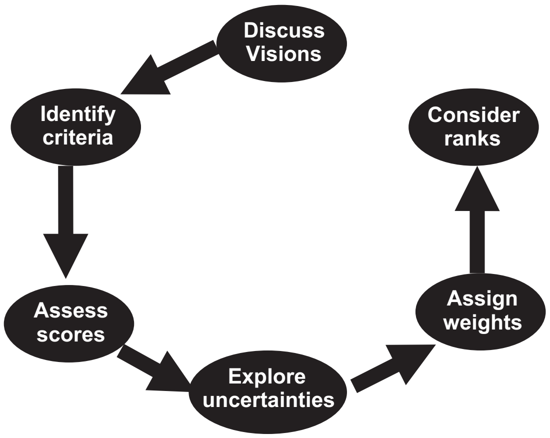

Fig. 1. The multi-criteria mapping process.

2.3. Multi-criteria sustainability appraisal

A wide variety of methods exists for multi-criteria appraisal (for a review see [11]). The highly uncertain and contested nature of long-term technological visions suggest that methods that attempt to find a single best choice are unlikely to be useful. In such a situation, a more appropriate approach seeks to capture alternative framings and value-based perspectives. Multi-criteria mapping (MCM), developed by Stirling [12,13], aims to "*explore the way in which different pictures of strategic choices may change, depending on the view that is taken – not to prescribe a particular 'best choice'.*" ([14, p. 5]). MCM thus maps the sensitivities of performance according to different perspectives, uncertainties and framing assumptions.

MCM is conducted through one-to-one interviews with stakeholders using a dedicated software package. Interviews are recorded, providing qualitative information on participants' reasoning. A brief overview of the method is outlined below, and further details are available from the MCM manual and interview protocol [14,15]. Some adaptations to the method were necessary for this study, as it has not been previously used to assess long-term visions in the context of a backcasting exercise. These amendments can be found in [9].

The expert panel which used MCM to appraise the UKSHEC visions was necessarily smaller than the group involved in vision development, involving 15 participants from a range of backgrounds (i.e., nuclear industry expert; carbon trust analyst; Department for Trade and Industry (DTI) policy maker; fuel cell industry participant; sustainable energy policy consultant; industrial gases industry participant; energy technology researcher; environmental campaigner; health & safety regulator; energy policy researcher; senior oil industry participant; department for transport (DfT) policy maker; automotive industry participant; regional government policy maker; and climate scientist).[2]

The MCM interview takes the participant through a structured series of stages: (i) discuss visions; (ii) define criteria; (iii) assess scores; (iv) explore uncertainty; (v) assign weights; (vi) consider ranks (see Fig. 1). Finally, the software produces a visual 'map' of the rankings of the visions, using a weighted sum method.

3. Visions of a hydrogen economy for the UK

This section sets out the six UKSHEC visions together with an additional status quo or reference vision, describing the current UK energy system. The six visions differ both in relation to the role of hydrogen (as a transport fuel only, or as providing both transport and broader energy services), the means of hydrogen generation and storage, and the degree of centralisation/decentralisation of its production and supply (see Fig. 2 below). In terms of time scales, the intention is to imagine them far enough into the future that substantial infrastructural changes are conceivable, but not so far into the future that the technologies envisaged today will be obsolete, that is, around 2040–2050.

Data for the indicative figures (such as number of wind turbines, or volumes of gas required) were taken from the CONCAWE and GM wells-to-wheels studies [16,17]. The calculations applying them to the UKSHEC visions can be found in [29].

3.1. Vision 1. Central pipeline (Fig. 3)

In this future, hydrogen has become the dominant road transport fuel. Hydrogen-powered lorries, buses and passenger cars–and even motor cycles—have become widespread, using PEM fuel cells. There is some use of hydrogen fuel cell systems for off-grid and back-up power, but this is a niche market with little significance for the wider energy system. Hydrogen is also used as a marine transport fuel, and there is increasing interest in the use of hydrogen as an aviation fuel, with significant R&D and demonstration activities in this area.

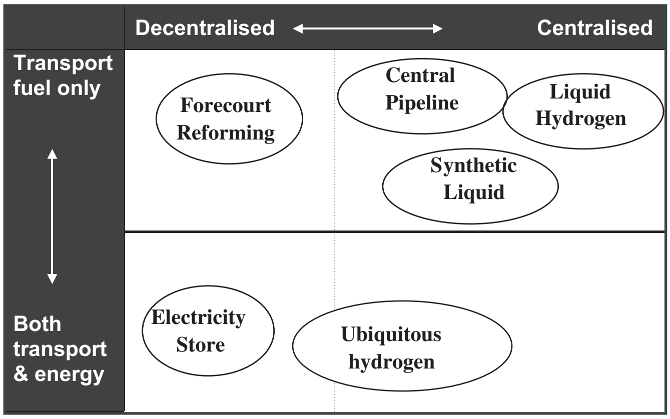

Fig. 2. The six UKSHEC visions.

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[2] Participants took part on the basis of their individual expertise, rather than as organisational representatives.

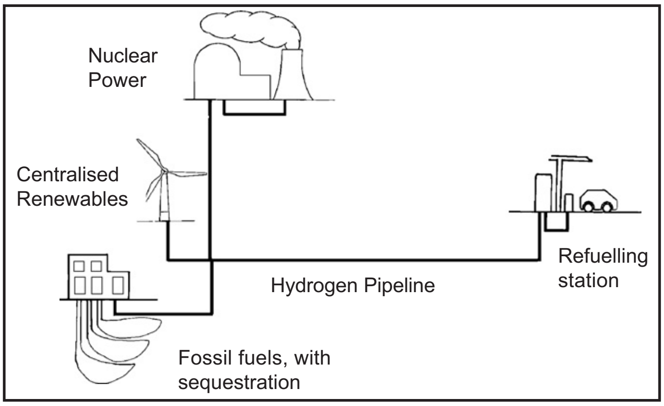


Fig. 3. Central pipeline.

There are three major hydrogen production routes in this future. Hydrogen is produced from:

- Nuclear power, either electrolytically, or through direct thermal or chemical routes in high temperature reactors (such as the sulphur–iodine process);
- Fossil fuel plant, both coal gasification and natural gas reforming, with sequestration of the carbon dioxide;
- Large renewable electrolysis installations, principally large offshore wind farms and marine power stations around the UK's coastline.

Energy for road transport is distributed as gaseous hydrogen. Heat and power for industrial, commercial and domestic use continue to be supplied by the electricity and natural gas grids. There is a hydrogen pipeline infrastructure connecting production facilities with refuelling stations in major centres of hydrogen use, such as city centres and along motorways, and supplying ports and airports. In areas of very low demand, hydrogen is provided by truck, much as petrol is distributed today. On-board storage is in solid state or compressed gas tanks; there is medium-term bulk storage in salt caverns and on-the-forecourt storage in solid-state stores.

This vision draws on: E4Tech et al. [18], Ogden [19], and the visions workshop [10].

If transport demand remains much as it is today, this future would require the following hydrogen production capacity:

- coal gasification: 40.6 million t of coal, or 76% of UK coal consumption in 2003, or
- steam methane reforming: 250 TWh, or 23–25% of UK gas consumption in 2003, or
- 32 Sizewell B sized nuclear power plants (1.2 GW; assuming electrolysis rather than thermal routes), or
- 27,700 3 MW wind turbines (compared to 1200 wind turbines currently installed in the UK).

3.2. *Vision 2. Forecourt reforming (Fig. 4)*

Hydrogen produced locally from natural gas is the dominant road transport fuel. The existing natural gas network provides the delivery infrastructure, and hydrogen is generated on-site by steam methane reforming at the refuelling station.

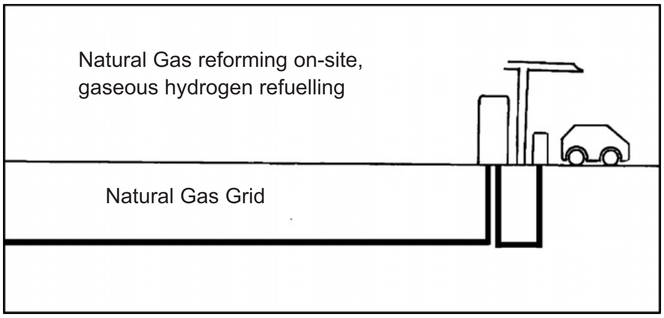


Fig. 4. Forecourt reforming.

The role of hydrogen is restricted to use as a transport fuel. Hydrogen-powered lorries, buses and passenger cars have become widespread, using PEM fuel cells, and storing hydrogen onboard as a compressed gas or in solid stores. Hydrogen is produced from natural gas, reformed at refuelling stations.

Energy for transport is thus distributed as natural gas, which plays a leading role in the energy system. As well as providing fuel for transport, most buildings are equipped with a CHP unit (possibly fuel cell) running on natural gas. There is some use of hydrogen fuel cell systems for off-grid and back-up power, but this is a niche market with little significance for the wider energy system. There is little significant hydrogen distribution infrastructure, as hydrogen is produced at refuelling stations, where it is needed. Local electrolysis or hydrogen trucks have a niche role where natural gas networks are poor. Hydrogen is stored at refuelling stations as compressed gas or in solid storage media. There is no large scale, long-term storage of hydrogen.

This vision draws on the vision workshop [10].

If transport demand remains much as it is today, this future would require 270–346 TWh of natural gas to satisfy demand for hydrogen for transport, equivalent to 24–31% of UK gas consumption in 2003.

3.3. *Vision 3. Liquid hydrogen (Fig. 5)*

Liquid hydrogen produced by nuclear power and large scale renewable installations has become the dominant fuel for both road and marine transport. There is an international market in liquid hydrogen. This is largely a scenario of substitution, with current energy and transport paradigms remaining unchanged.

Hydrogen powered lorries, buses and passenger cars have become widespread, using either 'flexible-fuel' combustion engines or PEM fuel cells. However, the size of on-board liquid hydrogen fuel tanks remains an issue for smaller city cars—where a niche market for battery vehicles exists.

In this future, liquid hydrogen is an internationally traded product, produced from nuclear power (either electrolytically or by direct thermal or chemical routes in high temperature reactors), and from large scale renewable installations, many of which are outside the UK. Regions of the world with large renewable resources, particularly solar, hydroelectric and wind, supply much of the world's demand for hydrogen.

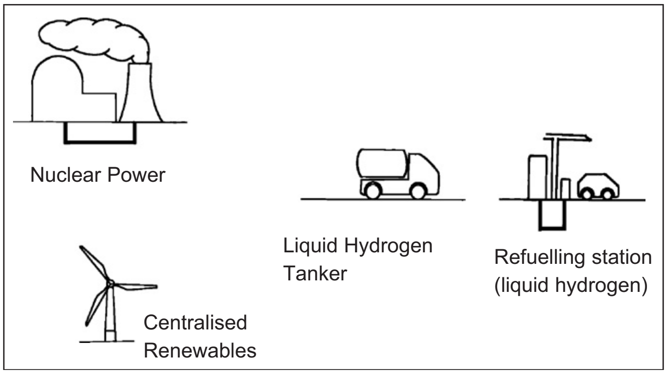


Fig. 5. Liquid hydrogen.

While energy for transport is distributed as hydrogen, heat and power for industrial, commercial and domestic use continue to be supplied by the electricity and natural gas grids. Hydrogen is distributed primarily as a liquid, by tanker, train and road, serving a network of refuelling stations around the UK. On-board storage is in cryogenic tanks, with liquid hydrogen. There is also bulk storage of liquid hydrogen at refuelling stations and fuel depots.

This vision draws on: BMW [20], Ogden [19].

Neither the GM nor the CONCAWE study provide wells-to-wheels energy for nuclear-liquid hydrogen or renewables-liquid hydrogen pathways, and we therefore have not calculated indicative generation capacities for this pathway.

3.4. Vision 4. Synthetic liquid fuel (Fig. 6)

Renewably produced hydrogen again provides the dominant transport fuel. In this case, however, it is ‘packaged’ in the form of a synthetic liquid hydrocarbon, such as methanol (or other alternatives, such as formic acid), to overcome the difficulties of hydrogen storage and distribution. The carbon for fuel synthesis comes from biomass and from the flue gases of carbon-intensive industries.

Hydrogen is produced from electrolysis based on renewables, particularly wind and marine installations around UK’s coastline. The hydrogen is then used as a feedstock for the production of methanol, adding hydrogen to carbon derived from biomass or from carbon intensive industries.

Energy for heat and power is distributed as electricity; energy for transport is distributed as methanol. Fuel distribution infrastructures remain largely as they do today, with liquid fuel tankers serving refuelling stations from large fuel depots. This future has little need of hydrogen storage. Hydrogen is ‘stored’ in the form of a hydrocarbon fuel, which is used much as petrol is today.

This vision draws on: Bossel et al. [21]; Arnasson and Sigfusson [22].

No wells-to-wheels energy data were found for this pathway, though a recent feasibility study claimed that up to 62% of the renewable electricity input can be stored as methanol [23].

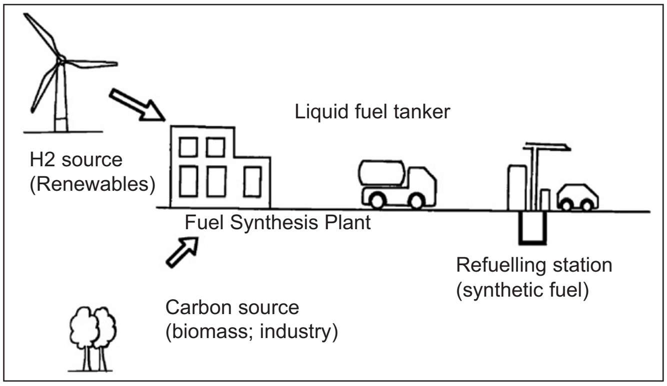


Fig. 6. Synthetic liquid fuel.

3.5. Vision 5. Ubiquitous hydrogen (Fig. 7)

Renewably produced hydrogen is a major energy carrier for heat and power as well as the dominant transport fuel. A national hydrogen pipeline grid serves most buildings. Many homes and businesses use fuel cell CHP systems running on hydrogen, and it is common to refuel vehicles at home. Hydrogen is produced from a mix of larger centralised and smaller scale distributed renewables and biomass.

Hydrogen-powered lorries, buses and passenger cars have become widespread, and hydrogen is also a major means of distributing energy for heat and power competing with electricity in much the same way as natural gas does today.

Hydrogen is produced both centrally and locally, using a variety of technologies, with a significant proportion from distributed renewables (such as wind turbines and building-integrated PV) and biomass (such as wood from short rotation coppice and forestry, agricultural, food industry and municipal waste streams via gasification, and from ‘wet biomass’ such as grasses and sewage sludge via fermentation). Large scale renewable hydrogen installations operate in renewable-rich areas (for example, highland Scotland, and offshore zones with wind, tidal and wave power potential), and some limited fossil fuel production of hydrogen with sequestration of CO_2.

An extensive hydrogen pipeline network competes with the electricity grid as the dominant means of distributing energy for all sectors: transport, heat and power. The hydrogen pipeline infrastructure has become ubiquitous, driven by the twin demands of vehicle refuelling and stationary use of hydrogen for the provision of heat and power in micro-CHP units. Vehicle refuelling is common in homes and businesses, and it is possible to ‘plug-in’ vehicles and sell electricity to the local electricity grid. On-board storage is in solid state or compressed gas tanks. The hydrogen pipeline network represents significant storage capacity, but this is supplemented with large scale storage in salt caverns and refuelling station installations.

This vision draws on: Rifkin [24], Lovins and Williams [25].

If transport demand remains much as it is today, providing hydrogen *for transport only* in this future would require either:

- 47–57 million t of dry short rotation coppice biomass, about 4.7–5.7 million ha, assuming average yield of 10 t/ha, or
- 27,700 3 MW wind turbines.

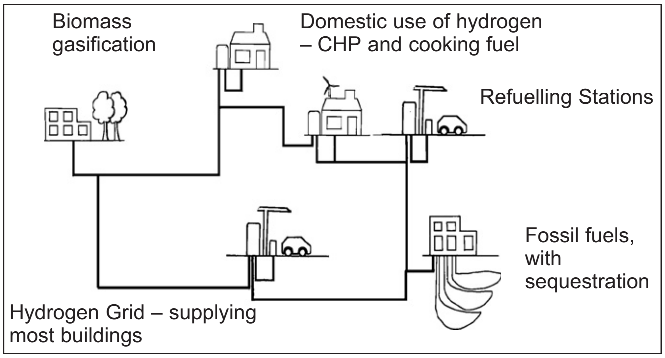


Fig. 7. Ubiquitous hydrogen.

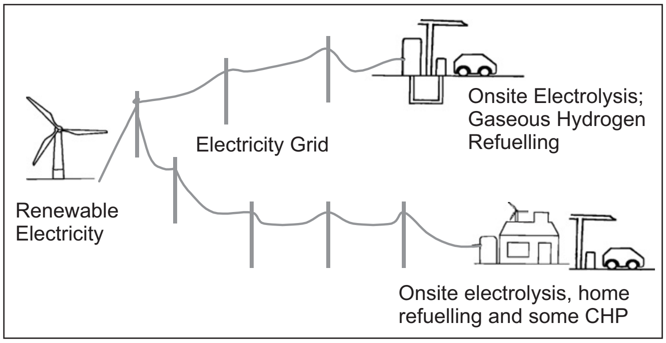


Fig. 8. Electricity store.

Clearly significantly more capacity would be required for the heat and power loads envisaged in this future.

3.6. Vision 6. Electricity store (Fig. 8)

Hydrogen, produced through onsite electrolysis, is the dominant road transport fuel, and also plays a vital role overcoming the intermittency problems of a renewables-based electricity system. Hydrogen production is flexible, and can respond to variable electricity supply conditions, easing load-balancing. Since hydrogen is produced onsite it requires no distribution infrastructure. Locally stored hydrogen provides back-up power for domestic and commercial CHP units at times of peak electricity demand/limited supply.

Large scale renewables have achieved near total domination of electricity generation, particularly offshore wind and marine installations around the UK coastline.

Electricity is the dominant energy carrier with gaseous hydrogen serving only as the storage medium and vehicle fuel. There is therefore no hydrogen distribution infrastructure. Hydrogen is produced (electrolytically) and stored onsite in refuelling stations or in private homes. Hydrogen is stored in solid state or compressed gas tanks.

This vision draws on: Sorenson et al. [26] and the vision workshop [10].

If transport demand remains much as it is today, this future would around 27,600 3 MW wind turbines, for transport alone. There are currently 1200 wind turbines in the UK. Clearly significantly more capacity would be required for the heat and power loads envisaged in this future.

3.7. Status quo vision

Hydrogen plays a negligible role in energy and transport systems. Transport is dominated by oil, refined in large centralised refineries into petrol and diesel for internal combustion vehicles in road transport, and kerosene and fuel oil for aviation and shipping. Transport fuel is distributed by road tanker from refineries to refuelling stations.

Power is provided by the electricity grid, and is generated from a combination of centralised natural gas, coal and nuclear plant. Renewable generation is a small proportion of total electricity supply. Heat is largely provided through the natural gas grid, and most homes have a domestic boiler burning natural gas for hot water and space heating. CHP plants, mostly in industry, provide only a small percentage of the heat and power consumed in this vision.

4. Results: appraising the sustainability of hydrogen futures

This section gives an overview of results from the multi-criteria appraisal, presenting the broad outputs. It is structured as follows. Firstly the panel's responses to the overall set of visions they were asked to appraised are briefly discussed. The criteria defined by the panel members and weightings attributed to these are then presented. Finally, the detailed pattern of appraisal, for example, rankings of the visions and associated uncertainties, are explored.

4.1. Visions

Overall, participants were comfortable appraising the set of visions developed, with none feeling that major elements of a possible hydrogen future were obviously missing. One participant defined an additional vision, while a further two explored hybrids of two of the UKSHEC visions. These additional visions are described in McDowall and Eames [9].

4.2. Criteria and weighting: dimensions of sustainability for hydrogen

In order to provide an integrated appraisal of the sustainability of the visions, participants were invited to define criteria under the following broad headings: (i) environmental; (ii) economic; (iii) social; (iv) energy security; (v) other. Between them, the 15 panel members defined a total of 98 criteria, of which many were very similar across different participants (for example, various criteria exploring carbon emissions, social acceptability, energy security and so on) (Fig. 9).

The overall picture of weightings provides an overview of the groups of issues that participants judged to be most important. There is a clear tendency for environmental issues to receive high weightings, with social issues in general receiving much

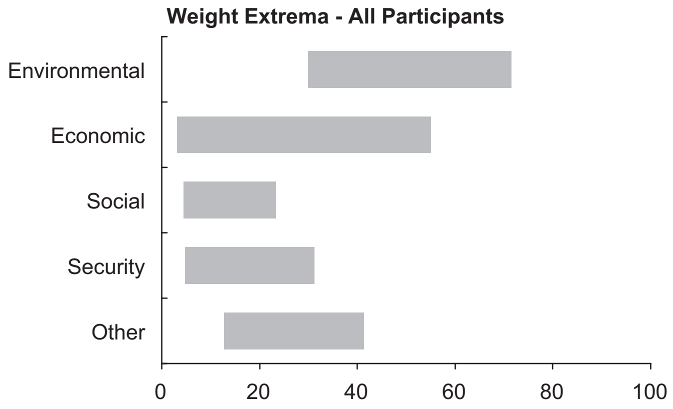


Fig. 9. Shows the spread of weightings from all participants. Each participant distributed 100 weighting 'points' among their criteria, to indicate relative criteria importance.

less attention, and with a substantial spread of views around the importance of economic criteria.

4.2.1. *Environmental issues*

The six visions were clearly differentiated on the basis of their environmental performance. This was dominated by carbon emissions, but included a range of other criteria (see Table 1). Uncertainties with respect to these scores occurred despite relatively well characterised 'wells-to-wheels' data for different hydrogen infrastructure pathways. Some participants were sceptical of, for example, the viability of sequestration technologies, and gave visions involving sequestration a range representing that risk of technological failure. In terms of weightings across the participants overall, carbon emissions were clearly considered to be the most important single determinant of a vision's sustainability.

Five participants scored an 'air quality' criterion that focused on the emissions from vehicles, although in general these were not weighted highly. There was little difference among the visions from a local air quality perspective, with lower scores for *synthetic liquid fuels*. Environmental issues other than carbon and local air quality favoured *electricity store*. Visions involving nuclear power, and with a predominance of large scale fossil fuels, tended to do less well.

4.2.2. *Economic issues*

The economic sub-rankings are interesting, with none of the visions coming out as obviously better or worse when the appraisals of all participants are examined as a whole. However, many of the individual participants did see significant variation among the visions in terms of economic performance. All participants scored some form of economic criterion (although for the *health and safety regulator* this was through a 'feasibility' criterion in the 'other' category of issues) (Table 2).

The most highly weighted economic criteria concerned feasibility, and economic attractiveness of the vision to investors. Nine participants scored some kind of 'cost' criterion. However, these were varied. Some concerned costs to society overall, while others were intended to represent what consumers might pay at the pump. Moreover, variations in the appraisals of the economic performance of the visions were also

Table 1
Environmental criteria

Nuclear industry participant	GHG emissions Local air quality Toxicity Visual impact
Carbon trust analyst	Global impacts Regional impacts Local impacts
DTI policy maker	Carbon emissions Other environmental issues
Fuel cell industry participant	Carbon emissions Local air quality Other environmental impacts
Sustainable energy policy consultant	Cost effective carbon reductions Local environmental impact
Industrial gases industry participant	Carbon emissions Local air quality
Energy technology researcher	Greenhouse gases Local air quality Other environmental impacts Biodiversity
Environmental campaigner	Greenhouse gases No nuclear power
Health and safety regulator	Greenhouse gases Non-carbon pollution
Energy policy researcher	Carbon emissions trajectory Natural environment/wilderness Catastrophic risk
Senior oil industry participant	Energy efficiency Physical integrity
DfT policy maker	Carbon Other environmental issues
Automotive industry participant	Carbon Utilisation of available resources
Regional government policy maker	Carbon Air quality Complementarity with renewables
Climate scientist	Global environmental improvement

Table 2
Economic criteria

Nuclear industry participant	Affordability of H_2 fuel
Carbon trust analyst	Cost of fuel Impact on UK economy Degree of consumer choice
DTI policy maker	Impact on UK economy Impacts on local economy
Fuel cell industry participant	Fuel cost Business case feasibility
Sustainable energy policy consultant	Economic attractiveness
Industrial gases industry participant	Upfront capital costs Ongoing fuel cost
Energy technology researcher	Cost
Environmental campaigner	Cost
Energy policy researcher	Least cost portfolio
Senior oil industry participant	Affordability
DfT policy maker	Business case feasibility
Automotive industry participant	Economic feasibility
Regional government policy maker	Cost
Climate scientist	Cost competitiveness

Table 3
Social criteria

Nuclear industry participant	Socio-political acceptability
Carbon trust analyst	Access to energy services Public acceptability
DTI policy maker	Social acceptability
Fuel cell industry participant	Social acceptability
Energy technology researcher	Public acceptability
Health and safety regulator	Public acceptability
Energy policy researcher	Social justice
Senior oil industry participant	Physical intrusion Control of energy Usability
DfT policy maker	Public acceptability
Automotive industry participant	Degree of state intervention required
Regional government policy maker	Acceptability/risk

dependent on different assumptions about policy frameworks around carbon; fossil fuel prices; the costs of nuclear power; and the relative affordability of more decentralised, modular systems or capital-intensive centralised systems.

4.2.3. Social issues

Seven participants scored only a ‘social acceptability’ criterion under this heading, and the way in which these were scored suggested that acceptability was seen as a barrier to uptake, rather than an ongoing dimension of sustainability. The performance of the visions varied amongst participants, with some arguing that ‘out of sight’ centralised systems such as *central pipeline* would be most acceptable, and others arguing that publics would be most willing to accept the least polluting visions, such as *electricity store* (Table 3).

Some participants scored visions on a wider range of social and political concerns: for example, the degree to which the system enabled access to energy services, or the degree to which the future was seen as necessitating interference of the state. These other social issues tended to be given higher weightings than acceptability criteria. In general, visions involving greater decentralisation tended to do well under these criteria.

4.2.4. Energy security issues

All but three participants scored criteria under ‘energy security’, including primary energy security, infrastructural integrity, and diversity of sources. Unsurprisingly, *forecourt reforming* did badly under energy security criteria, given its dependence on natural gas (Table 4).

Table 4
Energy security

Nuclear industry participant	Redundancy/security of primary supply Diversity of primary
Carbon trust analyst	Security/diversity
DTI policy maker	Security
Industrial gases industry participant	Security of supply
Fuel cell industry participant	Supply security
Sustainable energy policy consultant	Upstream energy security
Energy technology researcher	Resource scarcity Diversity of supply
Energy policy researcher	Primary supply Infrastructure
Senior oil industry participant	Diversity of sources
DfT policy maker	Security of supply
Automotive industry participant	Security/diversity
Regional government policy maker	Compatibility with decentralised

Table 5
Others

Nuclear industry participant	Quality of supply Technical feasibility
DTI policy maker	Health and safety Feasibility
Environmental campaigner	Public safety Flexibility Upheaval Geo-political issues
Health and safety regulator	Practicability/feasibility Flexibility
Energy policy researcher	Radioactive waste Complementarity
Climate scientist	Scale of tech deployment

4.2.5. Other issues

This diverse category included criteria addressing issues of feasibility and practicality, health and safety, flexibility and adaptability of the system, the degree to which the visions promote decentralised renewable energy options, and radioactive waste (seen here as having both environmental and social implications, and therefore not confined to one or other category). *Liquid hydrogen* tended to do badly here, based on concerns about practicality, safety, flexibility and the inclusion of nuclear power, among other factors. Perhaps surprisingly, *synthetic liquid fuel* was, on aggregate, seen as the best performing under these criteria (Table 5).

4.3. Ranking the visions

Fig. 10 presents the panels’ final appraisal of the visions sustainability. These aggregated results provide a rough picture of the contours of the appraisal, and allow us to examine where individual participants’ appraisals differ markedly from the panel as a whole.

Fig. 11 above provides final outputs for each participant, and demonstrate the wide variety of individual appraisals.

This analysis confirms the highly contested nature of the debate, with no absolute winners or losers, and with a wide range of rankings for all visions. However, examination of the relative performance of each vision, under both optimistic and pessimistic assumptions, provides some clear messages about the likely sustainability of the different visions.

4.3.1. Central pipeline

All participants recognised this future as playing a well-established role in hydrogen debates, but it was the vision with

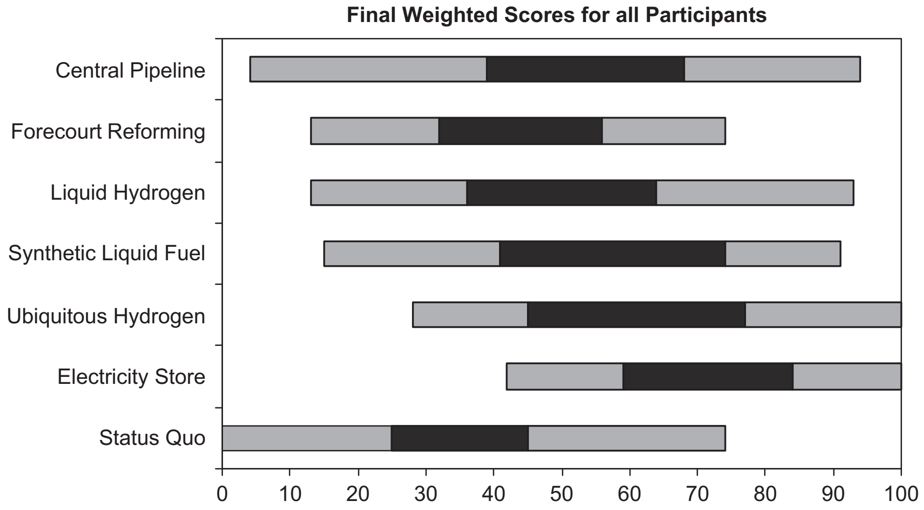


Fig. 10. Final weighted scores aggregated across all participants. Bars indicate extreme (grey) and average (black) pessimistic and optimistic scores, capturing the degree of uncertainty about future performance. The x-axis is a relative scale indicating low (0) to high (100) performance.

the widest range of rankings. *Central pipeline* was ruled out by the *environmental campaigner* because of its inclusion of nuclear, and in the view of the *energy policy researcher* and *regional government policy maker* it performed worse than any other vision. In these participants' views, centralised systems with fossil fuels, nuclear power and pipelines performed poorly. In contrast, the *sustainable energy policy consultant* ranked this vision as the best performing, arguing that it provided the most cost effective way to reduce carbon emissions and enhance energy security.

4.3.2. *Forecourt reforming*

Eight participants saw this as having little role as a viable ‘end-point’ vision, but spoke of it as having a valuable role to play as a transitional step in terms of infrastructure development. However, there was also some support for it as an ‘end-point’ vision, if natural gas remains plentiful. An interesting feature of this vision was the debate over its practicality, with the panel showing sharply opposing views on the feasibility of widespread distributed natural gas reforming.

This vision was seen as the worst performing by six participants. This was because of poor performance on carbon criteria, and for some participants, poor performance on energy security criteria. In no case was this seen as the best performing vision. The overall poor performance of this vision is confirmed at the aggregate level, where it performs worst under both optimistic and pessimistic assumptions.

4.3.3. *Liquid hydrogen*

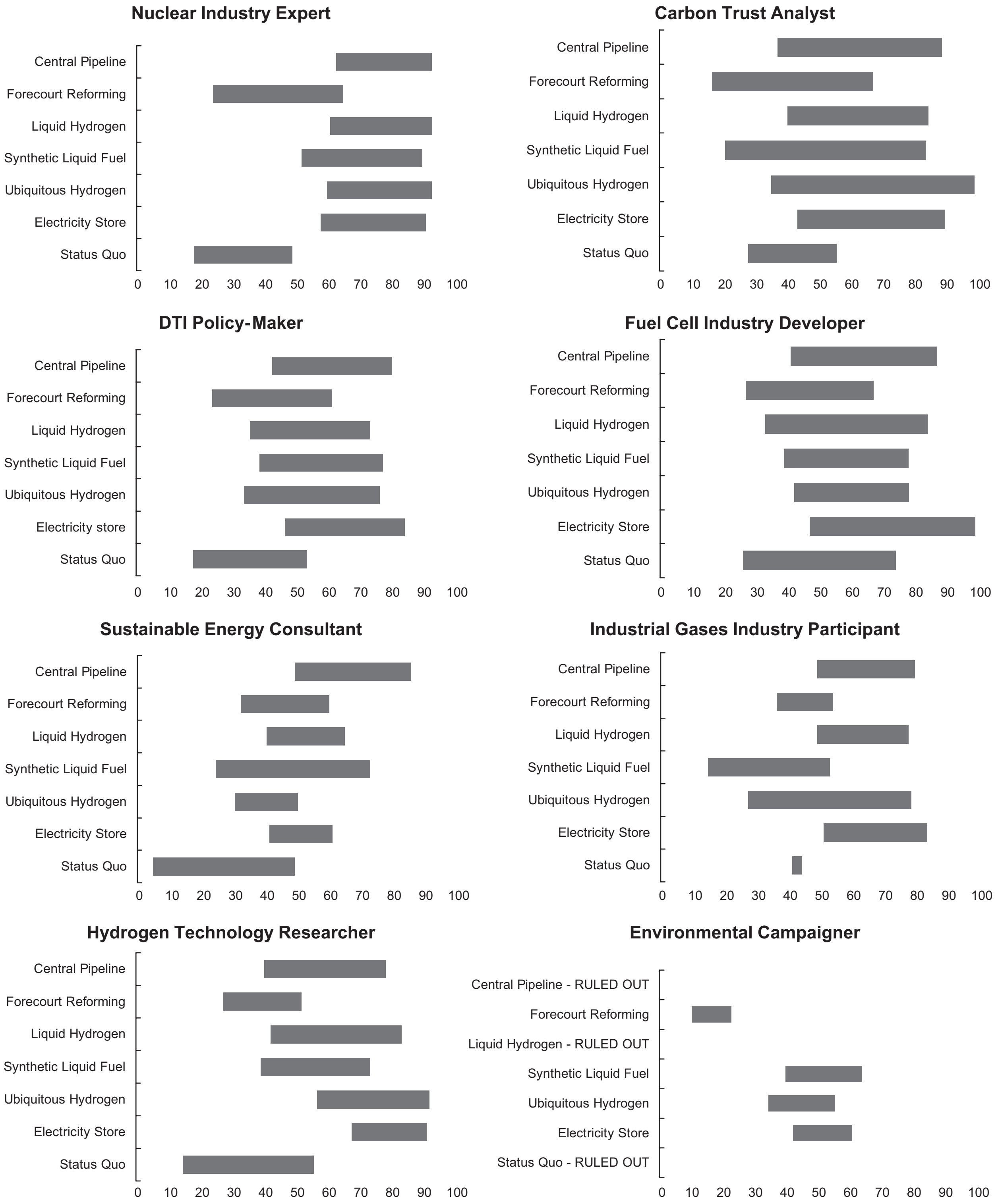
Several participants felt that this was one of the least likely visions presented in the set. However, the technologies within the vision were all felt to be relevant and worth exploring. The *industrial gases industry participant* felt it was not likely, but broadly plausible: “the technology's known, it's a current way of distributing hydrogen, … if you can justify the investment in the plant and you know there's a market there, then… it doesn't seem unreasonable to me.” The feeling overall seemed to be that while liquefied hydrogen is likely to play an important role in the distribution and storage of hydrogen in some circumstances, the sole use of liquid is unlikely.

The *health and safety regulator*, the *senior oil industry participant*, and the *DfT policy maker* ranked *liquid hydrogen* worst under both pessimistic and optimistic assumptions. A further participant (the *environmental campaigner*) ruled it out entirely, on the basis of its inclusion of nuclear power. In no case was the *liquid hydrogen* vision the best performing. However, the *automotive industry participant* created an additional vision, a hybrid of liquid hydrogen and ubiquitous hydrogen, and this performed very highly in this participant's appraisal.

4.3.4. *Synthetic liquid fuel*

Unlike the other visions, this was new to many of the participants, but in general it was thought to be an interesting addition to the overall set. The *industrial gases industry participant* and the *regional government policy maker* both felt that it was not plausible, given the apparent direction of automotive firm R&D, which was seen to have ‘turned its back’ on synthetic fuels such as methanol. The *DTI policy maker* had been sceptical at the scoping interview stage, but was more positive in the MCM interview: “I was sceptical because… all the vehicle manufacturers seem to be assuming gaseous hydrogen as storage or possibly solid-state hydrogen storage as being, the means of introducing fuel cell vehicles. Having looked at the arguments for synthetic liquid fuels, I think there's definitely a case to be made there.”

The *sustainable energy policy consultant* and *industrial gases industry participant* saw scope for this being the worst performing vision, but both of these participants gave this ranking a high degree of uncertainty. Only in the view of the *industrial gases industry participant* did it remain the worst performing even under most positive assumptions. Both of these participants were sceptical of the carbon balance of



Nuclear Industry Expert

Carbon Trust Analyst

DTI Policy-Maker

Fuel Cell Industry Developer

Sustainable Energy Consultant

Industrial Gases Industry Participant

Hydrogen Technology Researcher

Environmental Campaigner

Fig. 11. Individual weighted score ranges. The *x*-axis is a relative 1–100 scale showing performance, with better performing visions further to the right. Bar length is a result of the degree of difference between pessimistic and optimistic scores, and is thus a function of the degree of uncertainty.

this vision, and of its likely feasibility and costs. No participant saw this as the best performing vision, but in the views of six participants it performed well under positive assumptions.

4.3.5. *Ubiquitous hydrogen*

Opinion on this vision was sharply divided. The *sustainable energy policy consultant* felt it to be implausible, because of the efficiency issues around distributing energy for stationary

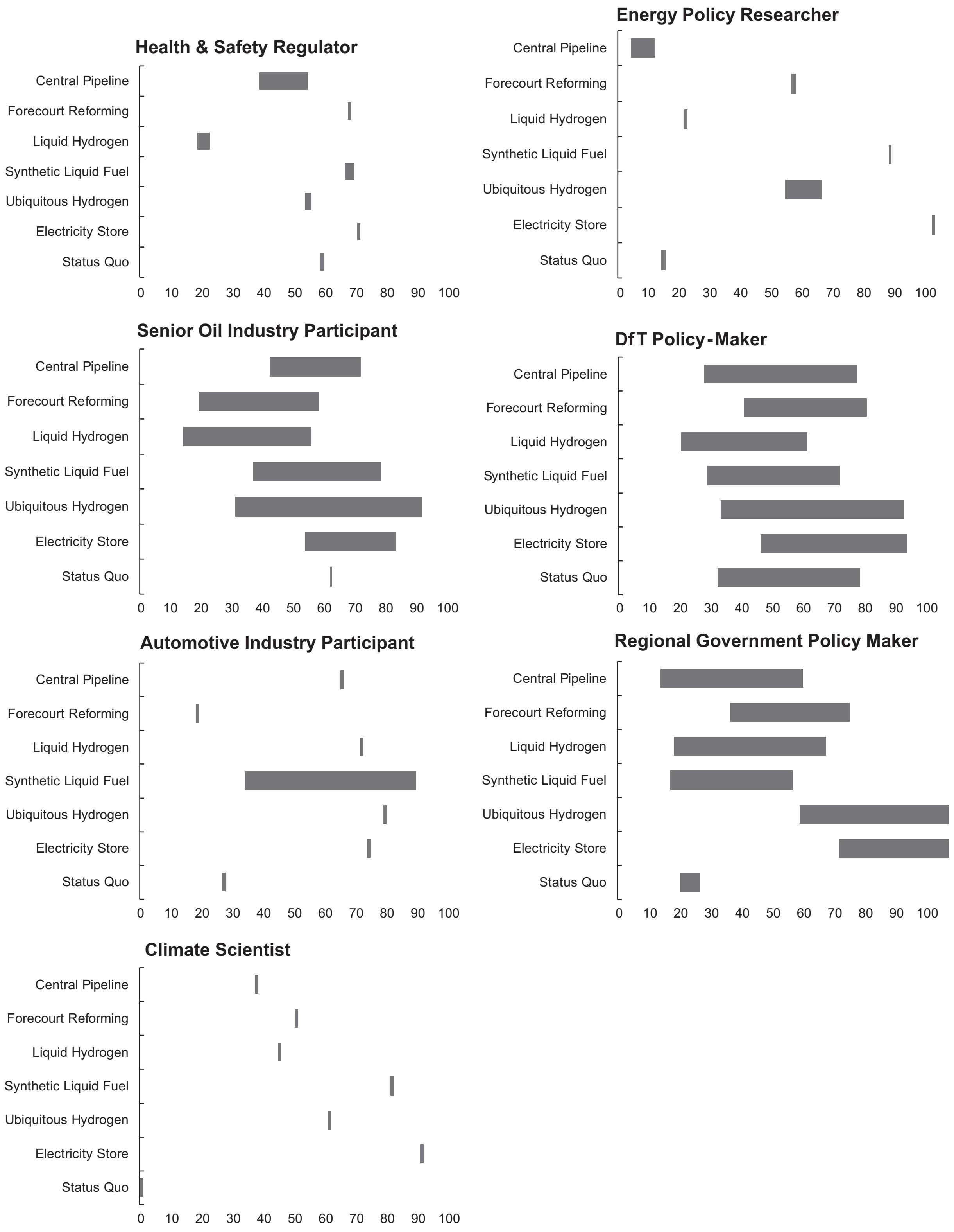


Fig. 11. (*continued*).

applications as hydrogen. For others, it is the most sensible and desirable system. A common attitude to this vision was summed up by the *DTI policy maker*, who commented that "it's credible when there aren't really any alternatives left", and particularly when natural gas is no longer economically available.

Only the *sustainable energy policy consultant* saw this as potentially the worst performing vision. This was largely on the basis of cost and feasibility, and the feeling that hydrogen should not compete with electricity for stationary power. Two participants (the *carbon trust analyst* and *senior oil industry participant*) saw this as potentially the best performing vision, and a further two participants saw it as joint best with *electricity store*. However, no participant ranked it best under least favourable assumptions, suggesting that it would not be seen as a fall-back option.

4.3.6. Electricity store

All participants recognised this as a major part of the hydrogen debate. Most saw it as only viable in the very long term, given its reliance on renewables, and the *industrial gases industry participant* and *DfT policy maker* were concerned that pursuit of this vision would lead to less efficient use of limited renewable electricity supplies. The *nuclear industry expert* felt that the inclusion of nuclear power in this vision would make it more robust and more feasible.

No participant saw this as the worst possible vision, and where it did perform poorly, this was on the basis of concerns about feasibility and cost, and scepticism about the availability of sufficient renewables capacity. Several participants saw it as only viable in the very long term. *Electricity store* was seen as performing the best under five participants views, and as joint best along with *ubiquitous hydrogen* under a further two. This vision did best among participants that strongly supported renewables, rejected nuclear and carbon sequestration, and preferred decentralised systems. *Electricity store* also performed best overall at the aggregate level.

Finally, it is interesting to compare the performance of the *status quo* vision with the hydrogen visions.

4.3.7. Status quo

In the appraisals of many participants, there were conditions under which the status quo was not the worst performing option, implying that some hydrogen visions could be less sustainable than current, or business as usual, activities. However, status quo was frequently the worst performing option, and in no case was it the best performing, suggesting broad agreement that many hydrogen systems bring sustainability gains.

4.4. Key uncertainties affecting vision performance

The picture as a whole shows huge uncertainty. In the views of some participants, the scale of uncertainties within the visions is as important as the differences between them, a conclusion that should not be surprising given the long time horizons involved. Quantitative and qualitative analysis of the MCM interviews suggests two key dimensions to this uncertainty.

4.4.1. Uncertainty about technologies

There are uncertainties surrounding technologies, not only in terms of their physical performance, but in terms of what impacts the technologies might have in broader socio-economic and environmental terms. The following uncertainties were each identified by more than three participants, and were reflected in variations between pessimistic and optimistic scores.

- Potential leakages of CO_2 from carbon capture and storage.
- Fuel cell performance.
- Performance of small scale natural gas reformers—in terms of both cost and pollution.
- Likely carbon balance and toxic emissions from synthetic liquid fuel synthesis and use.
- Costs for all technologies were subject to uncertainty, but in particular uncertainties relating to the costs of synthetic liquid fuels, nuclear power, and pipeline infrastructures were raised.
- Significant uncertainties around public acceptability of technologies in general.
- Performance, integrity and vulnerability of pipelines.
- Very large uncertainties around the possible impacts on the UK economy as a whole.

Other areas of uncertainty, raised by fewer participants, included: hydrogen storage, safety of handling hydrogen in a domestic environment, safety of liquid hydrogen, likely developments of fast-breeder reactors (seen as necessary if uranium resource constraints are to be avoided), efficiency of liquefaction, performance of electrolysers, likely pollution from biomass gasification, whether the natural gas network can be upgraded to take hydrogen, and whether decentralisation constrains or enhances access to energy.

4.4.2. Sensitivity of vision performance to different possible future contexts

Variation between optimistic and pessimistic scores also occurs where there is uncertainty about the broader context in which the visions exist, such as:

- Future natural gas availability and price—particularly important for the feasibility of *ubiquitous hydrogen*, and the feasibility and costs of *forecourt reforming*.
- Future national and international climate change policy frameworks, such as carbon taxes, clearly have an important effect on the feasibility of the visions, and on their relative costs.

Other context uncertainties of this kind included broader social attitudes towards technology and the environment, and the strategic direction taken by the automotive industry.

5. Analysis and discussion: issues in the appraisal of hydrogen futures

This section explores what the process tells us about the sustainability of competing hydrogen futures, by examining the issues which most clearly divided participants' perspectives. Overall, carbon emissions were the most important factor in the panels' appraisals. However, participants differed strongly over three key issues and it was their attitudes towards: (i) nuclear power; (ii) decentralisation; and (iii) feasibility that most clearly defined their differing perspectives on how to judge the future sustainability of hydrogen systems.

5.1. Nuclear power

Nuclear was the only component of the visions that any participant (the *environmental campaigner*) ruled out on principle, as fundamentally unsustainable. For many participants, nuclear provoked concerns about the environmental and health risks of radiation, but nuclear was also a more significant factor in the appraisals of the *energy policy researcher* and the *regional government policy maker*. Their reasons for opposing nuclear power extended to political issues, and perceived implications of nuclear to the development of alternative energy systems.

In the *energy policy researcher's* view, nuclear power is a fundamentally 'anti-democratic' technology that would be dangerous in a destabilised, climate change world. Both the *energy policy researcher* and *regional government policy maker* also opposed nuclear on the basis that the development of nuclear would undermine efforts to move towards energy efficiency and renewables. In the words of the *regional government policy maker*, "[*nuclear and renewables*] *work against each other*. *If you can do nuclear on that scale*, *you'd probably just do nuclear*".

However, a somewhat different view was articulated by the *sustainable energy policy consultant*, and as similar arguments were made by others it is worth quoting at length:

> "Nuclear… is fundamentally opposed to the notion of sustainable development. The idea that you have to bury waste in a hole for a hundred years before you can even deal with it flies in the face of the leaving the world in the state that you found it. However, I see it as a lesser of evils debate, because leaving the world closer to the risk of catastrophic climate change is probably a worse thing to do."

By contrast the *nuclear industry expert* felt that good management could overcome the difficulties associated with waste and with the global political implications of nuclear power, and that nuclear would not necessarily undermine the development of renewables. This view is in sharp opposition to the view of the *energy policy researcher*, and illustrates very different beliefs about the politics of this technology.

5.2. Centralisation and decentralisation: beliefs about the impacts of scale on society

There are claims in the hydrogen futures literature and popular press about the potential for hydrogen to enable decentralisation and consumer awareness of energy or even greater democratisation and empowerment (for example, [23]). The members of the expert panel took a range of views about such claims, and their approach to decentralisation and was an important factor distinguishing their appraisals.

Several participants (the *regional government policy maker*, *senior oil industry participant*, *automotive industry participant*, *DTI policy maker*, *energy policy researcher* and *environmental campaigner* saw value in distributed systems emphasising local energy production. These views were reflected through, for example, criteria examining the economic benefits to local communities and 'control over energy'. The case for distributed systems was put most forcefully by the *regional government policy maker*, who argued that decentralised hydrogen "*has the potential to revolutionise the way we use energy*", allowing much greater efficiencies, local control and empowerment.

Other participants were more sceptical about the benefits of decentralised hydrogen systems. The *sustainable energy policy consultant* broadly agreed with the social arguments in favour of distributed energy, but felt that the visions could not be differentiated on this basis. The potential benefits of decentralisation were seen as not coming from a particular structure of energy system per se, but instead on the structure of ownership and management. This participant felt that there was nothing inherent in the technologies that implied the social and technological worlds that go with them.

5.3. Feasibility, practicality and speed

Some participants felt that the most important issue was not to compare the likely sustainability impacts of the various hydrogen systems, since with the partial exception of *forecourt reforming*, all the visions tackle the basic problem of climate change. The question, for these participants, was more to do with the feasibility and practicality of arriving at the visions. As one participant argued "*in terms of prioritisation*, *what's important is how quickly will this particular route get to the end game* [*of low carbon emissions*]. *And … I would say that's probably THE most important issue*."

All visions were considered technically possible. The question of feasibility was more frequently seen as economic and political. As one participant argued: "*what I mean by practicability/feasibility is… why should that be done*? *…Why should the customer want to do this*? *And in a … reasonably democratic situation… The customer is going to have to want to do…one of these rather than being told to do one of these*." This raises some fundamental issues of what is possible in a democratic consumer society, and the extent to which governments can force technology choices onto the public in the name of sustainability.

Finally, participants differed in their perceptions of which visions might be more or less feasible, particularly from an economic point of view. Some felt that *electricity store* was more feasible because of its modularity and relatively low infrastructure costs; most felt that the high levels of renewables involved in the scenario made it feasible only over very long time horizons, and much less feasible than others. Two participants felt that *ubiquitous hydrogen* would only be possible when natural gas supplies are unavailable. Participants also differed in their perceptions of the feasibility of *forecourt reforming*, with most seeing it as relatively straightforward. In contrast, the *senior oil industry participant* argued that for most refuelling stations, there is no space for reforming technologies, saying

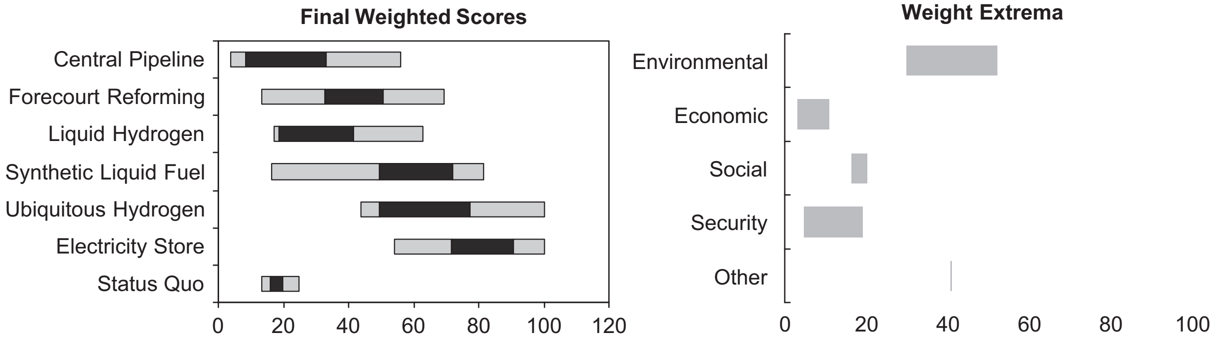


Fig. 12. Shows weighted scores and weightings for the *energy policy researcher*, *environmental campaigner and regional government policy maker*.

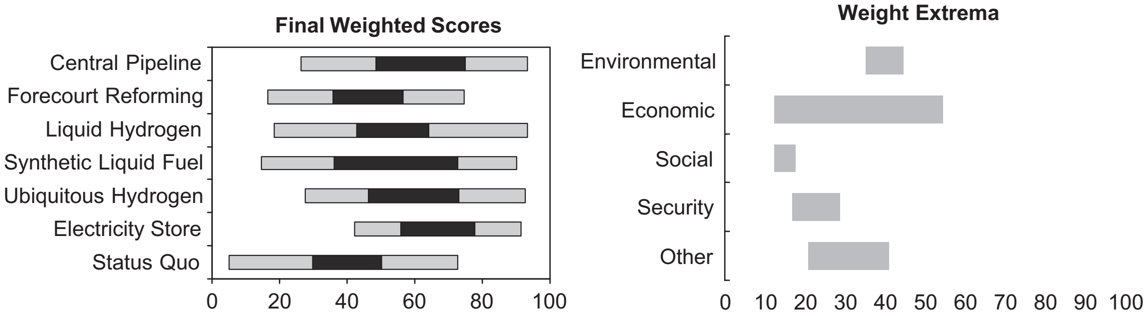


Fig. 13. Shows the rankings and weightings for the sustainable *energy policy consultant*, *industrial gases industry participant*, *DfT policy maker*, *health and safety regulator*, *automotive industry participant* and *nuclear industry expert*.

"*as somebody who actually runs one thousand three hundred petrol stations*, *I could tell you this is nigh impossible*". Similarly, the *regional government policy maker* also raised the issue of very limited space in urban environments.

5.4. *Differing perspectives on vision appraisal*

The way in which participants approached these three key issues had a major impact on their overall ranking of the visions.

Three participants (the *energy policy researcher*, *environmental campaigner* and *regional government policy maker*) were strongly opposed to nuclear power, and strongly favoured renewables and decentralised systems (Fig. 12).

A second group of participants took a view much more clearly defined by economic feasibility. This group comprised the *sustainable energy policy consultant*, *industrial gases industry participant*, *DfT policy maker*, *health and safety regulator*, *automotive industry participant* and *nuclear industry expert*. In this view, while social issues are recognised to be important, there is little sense that different technological systems have strong implications for social issues or political relations. Participants in this view tend not to be hostile to nuclear power, or at most to see it as a 'necessary evil'. Some of these participants felt that there would be little differences between the environmental performance of the six visions, with the exception of *forecourt reforming*. Instead, the important aspect of appraisal was the relative feasibility and economic attractiveness of the visions (Fig. 13).

Striking differences between the patterns of appraisal are clear, based on very different perceptions of what is important in determining sustainability.

Finally, the remaining participants sat between these two groups, voicing concerns about the more social and political dimensions of the different systems, but seeing these as either intractable, or as less important than other aspects of the problem. These other participants identified some criteria that explored broader social and political aspects (such as 'social control over technology, 'degree of consumer choice' and 'physical intrusion'), but did not have strong views about the social implications of any particular technologies, or about the nature of centralised rather than decentralised systems.

6. Conclusions: insights on the road to a sustainable hydrogen economy

This MCM exercise yields two kinds of conclusions. First, in reflecting the judgements of leading UK hydrogen energy experts, it provides some direct insight into the likely relative performance of the different hydrogen energy systems under consideration, and helps us to decide which might be more sustainable to pursue. Secondly, it makes clear what issues and uncertainties are at stake, and opens up the range of social, political and ethical perspectives that lead to differing conclusions about the sustainability of the visions.

6.1. The sustainability of the UKSHEC visions

The results from the MCM indicate that, overall, *electricity store* was seen as the most sustainable option, subject to concerns about feasibility. *Forecourt reforming* was judged to be least sustainable, largely because of carbon emissions, but also concerns about the security and economic implications of natural gas dependence.

Central pipeline was the most contentious vision, with the widest range of rankings, reflecting divergent opinions on nuclear power, carbon sequestration and the viability of a large, centralised pipeline infrastructure. The relatively strong performance of *synthetic liquid fuels* reflected the potential benefits of a low carbon fuel that is straightforward to store and transport, and that offers fewer technological barriers than the use of pure hydrogen. It was also the vision around which there is greatest uncertainty. *Liquid hydrogen* did poorly, partly because of participants' concerns about nuclear power, but more importantly because liquefied hydrogen was seen as impractical and inefficient for use as a mainstream transport fuel (although it was widely seen as having niche applications). Finally, *ubiquitous hydrogen* performed relatively well, but as with *electricity store*, there were some concerns about its feasibility.

Since there are many possible configurations of the technologies that compose each vision, the final rankings of the visions tell us only a small part of the story. Alternative configurations of the visions, with technologies such as nuclear included in a different set of visions, might have lead to a rather different pattern of final rankings. The important issues, uncertainties and participants' perspectives on particular technological components are the second-order conclusions, and provide us with deeper insight into issues surrounding the sustainability of hydrogen.

6.2. Insights into the likely sustainability of a hydrogen future

The panel recognised that a hydrogen energy system has the potential to deliver substantial sustainability benefits over the status quo, or business as usual futures. Overall the panel's results support the view that carbon emissions are the single most important dimension of sustainability with respect to the hydrogen visions. However, a very wide range of issues were seen by the panel to be important in judging the sustainability of hydrogen systems, and the findings remind us that issues other than carbon and cost need to be considered if hydrogen energy is truly to deliver greater sustainability.

Furthermore, the appraisal suggested that hydrogen is not automatically a sustainable option, as the panel recognised a range of circumstances in which hydrogen energy might be less sustainable than the current system or some non-hydrogen business as usual futures. There was also significant disagreement about *which* visions were considered to be more or less sustainable. These findings reflect two important sources of divergence in the final sustainability rankings: uncertainties and contested views of sustainability.

Important uncertainties were expressed with respect to the performance and costs of: carbon capture and storage, nuclear power, hydrogen pipelines, small scale reformers, fuel cells and hydrogen storage technologies. These uncertainties go beyond purely technical performance to include the way in which technologies might be expected to work in the real world, in relation to the behaviour of users, firms and regulators. Uncertainties about the dynamics of technological change are also important—does pursuing some options close off others? Policy should seek to respond to such uncertainty by ensuring that a diversity of options are pursued, and that backstop technologies are available.

Hydrogen policy must also be robust in the face of uncertainties about future context conditions, such as the availability and price of natural gas, and public attitudes to technology. The future of political frameworks around carbon and climate change was a key uncertainty affecting the perceived feasibility of the visions.

However, the findings suggest that even with perfect foresight and no uncertainties it would not necessarily be possible to obtain a single consensus view on which futures are most sustainable. This is because participants have different ideas about what sustainability means, what elements are more or less important, and about what sort of society is desirable. In short, there is an inescapably political element to long-term technological choice. Different approaches to nuclear power and decentralisation were important in distinguishing participants' appraisals, and reflect different understandings of the social impacts of technology. Attitudes to feasibility were also very different, with some participants feeling that differences in the sustainability of the end visions were less important than differences in the feasibility of getting to them. These contested priorities and perspectives suggest that the broad advocacy coalition promoting hydrogen may be fragile. If hydrogen systems develop, there is significant potential for conflict and disagreement over the shape and direction that those systems take.

These findings complement technical appraisals such as wells-to-wheels carbon analysis. The findings broaden the range of issues considered, and are useful to policy-makers concerned with broader uncertainties. In a report to the European Parliament, for example, these results have been presented alongside wells-to-wheels data to provide parliamentarians with a broader insight into the issues at stake [27].

Finally, the appraisal suggests that 'business as usual' or the market alone are unlikely to deliver any of the visions, at least in the short term, and that shifts in fossil fuel supplies, policy frameworks, or social priorities with respect to climate change will be necessary to drive a transition to hydrogen. If and when such a transition occurs, it is essential that there is opportunity for open, accountable and democratic debate, to ensure that the interests of society as a whole are reflected in a sustainable energy future.

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Sustainability, foresight and contested futures: exploring visions and pathways in the transition to a hydrogen economy

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This paper reports an innovative foresighting study which constructed a set of hydrogen futures and pathways to them, in order to inform the transition to a sustainable hydrogen economy. Combining backcasting and multi-criteria appraisal the authors developed a participatory expert stakeholder-led methodology to build and appraise a set of visions, which sought to acknowledge the diversity of possible hydrogen futures and contested claims as to their sustainability. A set of transition scenarios were then developed exploring the dynamics and governance of the large-scale socio-technical changes that would be required for the emergence of the different visions. While aspects of this project have been reported elsewhere, this paper seeks to: (1) locate the work with respect to broader developments in the fields of foresight, expectations and socio-technical transitions to sustainability; (2) provide a description of the UKSHEC sustainable futures methodology; and (3) reflect on key insights for research and practice.

Keywords: scenario planning; technology and innovation studies; energy industry; foresight

1. Foresight, transition management and reflexive governance

In recent years a growing community of academics and opinion formers has argued for fundamental transformation in the socio-technological structure of human society to address the challenges of climate change and sustainable development. As Shove and Walker (2007) note, ‘for those concerned with sustainability, the idea of transition – of substantial change and movement from one state to another – has powerful normative attractions’. Indeed the concept of transitions and transitions management are central to the emerging discourse of reflexive governance of sustainable development, while the notion of a transition to a low carbon economy increasingly frames policy responses to climate change.

Drawing inspiration from ecology, systems and complexity science, transition theory seeks to develop an evolutionary perspective on societal change. With this perspective, addressing the inherently ‘wicked’ problem of sustainability becomes ‘a learning-by-doing exercise: experimenting with partnerships, new institutions, new technologies and new regulations within. . . ecological

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limits', informed by a co-evolutionary, non-linear, multi-level conception of systems innovation and socio-technological transition (Kemp and Loorbach 2006, 104–105). Transition management is by its very nature flexible and adaptive. However, processes of foresight, experimentation, evaluation and social learning, built upon stakeholder engagement and participation are central. Particular emphasis is placed on the development of shared problem definitions, normative visions and prospective transition pathways (Kemp and Loorbach 2006, 114).

In other words, transition management consciously seeks to mobilise and exploit the performative power of expectations: facilitating the alignment of actors around common goals, defining research priorities, stimulating resources for R&D and deployment, reducing uncertainty in decision making for technology developers, promoting political support for necessary institutional and regulatory change, etc. (Van Lente 1993; Dierkes, Hoffmann, and Marz 1996).

However, some have questioned the politics and practice of transition management (and the role of foresight therein). In particular, authors such as Berkhout, Smith, and Stirling (2004) and Shove and Walker (2007) have challenged the role of shared normative vision(s), and argued that transition management fails to adequately address the operation of power and deeply political and contested character of sustainable development. Berkhout, Smith, and Stirling (2004, 57–59), in particular, raise two substantive concerns over the centrality of guiding visions in driving the transition management process. First, noting what they see as a 'disjuncture' between the 'historically informed niche based model of regime transformation and the normative policy aspirations of transition management' they argue that there are many examples of past transitions where a consensus around a particular guiding vision was largely absent or where a guiding vision has played only a relatively modest role. Conversely they point out there are also many examples where guiding visions have failed to deliver upon the hype they generated. Second, they argue the notion of an unproblematic social consensus around any particular guiding vision is profoundly problematic as it ignores confounding issues of incommensurability in technological performance, divergent social values and interests, interrelationships between social and evaluative context, irreducible uncertainty, the operation of political and economic power and capture by incumbent interests.

Within the wider discourse of reflexive governance, Stirling (2006) has sought to move this discussion on by arguing for what he terms 'precautionary foresight'. He suggests using a variety of 'heuristic' tools to facilitate more pluralistic forms of 'iterative participatory goal formation', and radical institutional means to achieve greater reflexivity over the role of power through 'opening up' previously closed processes of strategy development. While in seeking to review and re-conceptualise the role of scenario methods in transition management, Sondeijker et al. (2006) have argued that transition management processes should work with multiple transition scenarios as an explicit response to the need to acknowledge and explore systemic uncertainties, avoid premature lock in and create space for new socio-technical solutions.

At the same time a stream of work has emerged which has sought to build upon insights from transitions theory and expectations dynamics in order to provide a more theoretically grounded and reflexive set of foresight tools and methodologies (see, for example, Elzen et al. 2004; Voss, Truffer, and Konrad 2006; Tyndall Centre 2005; Spath et al. 2006; Weber 2006; Truffer, Voss, and Konrad 2008).

This paper responds to Stirling's call for the development of 'precautionary foresight' tools to facilitate reflexive governance. In common with the sustainability foresight method developed by Truffer, Voss, and Konrad (2008), the UKSHEC sustainable futures methodology combines participatory scenario building, sustainability assessment and an exploration of transition pathways and innovation dynamics. Specifically the study aimed to construct a small number of plausible and internally consistent hydrogen futures and pathways to them, in order to better inform the ongoing deliberations and actions of policy, business and civil society actors engaged in shaping the prospective transition to a sustainable hydrogen economy.

Section 2 examines the challenges of foresight with respect to the transition to a sustainable hydrogen economy. Section 3 provides an account of the UKSHEC sustainability futures methodology. Section 4 describes the UKSHEC scenarios framework, and Section 5 summarises the transition scenarios. Section 6 draws together key insights with respect to hydrogen, while Section 7 provides reflections on the methodology.

2. Foresight and the transition to a sustainable hydrogen economy

Advocates of a hydrogen economy often claim that hydrogen has a vital role to play in the transition to a sustainable energy system: reducing carbon emissions, particularly from road transport, improving energy security, local air quality and boosting economic competitiveness. Indeed, at first sight the notion of a 'hydrogen economy' may appear to provide an unproblematic normative vision of a sustainable energy system. For a time, following President Bush's enthusiastic endorsement of hydrogen energy in his 2003 State of the Union address, it appeared that everyone from sections of the green movement to the coal and nuclear lobbies and industrial giants of the global energy and auto industries were in favour of hydrogen. However, upon closer inspection it is apparent that any prospective transition to hydrogen faces significant challenges: much of the technology is immature and expensive, or yet to be developed; mobilising the resources to develop a refuelling infrastructure is problematic in the absence of a market for hydrogen vehicles (and vice versa); there is an absence of an appropriate regulatory framework of codes and standards; and hydrogen is a potentially hazardous gas with explosive properties, resulting in questions over its safety and public acceptability. Moreover, there is in fact not one hydrogen economy but many contested visions of a hydrogen future. These range from decentralised systems based upon small-scale renewables, through to centralised systems reliant on nuclear energy or fossil fuels with carbon-sequestration. Some see hydrogen primarily as a transport fuel, while in others hydrogen competes with electricity as an energy vector (McDowall and Eames 2006a). Indeed, once we scratch the surface it becomes apparent that the notion of a hydrogen economy encompasses multiple contested socio-technological futures, value judgements and problem framings (Eames et al. 2006).

In this context reviewing the hydrogen futures literature reveals a number of insights. Hydrogen has provided a very active arena for the development of visions, scenarios and foresight exercises, and that the notion of a hydrogen economy has indeed functioned as powerful 'guiding vision', mobilising expectations and resources on a significant international scale. Not surprisingly given its performative role, much of this literature has an explicitly pro-hydrogen agenda. What is also apparent is that despite the diversity of hydrogen systems it describes the literature provides little systematic appraisal of the relative sustainability of different hydrogen futures. Moreover, much of the literature may be characterised by a lack of transparency and stakeholder participation, and few studies pay much attention to the dynamics of systems innovation and socio-technological change (McDowall and Eames 2006a).

The recognition that there is no single shared vision of a 'sustainable hydrogen economy' suggests that any attempt to articulate a desired hydrogen future must take seriously the issue of whose desires are being expressed as well as how in practical terms the transition to such a future could actually occur. This implies a need for an open and transparent scenario building process, using participatory approaches as a route to ‘social learning’ (e.g. Robinson 2003; Brown et al. 2003).

3. The UKSHEC hydrogen futures methodology

An overview of the participatory foresight methodology developed for the UKSHEC project is provided in Figure 1.

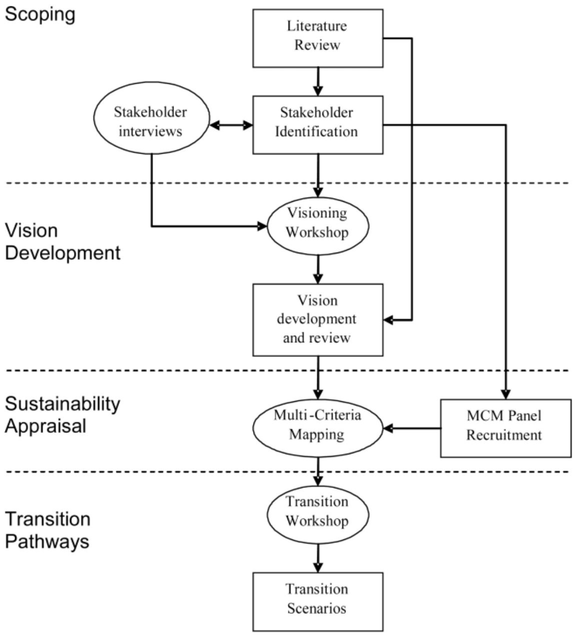
Phase 1: Scoping and literature review

The scoping phase (March–August 2004) comprised a literature review, stakeholder identification and recruitment, and small number of exploratory interviews.

A detailed review of the state-of-the-art of the (English language) hydrogen futures literature was undertaken (McDowall and Eames 2006a) Relevant stakeholders were identified by ‘mapping’ key actors involved in hydrogen production, supply and end-use chains. A ‘snowballing’ technique was also used with key informants to ensure participation from all relevant sectors, including academia, industry, government and civil society.

Phase 2: Vision development

A *Hydrogen Visions* workshop was held in September 2004, with some 40 leading UK hydrogen experts and stakeholders exploring and articulating visions of desirable hydrogen futures. The workshop was structured around four breakout groups, each exploring a different theme with



Project elements in oval boxes involved the participation of stakeholders

Figure 1. Overview of the UKSHEC hydrogen futures project.

respect to the 'hydrogen economy'. These themes (Climate Change, Energy Security, UK Competitive Advantage and Empowering Consumers) reflected key drivers drawn from the hydrogen futures literature and UK Government's 2003 Energy White Paper (DTI 2003). Each group undertook three 'brainstorming' exercises: (1) working with a series of technological 'building blocks' to develop long-term visions of a hydrogen economy; (2) exploring the socio-economic dimensions of these visions; and (3) exploring how change might come about. The workshop outputs were written up and circulated for participant review (McDowall and Eames 2004).

The UKSHEC visions

Building on the insights from the stakeholder workshop and literature review, the research team developed a set of six visions which sought to capture the diversity of stakeholder expectations about what a hydrogen future might or should look like. A key objective at this stage was to ensure that the set of visions as a whole encompassed the broad 'possibility space' and that no relevant future was excluded. The credibility, transparency and internal consistency of the draft visions were again refined in consultation with the project stakeholders.

The six visions differ both in relation to the role of hydrogen (transport fuel only, or providing both transport and broader energy services), the means of hydrogen generation and storage, and the degree of centralisation/decentralisation of production and supply (see Figure 2). The visions were set around 2040–2050.

Each vision comprised: (1) a structured narrative storyline describing archetypal configurations of hydrogen production, infrastructure (storage and distribution) and end-use technologies; (2) indicative quantitative indicators of the scale of primary energy demanded by the vision; and, (3) a systems diagram providing pictorial representations of each vision. See Eames and McDowall (2005). Summaries of each vision are given in the Table 1.

Phase 3: Sustainability appraisal

A key challenge for the UKSHEC hydrogen futures study was to find an approach to vision appraisal that recognised both the uncertainties involved in long-term futures, and differing stakeholder perspectives, values and framings of the debate. Debates within the field of environmental policy appraisal since the mid-1990s have highlighted the weaknesses of traditional approaches

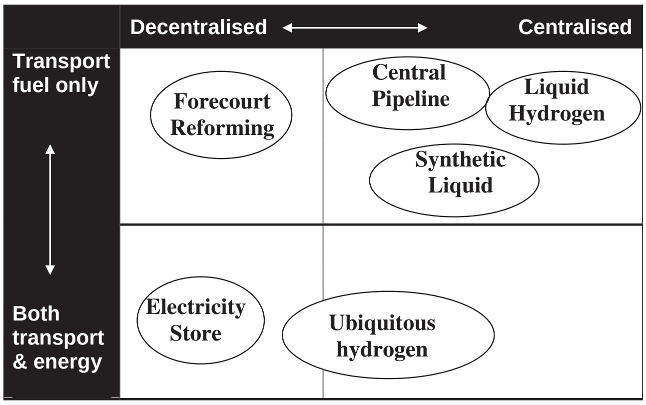


Figure 2. The UKSHEC hydrogen visions.

Table 1. Descriptions of the six UKSHEC hydrogen visions.

	Vision	Description
Transport futures (hydrogen only used as a transport fuel)	Central pipeline	Hydrogen has become the dominant transport fuel, and is produced centrally from a mixture of clean coal and fossil fuels (with C-sequestration), nuclear power, and large-scale renewables. Hydrogen is distributed as a gas by dedicated pipeline
	Forecourt reforming	Hydrogen produced locally from natural gas is the dominant road transport fuel. The existing natural gas network provides the delivery infrastructure, and hydrogen is generated on-site by steam methane reforming at the refuelling station
	Liquid hydrogen	Liquid hydrogen produced by nuclear power and large scale renewable installations has become the dominant transport fuel. There is an international market in liquid hydrogen. This is largely a scenario of substitution, with current energy and transport paradigms remaining unchanged
	Synthetic liquid fuels	Renewably produced hydrogen again provides the dominant transport fuel. In this case, however, it is ‘packaged’ in the form of a synthetic liquid hydrocarbon, such as methanol, to overcome the difficulties of hydrogen storage and distribution. The carbon for fuel synthesis comes from biomass and from the flue gases of carbon-intensive industries
Transport and energy services futures	Ubiquitous hydrogen	Gaseous hydrogen is not only the dominant road transport fuel. Many buildings also use fuel cell CHP systems running on hydrogen. Distributed renewable generation predominates, reducing need for long distance transmission and distribution, and allowing hydrogen to compete directly with electricity as the main energy vector for the provision of domestic and commercial heat and power. Regional grids of hydrogen pipelines connect (predominantly local) hydrogen supplies with local needs
	Electricity store	Hydrogen is not only the dominant road transport fuel, it also plays a vital role providing distributed energy storage to overcome the intermittency problems of renewable electricity generation. Hydrogen is produced locally in small scale electrolysis units for forecourt refuelling and onsite storage for use in domestic and commercial CHP units at times of peak electricity demand/limited supply

such as cost–benefit analysis, especially where ‘the facts are uncertain, values in dispute, stakes high, and decisions urgent’ (Funtowicz and Ravetz 1994). Critiques of such approaches stem from recognition that they are closed to alternative problem framings, criteria definitions and hence different social perspectives, that there is no uniquely rational way to aggregate different dimensions of value along a single metric and that their treatment of uncertainty is frequently insufficient (Munda 2004; Stirling 1999).

Proposed alternatives to traditional technical appraisal include a broad array of multi-criteria, participatory and deliberative techniques, all attempting to deal with what Vatn calls the problem of ‘institutionalising social choice’ (Vatn 2005). Many of these have been applied to problems in energy policy (Pohekar and Ramachandran 2004; Stagl 2006; Giampietro, Mayumi, and Munda 2006).

To this end the study adapted a multi-criteria decision analysis tool called multi-criteria mapping (MCM), originally developed by Stirling in the late 1990s (Stirling and Mayer 1999; Stirling 1999). It focuses on eliciting and documenting detailed technical and evaluative judgements concerning the performance of alternative options, through in-depth one-to-one interviews with expert stakeholders using a dedicated software package. Rather than seeking to identify an optimal solution or ranking, MCM maps the sensitivities of performance according to differing stakeholder perspectives, uncertainties and framing assumptions (for further details, see McDowall and Eames 2007; Stirling 2004, 2005).

The transdisciplinary panel that undertook the MCM appraisal of the UKSHEC hydrogen visions comprised 15 experts from a range of professional and disciplinary backgrounds.[1] Participants took part on the basis of their individual expertise and sceptical as well as pro-hydrogen viewpoints were represented. In addition to the six UKSHEC visions, a *status quo* or reference scenario, describing the current systems for energy and transport in the UK was also appraised, as a way of providing a benchmark comparison for the different visions.

Finally, the plausibility and sustainability of different visions are inevitably contingent upon implicit framing assumptions about the wider future, e.g. framing assumptions concerning geopolitical and social stability, rates of climate change, resource availability and fuel prices, and so on. While an MCM study attempts to record such framing assumptions, these are often implicit and remain tacit. In order to more fully explore participants’ framing assumptions, at the end of the interview participants were confronted with two short external ‘sideswipe’ scenarios – rapid climate change and sustained oil and gas crisis. They were then asked to comment on how such sideswipe might change their appraisal. This allowed some insight into the importance of tacit framing assumptions in the appraisal and the robustness of the ‘desirability and plausibility’ of the visions in the light of these major uncertainties. The opportunity to explore the importance of such sideswipes is often cited as one of the advantages of scenario approaches, although it is rarely done in practice (Van Notten, Sleegers, and Van Asselt 2005).

Phase 4: Transition pathways and scenario development

Having developed and appraised the sustainability of a set hydrogen visions, the next stage of the process was to articulate a series of plausible transition pathways. To this end a further expert-stakeholder Hydrogen Transitions workshop was convened in September 2005. Prior to the workshop, the project team drew on a range of sources to sketch a number of ‘prototype’ transition pathways. In breakout groups, participants worked through a series of structured questions in order to develop a picture of how each transition might take place. Drawing loosely on the multi-level perspective, these questions were organised around three themes: e.g. (1) Technologies, niches, and early markets; (2) Diffusion and market growth; (3) Context and timescales. The outcomes from the workshop were again written up and subject to stakeholder review (McDowall and Eames 2005).

In the final stage of the project the team developed an integrated set of transition scenarios, combining a revised set of four end-visions, with theoretically informed pathways describing a prospective transition to each of these hydrogen futures. The structure and key dimensions of these integrated scenarios drew heavily upon: (1) the multi-level perspective (MLP) on socio-technological transitions (Geels 2002); (2) SPRU’s work on transition contexts (endogenous renewal; re-orientation of trajectories; emergent transformation; purposive transition)

(Berkhout, Smith, and Stirling (2004); and (3) IVM's work on governance paradigms (governance by government; governance by policy networking; governance by corporate business; governance by challenge) for long-term technological change (Hisschemoller, Bode, and Van der Kerkhof 2006). To our knowledge this was the first time that the SPRU transition contexts have been used as part of a scenario study. The precise association of the transition contexts and governance paradigms adopted here appears to have been a good fit. While other combinations are possible, the point to recognise here is that by associating each of the transition contexts with a particular governance paradigm we were encouraged to enrich the institutional and governance dimensions of our scenarios.

The rational for reducing the number of end-visions from six to four was two-fold, driven both by insights obtained from the earlier sustainability appraisal and the need to work with a more limited set of visions which could be reconciled with the transitions framework adopted for the final phase of the project. *Forecourt reforming* was dropped from the final scenarios as many of our expert stakeholders saw this vision as a shorter-term intermediary step to a hydrogen economy. The *Central pipeline* and *Liquid hydrogen* visions were merged to form a *Central hydrogen for transport* end vision (see below).

4. The UKSHEC transition scenarios framework

The UKSHEC transition scenarios are not predictions. They are intended to shed light on possible innovation processes and transition pathways by which a future hydrogen economy might be achieved. They seek to illustrate different ways in which the large-scale socio-technological changes required for the establishment of a hydrogen economy might come about and so highlight the choices and policy options facing the research community, business, policymakers and civil society alike on the road to a sustainable hydrogen economy. While the scenarios have a UK focus, they seek to place prospective developments in a broader global context.

Each scenario comprised: (1) a short description of a distinctive hydrogen future (or end vision); (2) a 'storyline' summary; (3) a set of qualitative indicators; (4) a detailed 'multi-level' narrative describing the transition pathway in terms of landscape, niche and systems changes; and (5) a 'transition diagram' providing a visual representation of the innovation dynamics and key developments along the individual pathway.

The scenarios are framed by two key dimensions of change, adapted from work by Berkhout, Smith and Stirling (2004), which developed a quasi-evolutionary model of systems innovation: These dimensions are:

- The degree to which innovation is shaped by a shared normative guiding vision. This axis allows us to explore how hydrogen might emerge without a coherent action plan, as well as through concerted efforts to bring about a hydrogen future.
- The extent to which innovation is driven by existing actors and institutions, or by new actors and institutions (or existing actors taking on new roles). This axis invites us to think through the possible roles of the different actors and institutions involved in any possible transition.

As noted above, each quadrant was also associated with one of the four governance paradigms developed by Hisschemoller, Bode, and Van der Kerkhof (2006). Figure 3 illustrates the association of governance paradigms with transition contexts.

The four quadrants provide a useful way to distinguish different types of transition pathway. Each scenario is also described in terms of a second, multi-level, structure, adapted from the MLP,[2] as illustrated in Figure 4.

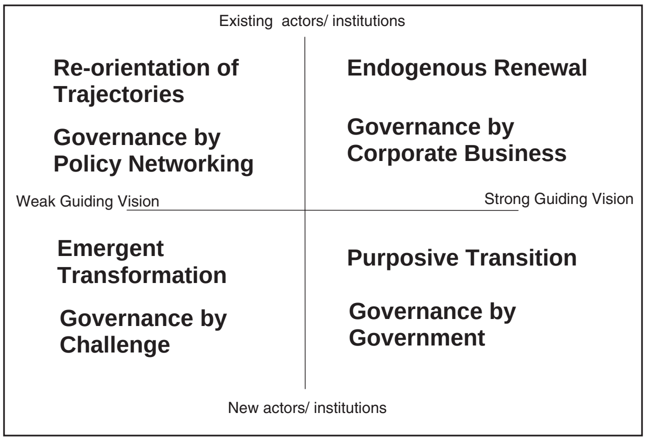


Figure 3. Mapping of the transition contexts and governance paradigms.

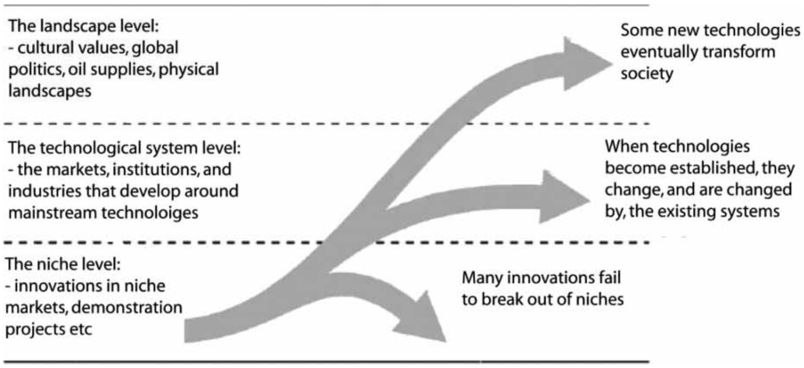


Figure 4. Multi level perspective on socio-technical transitions. Adapted from Geels (2002).

By simultaneously focusing on how technologies develop in niches; the dynamics of the incumbent systems; and the wider changes for society, we can get a better insight into the possible future for hydrogen. All of the UKSHEC scenarios are therefore described in terms of developments at niche, landscape and systems levels.

The major drivers for hydrogen at a landscape level, climate change and security of primary energy supplies, are well established. To a lesser extent local air quality and regional or national competitiveness also provide drivers for policy-makers to consider support for the development and diffusion of hydrogen technologies. In addition, landscape level drivers for the energy system more broadly include rates of economic growth (and hence of energy demand), and prevailing societal values.

In addition to these landscape level policy drivers, it is important to consider drivers at the systems and niche level that influence the dynamics of change by either articulating, or responding to, changes at the landscape level, such as the: strategic activities of firms and industries; national and regional energy and transport policies (e.g. carbon trading, zero emissions mandates); lobbying by hydrogen and fuel cell associations, activists, NGOs, etc.; the activities of scientists and engineers in advancing hydrogen and fuel cell technologies; and growth in portable and on-vehicle power demands, leading to funding, support and the creation of niche markets for fuel cell products, etc.

5. Summaries of the UKSHEC transition scenarios

The following section provides brief summaries of the four UKSHEC transition scenarios together with a summary table and multilevel transition diagram for each scenario. For details see Eames and McDowall (2006).

UKSHEC transition scenarios are shown mapped onto the 2×2 grid in Figure 5. Table 2 provides a summary of the four transition scenarios.

Structural shift → Electricity store

In this scenario the transition to *Electricity store* emerges from a restructuring of the energy market triggering rapid changes in the behaviour of existing firms, new entrants and their customers.

In the face of mounting concerns about climate change and energy security, the UK government restructures the market to provide much stronger economic incentives for renewable electricity and microgeneration. While developments in hydrogen transport are initially limited to a few high profile demonstration projects, hydrogen enters commercial use as a distributed storage medium to buffer intermittent renewable electricity supplies in the energy sector. As the use of hydrogen for distributed energy storage becomes widespread eventually it provides an alternative refuelling infrastructure allowing the rapid expansion of hydrogen transport.

This pathway results largely from a 're-orientation of trajectories', where radical innovation within the energy sector, and later transport, emerges as a result of an 'external' shock in the form of restructuring of the electricity supply market to promote low carbon generation and energy efficiency. Here restructuring of the energy supply market is considered an external shock as it is a manifestation of the landscape pressures acting upon the existing regime and is not directly intended to promote hydrogen energy *per se* (cf. the use of direct regulation to promote the use of hydrogen as described in Government Mission below). This scenario is depicted in Figure 6.

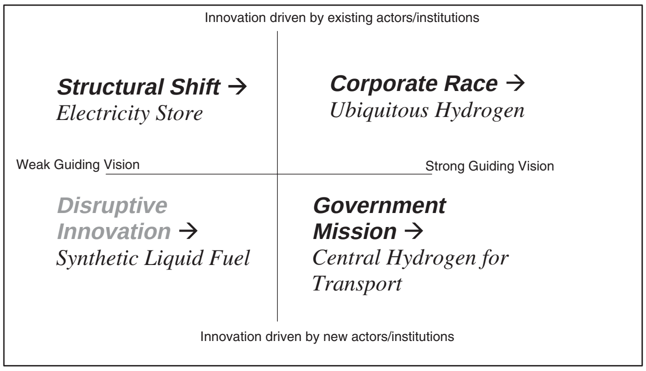


Figure 5. The UKSHEC transition scenarios. Note: *Disruptive innovation → Synthetic liquid fuel* is shown in the diagram in lighter text to highlight its status as an alternative or 'wild card' scenario. Source: Eames and McDowall (2006).

Table 2. Summaries of the UKSHEC transition scenarios.

	Structural shift	Corporate race	Government mission	Disruptive innovation
End vision	Electricity store	Ubiquitous hydrogen	Central hydrogen for transport	Synthetic liquid fuel
Dimensions	• Innovation driven by existing actors/ institutions • Weak guiding vision	• Innovation driven by existing actors/ institutions • Strong guiding vision	• Innovation driven by new actors/ institutions • Strong guiding vision	• Innovation driven by new actors/ institutions • Weak guiding vision
Drivers	• Strong UK Government and social concern for climate change and energy security • Greater social awareness of need for demand reductions • Societal rejection of nuclear and carbon capture and storage	• Strategic positioning by big auto and big oil in the face of climate change and energy security concerns • High demand and volatile supplies for oil and gas lead to increasing prices	• Strong UK/EU government concerns over climate and energy security • Societal acceptance of nuclear and carbon capture and storage, and greater social trust in science and technology	• Emerging climate and energy concerns • Emphasis on building competitive markets and high innovation • Social preference for liberalised markets and consumer economy
Key technologies	• Fuel cells • Storage and handling • Electricity grid updates • Smart metering • Renewables	• Gas separation • Fuel cells • Onboard storage • Gasification • Pipelines and metering • Carbon capture and storage • Waste, biomass gasification • Renewables	• Storage and handling • Fuel cells • High temperature nuclear • Pipelines and liquefaction • Gasification technologies • Carbon capture and storage • New nuclear power	• Direct methanol fuel cells (DMFC) • Synthetic liquid fuel synthesis • Fuel reformers or scale up of DMFC • Renewables • Carbon capture
Decision points and milestones	• Renewables reach a high enough proportion of grid electricity to require buffering of supply and demand	• Nuclear and CCS go/no-go decisions • Commercialisation decisions of big auto • Hydrogen injected into natural gas grids	• ‘Go’ decision on major hydrogen programme, and on nuclear	• ‘No-go’ decision on major government hydrogen programme

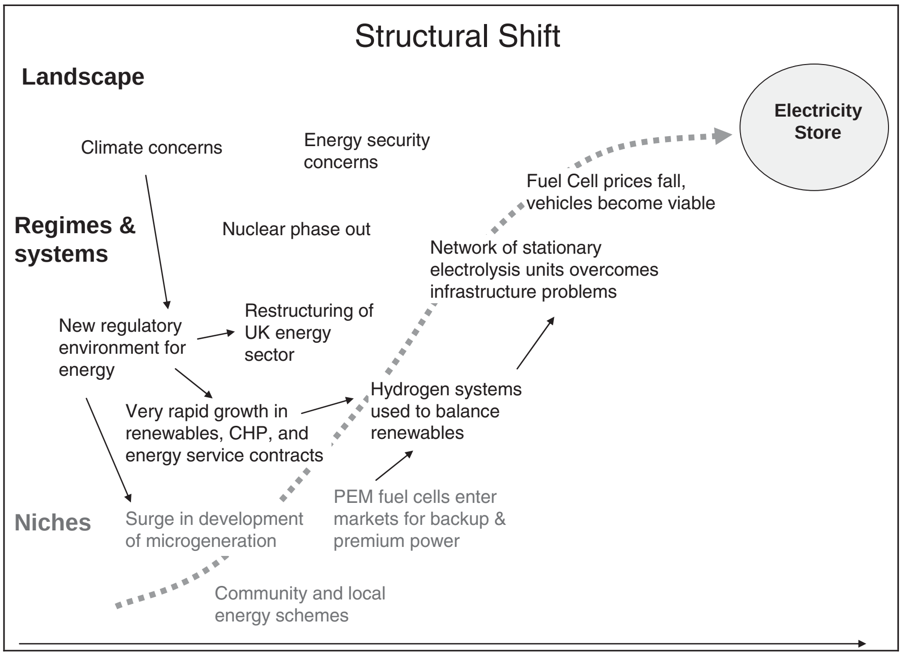


Figure 6. *Structural shift → Electricity store*.

Corporate race → Ubiquitous hydrogen

In this scenario, the transition to *Ubiquitous hydrogen* is driven by the actions of corporate business, initially by strategic competition between global companies within the auto–oil sectors.

Despite the continued failure of inter-governmental action on climate change, global automotive and energy companies increasingly see the shift to a low carbon energy system as in their long term interests. A strategic race develops to achieve leadership in hydrogen technologies. Regional and local governments play important role facilitating demonstration projects and early ‘flag ship’ initiatives in partnerships with corporate players. Rapid improvements in on-board storage and fuel cell technologies promote the rapid penetration of hydrogen in the transport sector. Later, as natural gas prices rise, fuel providers use the natural gas grid to supply hydrogen, ultimately moving to an integrated hydrogen grid, with decentralised as well as centralised hydrogen production.

This pathway is one of ‘endogenous renewal’, where innovation arises largely out of the R&D activities and investment decisions of companies within the existing transport system, more specifically the major global companies within the automobile and oil industries. This scenario is depicted in Figure 7.

Government mission → Central hydrogen for transport[3]

In this scenario, the transition to *Centralised hydrogen for transport* is driven by strong government at both a national and regional/international (EU) level. The public sector and ‘national champion’ industries work in partnership to build a hydrogen transport infrastructure.

Problems of climate change and energy security are increasingly seen as too pressing to be left to the market and as warranting more direct government intervention. National governments

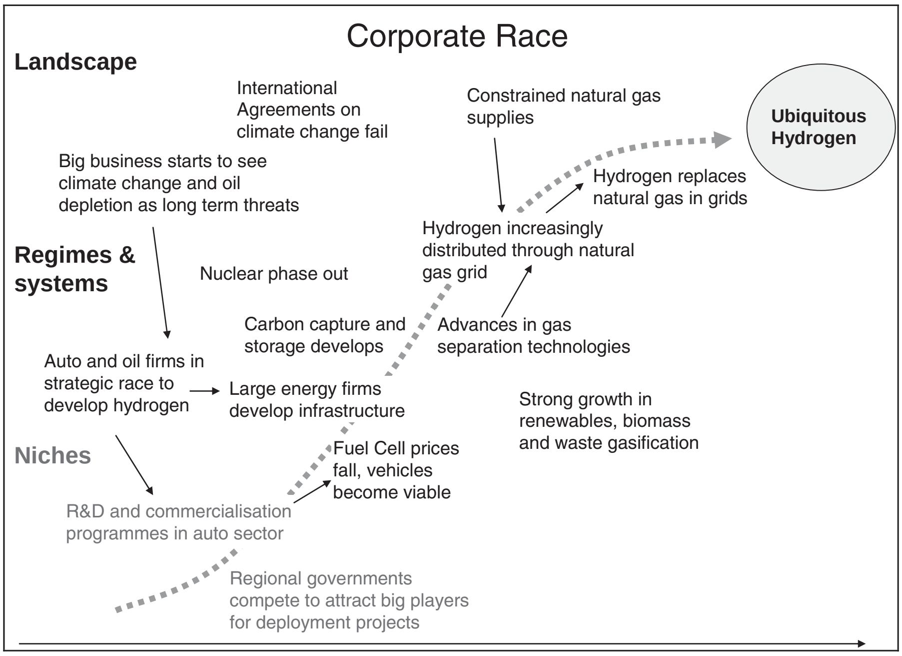


Figure 7. *Corporate race → Ubiquitous hydrogen*.

in the leading advanced and rapidly industrialising economies (US, Japan, China, India) and EU take strategic decisions to prioritise the rapid development of hydrogen transport. Partnerships are established with national industry champions. Regulation, subsidies and public procurement are all used to push hydrogen making extensive use of near-term technologies and large centralised supply routes.

This pathway is one of ‘purposive transition’, where innovation is driven by the goals and expectations of national political elites, and scientific, policy and business interests become enrolled in a shared mission to transform the existing system. This scenario is depicted in Figure 8.

Disruptive innovation → Synthetic liquid fuel

In this alternative scenario, the transition to *Synthetic liquid fuel* is driven by the market forces, with the role of government largely restricted to fostering competitive markets and the knowledge economy.

Despite ongoing concerns about climate change and energy security, hydrogen in its pure form fails to take off. On-board storage in particular remains a significant barrier to the widespread adoption of hydrogen as a transport fuel. However, innovation in the electronics sector and niches outside of the mainstream transport and energy systems opens up novel technological opportunities, changing consumer behaviour and expectations and resulting in the growth of new markets for portable power and synthetic liquid fuels.

This pathway is largely one of ‘emergent transformation’. Innovation outside of the mainstream transport and energy systems opens up novel technological and market opportunities, resulting in the growth of new industries and consumer services as well as unexpected solutions to existing problems. This scenario is depicted in Figure 9.

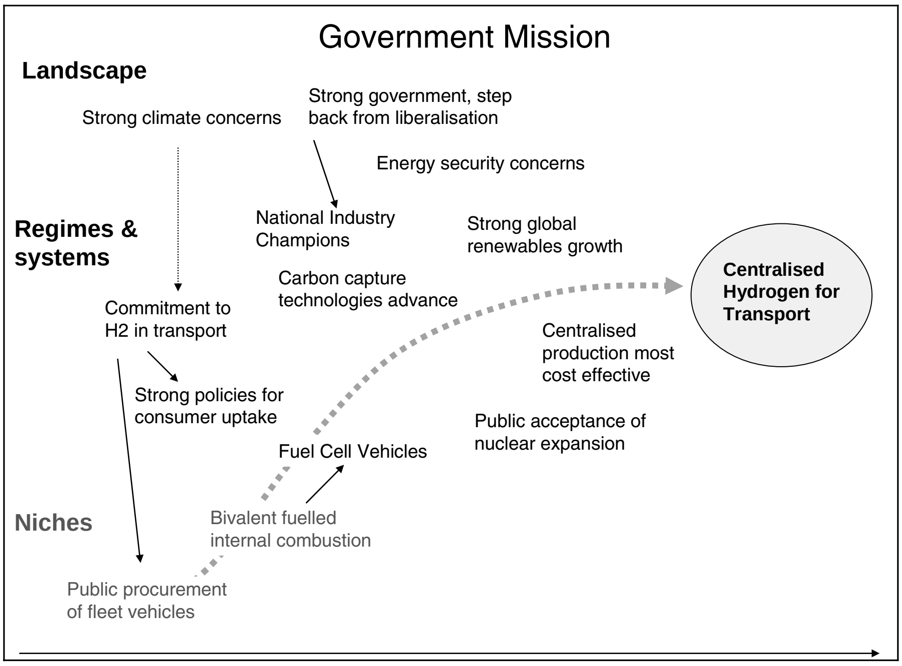


Figure 8. *Government mission → Central hydrogen for transport*.

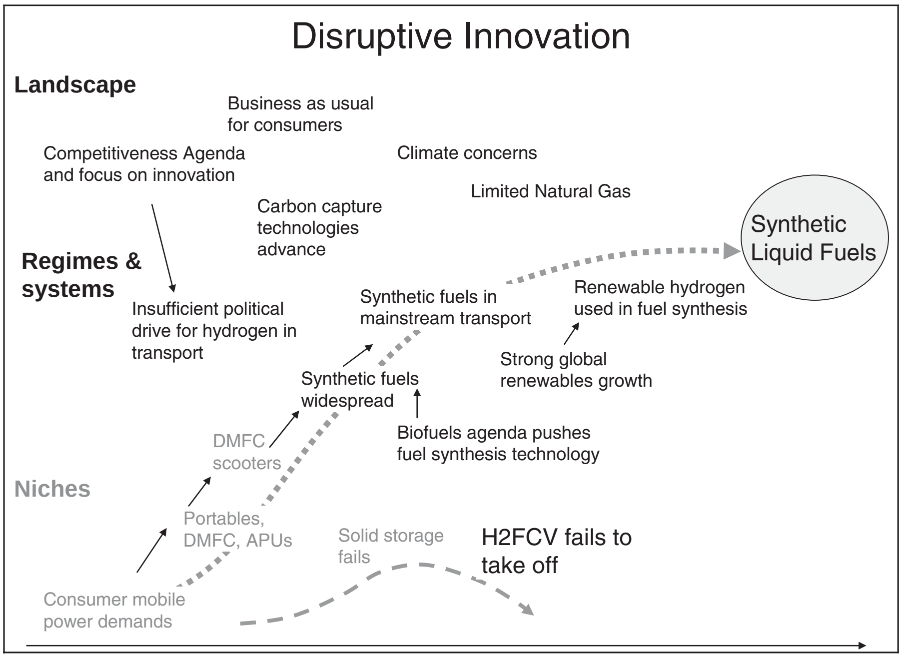


Figure 9. *Disruptive innovation → Synthetic liquid fuels*: an alternative scenario.

6. Insights into the future of hydrogen

Insights from the sustainability appraisal

The MCM process produced a qualitatively and quantitatively rich picture of the panel's expectations of the sustainability of the visions: their assessment criteria (environmental, economic, social and energy security criteria); the relative weightings attributed to these; and overall performance and rankings of the visions and associated uncertainties.

The results from the MCM appraisal have been reported in detail elsewhere (McDowall and Eames 2006b, 2007). These confirm the highly contested nature of the debate, with no absolute winners or losers and with a wide range of weighted scores for all visions, as shown in Figure 10. This does not mean no patterns are clear, but rather that there are no uncontested winners. Indeed, examination of the relative performance of each vision, under both optimistic and pessimistic assumptions, does provide some clear messages about the likely sustainability of the different futures.

Hydrogen is not automatically sustainable

Participants recognised a range of circumstances in which hydrogen energy might be less sustainable than the current system or some non-hydrogen business as usual futures. However, hydrogen was perceived as having the potential to deliver substantial sustainability benefits over a wide range of issues.

Multiple dimensions of sustainability

The panel identified carbon emissions as the single most important dimension of sustainability with respect to the hydrogen futures. However, a very wide range of other environmental, social, economic, political and technical issues were also seen to be important in judging the sustainability of hydrogen systems.

Risk and uncertainty are critical

Even for issues with relatively well characterised data sources (such as wells-to-wheels carbon studies) there were debates about how well technological systems could be expected to perform in

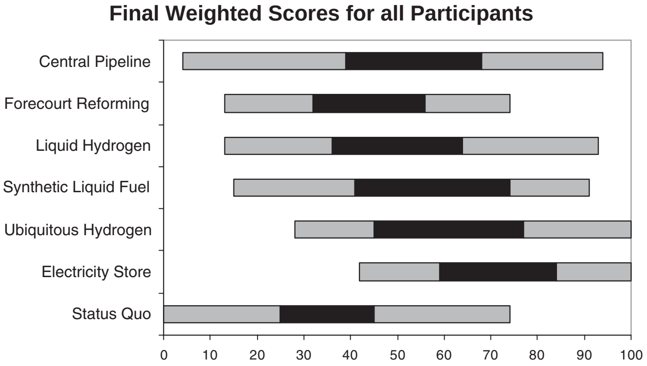


Figure 10. Final weighted scores aggregated across all participants. All participants score the visions with both optimistic and pessimistic assumptions, to provide a sense of the degree of uncertainty. Bars indicate extreme (grey) and average (black) pessimistic and optimistic scores, capturing the degree of uncertainty about future performance. The x-axis is a relative scale indicating low (0) to high (100) performance. Source: McDowall and Eames (2006b).

real world applications. There is significant uncertainty over the future costs and performance of the technologies, and these uncertainties have important impacts on the likely sustainability of the different futures. In particular, there are uncertainties concerning: the performance and costs of carbon capture and storage, nuclear power, pipelines, small scale steam methane reformers, fuel cells and hydrogen storage technologies. Figure 11 shows the final weighted scores for four of the participants, with the bar length indicating the range of uncertainty each participant expressed about the future sustainability of each vision.

Priorities and rationales for ranking futures are contested – values count too

There is a wide range of rationales for ranking different futures (e.g. political implications vs technical appraisals of likely system performance). While some of these issues are amenable to further research in order to reduce uncertainty about the future, others are based on normative value judgements about the way in which society should operate, and are therefore likely to be a continuing source of disagreement and dissent. Nuclear power, the degree of decentralisation and feasibility were key areas dividing participants' appraisals. For those concerned about nuclear power opposition was as much to do with social and political aspects of the technology as environmental concerns. These contested priorities and perspectives suggest that there is significant potential for future social and political conflict over the shape and direction of any transition towards a hydrogen economy.

Future surprises would shift appraisals

In discussing the 'sideswipes' scenarios that were presented at the end of the MCM interviews (on rapid climate change and sustained oil crisis), it was noteworthy that many participants felt these were plausible and not radically different from the futures they expected despite their somewhat extreme character. However, while many participants recognised the importance of the threats embodied in the sideswipes during the appraisal, they did not take into account the radically changed conditions that such sideswipes would imply. Rather, participants tended to explore future states in terms of current society's assessment of the importance of climate change and energy security. Their agreement with the sideswipes as plausible futures demonstrates their high levels of concern for these issues, but also demonstrates the difficulties of thinking through the implications of a radically altered future. Most participants felt that the sideswipes would alter the weightings given to energy security and carbon emission criteria.

While there was not the time to explore these possibilities, the fact that they were raised suggests that the exercise did promote broader thinking about background assumptions made in the appraisal and that such interventions might be useful in exploring tacit expectations and framing assumptions future studies.

Key insights from the UKSHEC transition scenarios

The UKSHEC transition scenarios highlight a number of broader strategic decision points, for government, business and wider society, which are likely to prove influential in shaping the direction of future technological developments with respect to hydrogen. These include decisions over: (1) the construction of new nuclear capacity, carbon capture and storage, and large scale renewables; (2) the viability of distributing hydrogen through natural gas pipelines; and (3) the commercialisation of FCVs by major automotive firms. More profoundly, the exploratory character of the

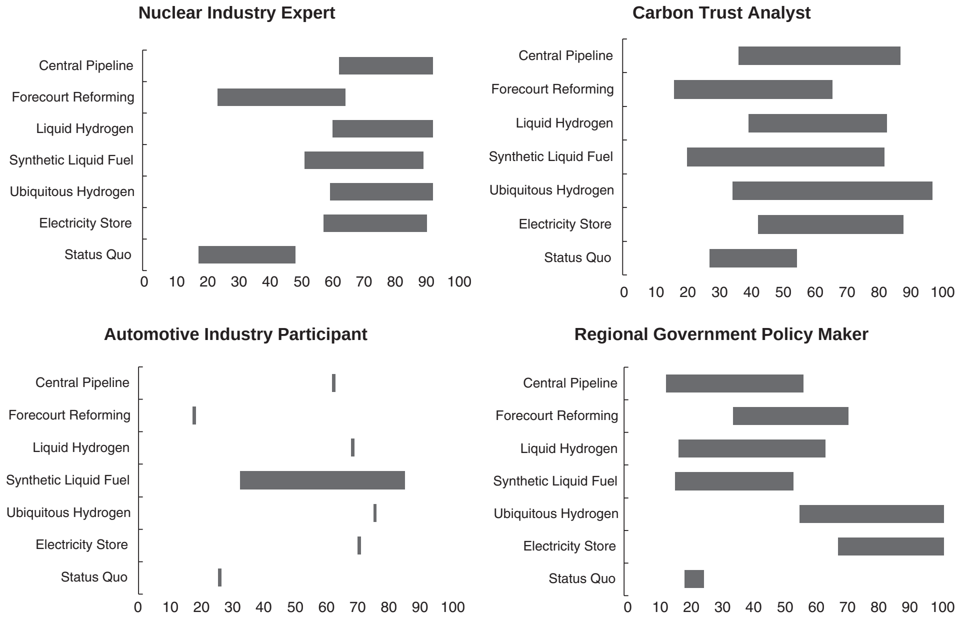


Figure 11. Individual weighted score ranges for four participants. The x-axis is a relative 1–100 scale showing performance, with better performing visions further to the right. Bar length is a result of the degree of difference between pessimistic and optimistic scores, and is thus a function of the degree of uncertainty. Source: McDowall and Eames (2006b).

scenarios focuses attention on the innovation dynamics and governance of the transition processes involved. Taking each scenario in turn:

Structural shift → Electricity store. Much of the literature and policy discussions around the future of hydrogen in the UK emphasise the role of hydrogen as a transport fuel and assumes that breakthroughs will come about as a result of developments with respect to fuel cell vehicles. By contrast this scenario illustrates a transition driven by moves towards a low-carbon energy system. Here the emergence of hydrogen is not driven by a particular guiding vision, but rather is an emergent response to a restructuring of energy markets and the broader technological changes this creates. This scenario therefore focuses attention on the importance of market structure and regulation as a driver of innovation. It challenges the assumption that a major programme of investment in infrastructure will be required for the development of a hydrogen transport system.

Corporate race → Ubiquitous hydrogen. Often it is assumed that government holds the key to the development of a hydrogen economy. This scenario emphasis the role and power of global companies, and the potentially positive outcomes of strategic competition as a driver for radical innovation. It draws attention to the relationship between global companies, niche experimentation and regional systems of innovation with respect to hydrogen, and the importance of environmental regulation in fostering new markets for clean technologies.

Government mission → Central hydrogen for transport. Despite the scale of the challenge posed the climate and energy security drivers of a hydrogen economy, much of the policy discussion about hydrogen is constrained by current assumptions about the dominance of the market, the limits of government and antipathy to 'picking winners'. In contrast to the *Corporate race* scenario, this storyline explores the idea that stronger government intervention may be required for a rapid transition to hydrogen and challenges us to critically reconsider the ability of liberalised markets to deliver the purposive, large-scale socio-technological and infrastructural developments that may be required in an increasingly unstable and hostile world.

Disruptive innovation → Synthetic liquid fuel. This is an alternative or 'wild card' scenario. Conventional wisdom suggests that the market alone will not deliver a transition to a hydrogen economy and that the automotive industry in particular has moved away from research into the use of synthetic liquid fuels such as methanol as a possible source of power for future fuel cell vehicles. The *Disruptive innovation → Synthetic liquid fuel* transition scenario challenges us to rethink these assumptions and re-examine the sorts of technological developments, firms and industrial sectors that might drive the transition to hydrogen, and indeed what a hydrogen economy might actually look like.

Despite very different governance structures and policies across the four scenarios, all contain at least some attempts by policy-makers to reduce carbon emissions and enhance energy security. This together with the results from the earlier MCM appraisal this suggests that, in the short term at least, 'business as usual' or the market alone are unlikely to deliver a transition to hydrogen.

7. Reflections on the UKSHEC hydrogen futures methodology

This final section reflects on the UKSHEC sustainable futures methodology. Some of the practical challenges and insights gained from undertaking the work are discussed. Finally we conclude by considering how the methodology promotes critical engagement with the three key themes of this special issue: *institutions*, *interests* and *ideas*.

As noted above both sustainability foresight (Truffer, Voss, and Konrad 2008) and the UKSHEC sustainable futures methodologies share a number of similar steps in terms of: (1) participatory scenario building; (2) sustainability assessment; and (3) the development of transition pathways. However, the specific combination of backcasting and MCM appraisal, the exploration of sideswipes and the adaptation of the SPRU transitions contexts to frame the prospective transitions pathways were unique to the UKSHEC study.

It is important to remember that scenario building is an art not a science. It requires expertise and creativity to design bespoke foresight processes which fulfil their users' needs. Combining participatory stakeholder engagement with the development of a conceptually rigorous and theoretically informed scenarios framework at times proved challenging and inevitably incorporated a certain degree of learning-by-doing.

While the process of 'opening up' the range of hydrogen futures to appraisal was not unproblematic, the individual format of the MCM appraisals proved particularly well suited to calm reflection. Given the scope for disagreement that clearly existed, a group-based process might have been much more difficult to manage and less productive at this stage. However, the MCM process is very resource intensive, with interviews typically lasting several hours.

One potential weaknesses of normative backcasting is that it may encourage a blind eye to unwanted or unexpected developments. Both working with multiple futures and the development of tools for more systematically exploring the impact of 'sideswipes' would help to better address issues of uncertainty and resilience within transition management.

In the latter part of the project challenges centred on our stakeholders' lack of familiarity with systems innovation and transitions concepts, with the rather abstract academic terminology of transitions theory proving a real barrier to be overcome. In order to make these concepts accessible and meaningful it was therefore necessary to think carefully about the language used and manner in which the final scenarios were presented.

While the sustainable futures methodology described in this paper was specifically designed to explore the transition to a sustainable hydrogen economy, it clearly has a wider relevance. The participatory backcasting approach adopted addresses Stirling's call for the development of tools for 'precautionary foresight' in that it allowed us to engage and explore a wide range of stakeholder *interests*, while combining the scenario and MCM tools allowed us to 'open up' the appraisal of the sustainability of different hydrogen futures: systematically mapping different social perspectives and uncertainties. In this way the process of articulating and challenging *ideas* – (normative) visions and expectations of the future – becomes an opportunity for real deliberation and debate about social and political priorities with respect to new technologies.

Moreover the findings from this study support Berkhout, Smith, and Stirling's (2004) contention that the notion of an unproblematic social consensus around any particular guiding vision is profoundly problematic. Indeed in the case of hydrogen our results suggest that even with perfect foresight and no uncertainties it would not necessarily be possible to obtain a single consensus view on which hydrogen futures are most sustainable. This is because stakeholders have different ideas about what sustainability means, what elements are more or less important and about what sort of society is desirable. In short, there is an inescapably political element to long term technological choice.

Drawing upon the systems innovation and socio-technical transitions literature encouraged particular attention to the role of *institutions* – in the form of market, regulatory and political frameworks – in the transformation of the energy system, and the importance of exploring a variety of alternative social, economic, technological and political choices in shaping prospective transition pathways. Moreover, the framework and structure of the scenarios, linking the SPRU transition contexts and IVM governance paradigms with the multi-level perspective enabled exploration of different transition dynamics and encouraged attention to the role of governance, agency and power in transitions.

Moreover, the two key dimensions of change used in framing the scenarios explicitly encouraged creative future thinking. The recognition that explicit normative guiding visions may play a greater or lesser role in driving transitions – and hence working with both emergent and normatively driven pathways – again addresses Berkhout, Smith and Stirling's criticism that transition management all too often assumes that a guiding vision is a necessary prerequisite of systems transformation, despite historical evidence to the contrary. The second dimension of the scenarios framework, focusing attention as it does on the extent to which innovation is driven by either existing or new actors and *institutions,* both helps us avoid simply prescribing future options which correspond with incumbent stakeholder *interests* and encourages precisely the sort of thinking about novel solutions advocated by Sondeijker et al. (2006).

Finally it is worth reflecting that in policy terms transition management itself represents a relatively new *institutional* innovation. To date much of the practical experience of transition management has been confined to the Netherlands, where it has evolved in a very particular governance and institutional context. However, it is too early to know whether the Dutch model of transition management will diffuse widely and succeed in overthrowing the dominate policy and institutional regime. A particular value of the UKSHEC transitions scenarios framework is that it encourages a rich exploration of alternate (emergent and purposive) transition pathways.

In addition to highlighting a number of strategic decision points for any prospective transition to hydrogen, the final scenarios also focus attention on a number of more generic challenges for reflexive governance and transitions management, particularly with respect to: the importance of market structure and regulation as a drivers of innovation; the role of corporate power and strategic competition between firms in shaping innovation; the limits of liberalised markets and place of direct government intervention; and the potential of disruptive innovation on the part of 'outsider' or non-regime actors to drive transitions.

Acknowledgements

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Notes

1. That is, Nuclear Industry Expert; Carbon Trust Analyst; Department for Trade and Industry (DTI) Policy Maker; Fuel Cell Industry Participant; Sustainable Energy Policy Consultant; Industrial Gases Industry Participant; Energy Technology Researcher; Environmental Campaigner; Health & Safety Regulator; Energy Policy Researcher; Senior Oil Industry Participant; Department for Transport (DfT) Policy Maker; Automotive Industry Participant; Regional Government Policy Maker; and Climate Scientist.
2. In order to make the scenarios more accessible to a UK policy audience unfamiliar with the concept of the socio-technical regime the multi-level structure is described in terms of the niche, *system* and landscape instead of the niche, *regime* and landscape.
3. *Centralised hydrogen for transport*. This vision is an amalgamation of the original *Central pipeline* and *Liquid hydrogen* visions. Hydrogen has become the dominant transport fuel and is produced centrally from a mixture of sources. Hydrogen is distributed as a gas by dedicated pipeline and as a liquid. In some applications, liquid hydrogen is the onboard storage mechanism, while in others, compressed gaseous hydrogen is used.

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Will McDowall is a Research Associate at the UCL Energy Institute. He has held research and policy advisory posts in both the UK and Canada. His research interests include climate change mitigation and adaptation, energy policy, innovation and governance for sustainability.

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Exploring possible transition pathways for hydrogen energy: A hybrid approach using socio-technical scenarios and energy system modelling

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ABSTRACT

Hydrogen remains an important option for long-term decarbonisation of energy and transport systems. However, studying the possible transition paths and development prospects for a hydrogen energy system is challenging. The long-term nature of technological transitions inevitably means profound uncertainties, diverging perspectives and contested priorities. Both modelling approaches and narrative storyline scenarios are widely used to explore the possible future of hydrogen energy, but each approach has shortcomings.

This paper presents a hybrid approach to assessing hydrogen transitions in the UK, by confronting qualitative socio-technical scenarios with quantitative energy systems modelling, through a process of 'dialogue' between scenario and model. Three possible transition pathways are explored, each exploring different uncertainties and possible decision points. Conclusions are drawn for both the future of hydrogen, and on the value of an approach that brings quantitative formal models and narrative scenario techniques into dialogue.

1. Introduction

Hydrogen remains an important option for long-term decarbonisation of energy and transport systems, and modelling studies often suggest that hydrogen could be an important part of an affordable and achievable transition to a low carbon economy. Despite a recent period of disappointment following several years of hydrogen 'hype' (Bakker, 2010), technological progress in hydrogen technologies has been promising. Automotive firms have focused on vehicles running on pure hydrogen with fuel cells, and on-board compressed hydrogen, moving away from earlier work with liquid hydrogen or on-board conversion of other fuels. Costs have fallen, and there is increasing confidence from automakers that fuel cell vehicles are approaching commercial competitiveness.

However, studying the possible transition paths and development prospects for a hydrogen energy system is challenging. The long-term nature of technological transitions inevitably means profound uncertainties, diverging perspectives and

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contested priorities. Both modelling approaches and narrative storyline scenarios are widely used to explore the possible future of hydrogen energy, but each approach has shortcomings.

This paper presents a hybrid approach to examining hydrogen transitions in the UK, by linking qualitative transition scenarios with quantitative energy systems modelling. The approach acknowledges the contested nature of ways of understanding future possibilities by placing two different methods (participatory storylines and energy systems modelling) in explicit 'dialogue'. 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 patterns identified in historical energy system transitions, reflecting insights relating to innovation system development and resistance to change.

2. Background and approach: scenarios and models for technology transitions

2.1. Modelling energy transitions

Formal models are powerful ways of exploring the dynamics of systems and hence play a crucial role in thinking about how those systems might develop in the future. A wide variety of models have been developed to inform the transition to a low carbon economy, and these have generated robust[1] insights into the likely importance and roles of various technologies, trends and policy instruments. In the context of hydrogen energy, three types of models[2] have been prominent:

- So-called "Bottom-up" energy system models (e.g. MARKAL and MESSAGE) evaluate the desirability of hydrogen within the context of overall decarbonisation. They model trade-offs with the wider energy system, and so provide greater techno-economic consistency than sectoral approaches, but they have weak spatial representation, and many have simplistic representations of technology dynamics and the economy-wide costs of energy transitions (Barreto & Kemp, 2008; Hourcade, Jaccard, Bataille, & Ghersi, 2006). Examples of studies addressing hydrogen transitions using such models include (Barreto, Makihira, & Riahi, 2003; Endo, 2007; Gül, Kypreos, Turton, & Barreto, 2009; Krzyzanowski, Kypreos, & Barreto, 2008; Mau, Eyzaguirre, Jaccard, Collins-Dodd, & Tiedemann, 2008; Strachan, Balta-Ozkan, Joffe, McGeevor, & Hughes, 2009; Yeh, Farrell, Plevin, Sanstad, & Weyant, 2008).
- System dynamics and agent-based simulation models examine interactions between agents (governments, consumers, car manufacturers). These models are valuable in showing how simple relationships can result in complex dynamics similar to previous attempts to foster alternative fuel transitions; and they can provide insights into the conditions under which heterogeneous actors might foster a transition through consumption, investment, policy and cooperation decisions. However, they lack the broader system view, without feedbacks and synergies between sectors in the wider economy. Examples in the field of hydrogen transitions include (Contestabile, 2010; Huétink, der Vooren, & Alkemade, 2010; Keles, Wietschel, Möst, & Rentz, 2008; Köhler, Wietschel, Whitmarsh, Keles, & Schade, 2010; Schwoon, 2008; Struben & Sterman, 2008).
- Infrastructure optimisation transition models. These optimise spatial and temporal aspects of infrastructure and vehicle deployment, but exogenise hydrogen demand. For a review, see (Agnolucci & McDowall, 2013).

Quantitative models used in the analysis of possible transitions have grown increasingly sophisticated, endogenising the effects of scale economies and learning (Schwoon, 2008), social network effects (Huétink et al., 2010; Mau et al., 2008), and strategic games between actors (Schlecht, 2003). Energy systems models have been adapted to incorporate better representation of behaviour (Daly et al., 2012; Mau et al., 2008), macro-economic developments (Strachan & Kannan, 2008); and technological change (Anandarajah, McDowall & Ekins, 2013).

However, on their own, none of these model types is able to provide a compelling account of transition dynamics, since in the real world the structure of the system itself evolves. In other words, the rules guiding development co-evolve with technologies, user behaviours and business strategies (Foxon, 2011). Moreover, there is scant agreement on the extent to which dominant rule structures used in models provide a good approximation of socio-technical developments over long time periods (Trutnevyte, 2014). As a result, existing models may be unable to represent the key issues that are widely recognised by stakeholders to be important. These issues then lie outside the scope of any formal analysis, potentially remaining unexamined tacit assumptions that guide decisions. Attempts to develop models of transitions dynamics that are informed by evolutionary and co-evolutionary thinking are developing, but are still in their infancy (Safarzyńska, Frenken, & van den Bergh, 2012).

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[1] At least, robust in the face of the uncertainties that are considered to be most well characterised, following Lempert and Groves definition of 'robustness' of model outcomes (Groves and Lempert, 2007). D.G. Groves, R.J. Lempert, A new analytic method for finding policy-relevant scenarios, Global Environmental Change, 17 (2007) 73–85.

[2] Others have also been applied, such as Computable General Equilibrium models, but these have been less frequently used.

2.2. Socio-technical scenarios

Scenarios[3] are widely used to help inform decision-making in the face of significant uncertainty, particularly in fields with long-term planning horizons such as energy policy. A major reason for adopting an exploratory scenario approach as an analytic tool for considering possible energy decarbonisation transition paths is a belief that formal quantitative models are unable to adequately represent the dynamics of socio-technical change, for the reasons discussed above (Söderholm, Hildingsson, Johansson, Khan, & Wilhelmsson, 2011; Swart, Raskin, & Robinson, 2004). Rather than ignore the issues that are already informing stakeholder decisions because they are not tractable in a formal model, scenario approaches draw these out, make them explicit, and conduct thought experiments to test judgements about their importance.

Scenario storylines informed by participatory processes, though not always as analytically coherent or internally consistent in techno-economic terms, are thus able to capture, distill and explore ideas about the future that are currently shaping stakeholder perceptions, but that cannot be adequately represented in formal modelling frameworks. The resulting scenarios do not incorporate the technical rigour of models, but they can be valuable in making explicit widely held views about possible technology dynamics. This does not necessarily mean that these are more 'accurate' in terms of predicting what kinds of dynamics are likely. Indeed, that is not the core aim. Scenarios are 'learning machines' (Berkhout, Hertin, & Jordan, 2002) that can enable reflection on the realism or implications of widely held views, and on how stakeholders understand and relate to different possibilities. Rather than provide evidence to inform concrete decisions, such scenarios foster 'conceptual learning', i.e. providing new insights, perspectives and ideas on policy issues, a function seen as very important within the literature on the use of evidence in policymaking (Hertin, Turnpenny, Nilsson, Russel, & Nykvist, 2009).

Recent years have seen the development of scenario approaches designed specifically to inform understanding of possible technological transitions—shifts from one dominant socio-technical system to another (archetypal examples being the shift from sailing ships to steam ships, or from gas lighting to electric lighting). Informed by the burgeoning literature on technological transitions (Markard, Raven, & Truffer, 2012), such scenario approaches attempt to reflect understanding of the dynamics of technological change, focusing in particular on the relative durability of different institutional and socio-technical configurations, and the co-evolutionary dynamics of technologies, users and institutions (Elzen, Geels, & Hofman, 2002; Elzen, Geels, Hofman, & Green, 2004; chap. 11; Foxon, Hammond, & Pearson, 2010). In the arena of hydrogen energy, there have been several attempts to develop qualitative socio-technical scenarios inspired by transitions research to examine potential hydrogen transitions (Eames & McDowall, 2010; Van Bree, Verbong, & Kramer, 2010).

2.2.1. The UKSHEC II scenarios approach

This project goes beyond those previous socio-technical hydrogen scenarios by developing qualitative scenarios in parallel with modelling work. Quantitative modelling has been used in combination with scenario planning since the origins of the field (Wack, 1985). One common approach is the use of scenario storylines as tools for identifying and differentiating the values of key parameters for modelling exercises, with the resulting dynamics of change still determined by the model (e.g. Barreto et al., 2003). A second common alternative is the detailed quantification of narrative scenarios, to ensure that they are technically feasible and consistent (for example, Dutton et al., 2004).

Others have highlighted the way in which the complementary strengths of qualitative storyline scenarios and quantitative modelling tools can be put to good use by comparing and contrasting the insights and dynamics produced in each method (Alcamo, 2008, chap. 6; Ault, Frame, Hughes, & Strachan, 2008; Fontela, 2000), often using multiple iterations between modelling and scenario writing. Alcamo describes this as the 'SAS' (storyline and simulation) approach (Alcamo, 2008), and describes its use by the IPCC and others. In the energy field, examples of work of this kind include (Ault et al., 2008) and (Fortes, Alvarenga, Seixas, & Rodrigues, 2014), both of whom use energy system models to explore qualitative scenarios developed through participatory stakeholder processes. Recent work within the UK's Realising Transition Pathways project has also linked models to qualitative socio-technical transition scenarios, through quantification of storylines and iteration with various modelling tools (Foxon, 2013).

The UKSHEC II project follows in that tradition, though with a looser coupling of model runs and scenario storylines than is typically undertaken. In this project, socio-technical scenarios and energy system modelling have been used in parallel. The model is not forced to reproduce the dynamics of each storyline, and model runs are not to be understood as quantified versions of the storylines. Instead, modelling exercises are used to examine and inform elements of the scenarios, while the scenarios are used to challenge and confront the results suggested by the model. This can be described as a 'dialogue' between the two approaches, rather than a process of using one to provide input into the other, and with no attempt to arrive at fully quantified model-based equivalents to the qualitative storylines. The approach has similarities with approaches based on 'constructive conflict' in stakeholder dialogue (Cuppen, 2010), which attempt to confront different stakeholder positions, and thereby promote "an open exploration and evaluation of competing ideas

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[3] There is frequently confusion about the purpose and utility of scenario approaches, in part due to the great diversity of applications, which arise from the fact that the future is profoundly uncertain and that not thinking about or making assumptions about the future is impossible. Confusion also arises because most models are run different with sets of input parameters, for which the term scenario is typically used. That model-specific use of the term scenario is distinct from what are here termed 'exploratory scenarios', which develop qualitative, narrative storylines of alternative possible futures.

and knowledge claims in order to achieve new ideas [and] new insights..." (Cuppen, 2010, p. 26). Here, the approach confronts two contrasting "worldviews", one derived from stakeholder opinion, the other a model that operates as a planner optimising the energy system.

3. Developing socio-technical storylines: methods and approach

The methodological approach used in this study followed a simple sequences of stages, similar to many other socio-technical scenario development exercises. The method draws on that suggested by Hughes (2013). Note that many of these stages are overlapping and iterative.

1. Development of theoretical framework for describing transitions.
2. Participatory involvement of expert stakeholders to scope key issues, uncertainties and possible dynamics.
3. 'Mapping' the system in terms of actors, regime structure, niches, and landscape developments, and identification of key strategic uncertainties and the branching points that they imply.
4. Writing of storylines, with a structure drawn from insights from transitions research, attempting to highlight key branching points and their possible implications.
5. "Dialogue" with modelling: use scenarios to identify issues that may not be addressed with models, and use models to highlight potential weaknesses in the scenarios.

3.1. Step 1: developing a theoretical framework for describing possible transitions

Two complementary and related theoretical frameworks, drawn from the technological transitions literature, are used to structure the analysis of the key uncertainties and the way in which they may unfold. This framework is briefly described here.

First, the analysis is situated within the multi-level perspective (MLP) on technological transitions (Geels, 2002), and draws on the typology of Geels and Schot in order to inform some basic transition 'types' (Geels & Schot, 2007). Their typology is based on two dimensions:

i. The timing of interactions (how mature is the niche when the regime comes under pressure).
ii. Nature of interaction (relationship of the niche innovation to the broader regime, i.e. is the niche innovation disruptive or re-enforcing to existing regime).

Beliefs about the status of hydrogen with regard to these dimensions differ. Geels and Schot offer four criteria for determining whether the niche innovation is mature: (a) the presence of a dominant design, (b) presence of powerful actors in the innovation system supporting the technology, (c) price/performance have improved and there are expectations of further improvement, and (d) the innovation is used in markets that cumulatively account for more than 5% market share. Hydrogen technologies meet the first three of these criteria, but fall short of the fourth, suggesting that they are not quite at the level of maturity that might enable a rapid transition. However, there is considerable uncertainty about how fast this level of maturity might arise. With regard to the nature of hydrogen as disruptive or re-enforcing the existing regimes, stakeholder opinions differ. Stakeholder interviews and participant observation make clear that while some see hydrogen as highly disruptive to existing regimes, others promote hydrogen precisely because they see it as fitting well into established industrial, commercial and consumer patterns of behaviour.

The typology provides a useful way of exploring the types of dynamics that may occur in the course of a transition, and in particular provides a way of structuring the types of interaction between events and processes occurring at different levels within the MLP. Each transition is therefore described in terms of its position within this broad typology.

The scenario-development approach used here complements the MLP by focusing attention on developments within co-evolving 'subsystems', drawing on Foxon's work on co-evolutionary processes in transitions (Foxon, 2011). While Geels and Schot's framework sheds light on archetypal dynamics between levels, Foxon's work provides a useful structure for thinking through the dynamics within the heterogeneous configurations of actors, networks and institutions that comprise regimes and niches. Based on observations of the hydrogen energy innovation system, Foxon's framework is adapted here, focusing as he does on user practices, technologies and business strategies, but also explicitly considering governments, and considering institutional changes as part of the dynamics of each subsystem, rather than existing as a distinct unit of analysis (similar to Freeman and Louca's (Freeman & Louca, 2001) treatment of institutional arrangements in each of their co-evolving subsystems[4]). This analysis of co-evolving sub-systems is used to shed light on the way in which niche-regime interactions may occur. These categories correspond well with the key areas of uncertainty highlighted by stakeholders and in the literature, and described in (McDowall, 2012a).

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[4] See F&L p. 125. The framework adopted here also follows Freeman and Louca in excluding the natural environment (Foxon's 'ecosystems') from analysis.

3.2. Steps 2: participatory scoping and issue identification

Socio-technical scenarios are a way of examining, extending and confronting themes prevalent in actor perceptions and discourse about the future of the technology in question. An important step for this project was thus to identify uncertainties and issues prominent in stakeholder expectations and discourse around possible hydrogen transitions. This was undertaken through an initial participatory expert workshop, and a series of stakeholder interviews. Insights into stakeholder views were also gathered through participant observation at a series of UK and international hydrogen stakeholder events between 2010 and 2012. The storylines are thus rooted in ideas and views common among stakeholders engaged in debate and dialogue around hydrogen energy in the UK.

3.3. Step 3: mapping the system

A key step in the construction of socio-technical scenarios is an analysis of the incumbent socio-technical regime, an assessment of the various niches and emerging innovation systems that may threaten it, and an overview of the pressures at the landscape level. For the sake of brevity, this paper does not elaborate these issues in detail, and in any case socio-technical accounts of these are given by a number of authors (see summary in Table 1).

3.4. Step 4: identification of strategic uncertainties and possible branching points

The fourth stage identified key uncertainties and possible branching points. This step identified the uncertainties and transition dynamics prominent in stakeholder discussions, in the literature, and which have been important in historically analogous transitions. These were structured according to the theoretically-informed framework developed in stage 1. Uncertainties and potential branching points are highlighted for each of the subsystems identified as relevant in niche-regime interactions, and at the landscape level.

This section reports briefly on insights from literature review, a stakeholder workshop and stakeholder interviews. Based on the adaptation of Foxon's co-evolutionary approach and the Geels and Schot multi-level framework, critical uncertainties for three dimensions of niche-regime dynamics are identified: (i) technologies, (ii) user practices, (iii) business strategies and government policies (i.e. strategic actions of major actors). In addition to these three, a fourth set of critical uncertainties that occur within the broader energy system landscape is also examined.

3.4.1. Technologies

Despite significant technical progress in recent years (James & Spisak, 2012), including related to reductions in platinum catalyst requirements and associated costs, doubts remain about the ability of hydrogen technologies to reach benchmark performance targets at an acceptable cost. Significant analysis has gone into examining the implications of these technological uncertainties, and as a result the uncertainties can be regarded as relatively well characterised. That is to say, there is a high degree of alignment about which unknowns are known and how important they might be.

Possible branching points:

- Automotive hydrogen fuel cell and storage systems reach performance and costs that are close to incumbent vehicles, such that foreseeable carbon prices or air quality regulations are expected to render them a truly competitive option in the near term, with mass production.
- Battery electric vehicle technologies undergo sufficient range enhancements, cost reductions, and recharging speeds to render them an attractive option for a sizeable portion of consumers. This branch would greatly diminish the prospects for hydrogen.

Table 1
Key features of the niches, regimes and emerging innovation systems of relevance to hydrogen and fuel cells.

	Key features	References
Hydrogen niches	Market niches (forklift trucks, back-up power, telecoms remote power); Also 'technological niches': the California Air Resources Board's Zero Emission Vehicle mandate; demonstration programmes; the R&D units in automotive firms	Agnolucci and McDowall (2007), McDowall and Eames (2006)
Car-based transportation regime	Dominance of car as a mode of personal mobility; close relationship of car industry and state; ubiquity of road, refuelling and maintenance infrastructure; well-articulated rules and user needs, etc.	Marletto (2011) and Van Bree et al. (2010)
The broader UK energy system regime	Dominance of natural gas (for space and water heating) and electricity (for lighting and consumer appliances). Mature and well established infrastructures, increasing pressure to decarbonise energy use by deploying renewable power technologies and fuel switching to electricity.	Foxon et al. (2010) and Shackley and Green (2007)
The emerging hydrogen and fuel cell innovation system	Strong R&D capabilities, entrepreneurial firms, clear articulation of search and alignment of actors; failure so far to build significant markets.	Bakker, Van Lente, and Meeus (2011), McDowall and Ekins (2011), Ruef and Markard (2010) and Schaeffer (1998)

3.4.2. User practices

User practices have generally been less well addressed in the literature examining hydrogen energy transitions than have other aspects (McDowall, 2012a; McDowall, 2012b). Many studies simply ignore this as a source of uncertainty, choosing to believe that users will continue to relate to vehicles in the same way as they currently do. Four issues with respect to user behaviour appear particularly important: (i) Consumer willingness to adopt limited-range electric vehicles; (ii) Plugging-in behaviour, and the resulting implications for electric charging infrastructure; (iii) Consumer willingness to adopt vehicles when only a portion of fuelling stations provide hydrogen; (iv) Emergence of new models of ownership, and potential for new technologies to lead to changing user practices, resulting in a co-evolution of user practices and technologies.

These are issues seen as having critical importance within the leadership of automotive companies (KPMG, 2012), but they have received relatively little attention in the research literature. The issue that has received least attention is that concerned with the potential of new ownership models, such as car sharing, which has been shown to reduce overall ownership and change the profile of the fleet (Firnkorn & Müller, 2012; Martin, Shaheen, & Lidicker, 2010). With different ownership options, it is possible that existing market segments for vehicles will become more pronounced, as consumers would no longer need a vehicle that met all conceivable needs. Alternative ownership options for infrastructure have also been suggested, such as through user co-operatives (Thomas, 2012).

Possible branching points:

- Rejection/acceptance of significant numbers of BEVs and other plug-in vehicles.
- Rejection/acceptance of fuel cell vehicles following market introduction.
- Differentiation of vehicle demands as a result of market changes and social innovation in ownership models.

3.4.3. Business strategies and government policies

In addition to consumers, whose practices were addressed above, four groups of actors will be critical in determining how and whether a transition to a hydrogen energy system takes place:

1. **Governments**. Both national and local governments play a key role as regulators, and in shaping the market environment for hydrogen technologies through supportive policies for low carbon transport.
2. **Incumbent automotive firms**. These firms are the technology leaders, but all of them maintain a portfolio of low-carbon vehicle options and none are likely to commit wholly to any one technology choice.
3. **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.
4. **Emerging hydrogen and fuel cell firms**. These are the actors at the core of the advocacy coalition lobbying for hydrogen.

Possible branching points include:

- Widespread local government adoption of zero emission zone policies
- The success of failure of initiatives to commercialise hydrogen vehicles, potentially backed by national governments concerned to protect and promote their automakers' technology. In particular, the emerging 'H2Mobility' programmes in Germany and the UK and equivalent exercises elsewhere.

3.4.4. Uncertainties in related regimes and at the landscape level: what is happening within the wider energy system?

How might the wider energy system evolve, and how would this affect the prospects for hydrogen? Most studies examining possible transition pathways for hydrogen focus on the transport sector and the potential adoption of hydrogen in vehicle fleets. However, there has been increasing interest in the ways in which hydrogen energy systems may play broader roles in sustainable energy systems, facilitating the deployment of low carbon primary energy sources by enabling long-term, inter-seasonal storage of energy, and by mediating between power, heat and transport markets. In particular, there is growing interest in the potential of "power-to-gas" projects, in which hydrogen is produced when surplus renewable electricity would otherwise be curtailed, and is then injected into gas networks, decarbonising gas while providing a flexible demand service to the power system. In the UK, where distributed gas dominates domestic heating, there is a question as to whether the gas network will need to be decarbonised or decommissioned in order to meet carbon targets.

Key uncertainties include the possible evolution of markets for the provision of heating in a low-carbon future; the availability and cost of key resources; and the ability of energy systems to cope with increasing levels of intermittent generation.

Possible branching points of relevance to hydrogen include:

- Decision (or not) to begin decommissioning the natural gas distribution system in the 2020s, with heating increasingly provided by electricity instead of gas.
- Failure to achieve sufficient electricity grid management through 'smart' systems and efficiency measures.

3.5. Write scenario storylines

This step involves combining scenario elements and uncertainties as described in Sections 3.3 and 3.4 into narratives that illustrate the implications of key uncertainties and capture the major issues discussed by stakeholders.

3.6. Step 5: the dialogue between scenarios and modelling

The final stage is to test elements of the scenario storylines with a quantitative modelling framework, and use the scenario storylines to interrogate the model, by bringing them into a dialogue of 'creative conflict' (Cuppen, 2010). This project used a single model, the UK MARKAL model (Kannan, Strachan, Balta-Ozkan, & Pye, 2007). MARKAL is a technologically detailed optimisation model that uses linear programming to find the least cost energy system from a database of energy technologies to meet an exogenously specified set of energy service demands (Fishbone & Abilock, 1981; Loulou, Goldstein, & Noble, 2004). MARKAL models have been widely used to examine possible hydrogen transitions in the UK and elsewhere (Endo, 2007; Gül et al., 2009; Krzyzanowski et al., 2008; Strachan et al., 2009; Tseng, Lee, & Friley, 2005; Yeh et al., 2008).

Much of the modelling work discussed here is published in fuller form elsewhere (Dodds & McDowall, 2013; Dodds & McDowall, 2014). Further description of the basic model details are therefore not provided here, and this paper focuses instead on the way in which the modelling and scenario work was used in complementary ways. The dialogue between the scenario and modelling involved two elements.

First, the scenario storylines were used to 'ask questions of the model', by examining where the storyline differed from the explicit or implicit assumptions embedded in the model structure and data. This process revealed ways in which the model was unable to reflect either options or dynamics thought likely to be important in stakeholder discourse. This process revealed assumptions that would otherwise have remained implicit and opaque within the model. Where possible, the model was adapted to enable exploration of potential transition options that had previously been missing (such as differentiation of vehicle markets). Resulting model runs were conducted to examine the implications of introducing these different possibilities, and testing their techno-economic characteristics.

Second, the model was used to question and confront the scenarios, by showing where certain scenario elements may involve unrealistic energy market dynamics, such as the penetration of technologies that appear to be far from cost-effective, or where scenarios appear to overstate the importance of elements whose techno-economic significance appears less when examined in a formal quantitative framework. Where scenario storylines were found to involve elements that appeared unrealistic when analysed with the model, these were re-examined and if necessary revised (see Fig. 1).

4. Hydrogen transition scenarios and modelling for the UK

4.1. Background common to all scenarios

There are common features of all scenarios, which define the broader 'state of the world' in which these futures unfold. In this state of the world, there is (a) continued global emphasis on achieving decarbonisation; (b) continued global geopolitical

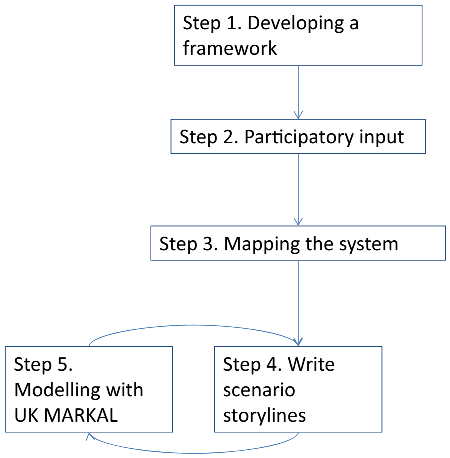

Fig. 1. Diagram showing development of scenarios and interaction with modelling.

stability; (c) continued long-run economic growth, periodic recessions notwithstanding. These background conditions provide part of the landscape conditions common to each scenario.

4.2. Scenario summaries

Summaries of all scenarios are presented in Table 2.

Scenario 1. "Car of the future" – 2010–2050

Headline summary

This scenario is a relatively straightforward **transformation** of the existing transport vehicle regime, in response to continued and increasing pressure from governments to reduce transport sector GHG and air pollution emissions. In this scenario, the behavioural and structural dynamics of the transport sector remain intact, with hydrogen FCVs replacing the ICE as the dominant form of personal transport. This scenario is similar to many found within the broader hydrogen futures literature, which tends to envisage relatively unproblematic shifts towards use of hydrogen as a direct replacement for petroleum in fuelling road vehicles.

Key branching points: Failure of battery electric vehicles to attract significant customers; tepid performance of PHEVS because of challenges in charging and consumer behaviour shifts. Alignment among automotive firms and governments around hydrogen as the technology for decarbonisation of the transport sector, along with good progress in technology performance and cost reduction.

How key areas of uncertainty play out in the scenario:

- **Technological uncertainties**. Research and development activities in hydrogen and fuel cell vehicles continue to yield strong progress in driving down costs and improving performance.
- **Behavioural uncertainties**. Consumers prove resistant to battery electric vehicles, which only penetrate in niches and in response to generous but expensive government incentives. PHEVs are more popular, with increasing uptake in the medium term, but limited plug-in opportunities and high battery costs continue to act as a barrier to dominance.

Table 2
Summaries of the scenarios.

	Car of the future	Horses for courses	Hybrid fuels
Transition type	Transformation	Reconfiguration	De-alignment/re-alignment
Key branching points	Weak uptake of BEVs and PHEVS Alignment among automotive firms and governments around H_2. Good progress in technology	Rapid growth of car-clubs; ownership of BEVs as second-cars; new business and ownership models enable FCVs to enter market in some market segments.	Decarbonisation of gas becomes increasingly prominent, with rise of 'power-to-gas'.
Technology	R&D activities in H_2 and FCVs continue to yield strong progress in driving down costs and improving performance.	H_2 technologies show steady development, as do other low carbon vehicle technologies	H_2 technologies show steady development, as do other low carbon vehicle technologies.
Behaviour	Private car remains dominant. Consumers are resistant to BEVs, which only penetrate in niches. PHEVs are more popular, but limited plug-in opportunities and high battery costs prevent dominance.	Consumer behaviour evolves with the introduction of new technologies, and the emergence of social innovations in car ownership, particularly car clubs.	Consumers maintain similar characteristics as today. There is a reluctance to embrace new vehicle technologies unless they provide significant personal benefits.
Business strategies and government policy in the transport regime	Automotive firms turn to FCVs as the long-term goal for their vehicle portfolios. Governments of countries with large automotive sectors attempt to initiate a transition. Major launches of vehicles are accompanied by a big infrastructure investment programme.	Uptake of BEVs as second cars; growth of car clubs using FCVs, which act as a key niche for the establishment of hydrogen infrastructure. Urban emissions standards become important in converting taxis to hydrogen.	There is a system failure: despite evidence that FCVs would work well, there is a failure to overcome the barriers to it. Some efforts are made, but these are not strong enough in the near term. H_2 is developed elsewhere in the energy system, and introduced by infrastructure and utility companies to support power and heat system, ultimately facilitating adoption in the transport sector.
Energy system	Early power sector decarbonisation; electrification of much of heat demand; integration of renewables is facilitated through smart grid and demand-side management. Concerns over bioenergy sustainability limit the contribution of biofuels.	Similar to car of the future scenario.	Significant deployments of renewables create a looming 'balancing crisis', with significant costs associated. In response, the gas industry actively promotes decarbonisation of gas, exploring biogas and hydrogen injection.
Implications for hydrogen	Rather rapid adoption of hydrogen FCVs, beginning in the mid-2020s.	Slower transition to H_2 in transport, beginning in earnest from the mid-2030s.	H_2 becomes important niche in heat and power. Longer term sees H_2 widespread in transport (in 2040s) and throughout energy system.

- **Business strategies and government policy in the transport regime**. Automotive firms increasingly see fuel cell vehicles as the long-term goal for their vehicle portfolios. Governments of countries with large automotive and fuel cell sectors provide support for attempts to initiate a transition, seeing potential first-mover advantages – or the slightly different first mover defence – in which governments use stringent air quality legislation to 'lock-out' cheaper but less technologically advanced imports from emerging economies. The infrastructure strategy is a 'build it and they will come' approach, in which major launches of vehicles are accompanied by a big infrastructure investment programme.
- **Energy system dynamics**. This scenario envisages an energy system decarbonisation trajectory similar to that illustrated in the UK Carbon Plan: early power sector decarbonisation is followed by electrification of much of heat demand, and is facilitated through smart grid-enabled demand-side management and conservation measures. However, political uncertainty continues to surround bioenergy, inhibiting both policy and investments in capacity for biofuels production.

Scenario narrative

This scenario sees the major automotive firms increasingly backing hydrogen and fuel cells from 2015 onwards, in the face of tepid consumer responses to battery electric vehicles, political battles over the sustainability of biofuels, and intensifying decarbonisation and low-emission vehicles policy in key market regions (Japan, Germany, and California). Leadership in hydrogen FCVs is increasingly seen as a key route to long-term dominance of automotive markets. Plug-in hybrids are an important transition technology, with range extending engines being replaced with fuel cells. Battery electric vehicles remain a niche, popular as a second car in wealthier regions, but never replacing more than a portion of vehicle kilometres. As markets for hydrogen vehicles become established during the early 2020s in Germany, Japan and the US, prices for such vehicles fall. In the face of competition from automotive producers in emerging economies, the Japanese, European and American automotive giants increasingly lobby for tighter emissions standards to ensure that only firms with advanced powertrain technology can compete.

Following success of initial markets elsewhere, the UK government facilitates the development of initial infrastructure, introducing strong tax incentives for FCV purchases, infrastructure investments, and hydrogen fuel. Regional governments concerned to protect their automotive sectors (e.g. Midlands) provide support for some early infrastructure, as do regions (e.g. London) with air quality problems.

Buses provide an important early market in the UK, with hydrogen buses increasingly on the roads in the largest UK cities by 2020–2025 on a commercial basis rather than as demonstrations. Hydrogen FCV market entry into car markets begins in earnest from about 2025, following introduction among early adopters in 2016. Hydrogen is produced largely from fossil fuels, with carbon capture and storage.

4.2.1. Insights from modelling in UK MARKAL

As a perfect-foresight[5] optimisation model, UK MARKAL represents a world with low barriers to transition, perhaps implicitly assuming high alignment among stakeholder deploying infrastructure and vehicles together. The model decision-structure is thus relatively close to the dynamics of the storyline, in which alignment is high and barriers to technology adoption are minimised through strategic cooperation of dominant actors.

Cost assumptions for hydrogen vehicles used in the modelling are based on cost forecasts that assume global hydrogen technology success (as indeed is common in energy system model representation of new technologies including hydrogen, except those applying endogenous technology learning; Anandarajah et al., 2013). Even so, the model prefers to deploy hydrogen only from 2035 onwards, rather later than the 2025 described in the narrative. The optimisation procedure means that the least-cost carbon abatement opportunities are pursued, and options are not selected until they form part of that least-cost low-carbon solution. Even if hydrogen vehicles are relatively attractive, they will only enter the market where there are no cheaper uses for limited supplies of low-carbon energy. The model suggests that in earlier periods low-carbon primary energy is better used to displace coal-fired power generation, and the unabated use of gas in heating, while the adoption of more-efficient hybrid electric vehicles reduce the competitive edge of hydrogen vehicles. The model does not take into account, however, the market preparation work and niche markets required to enable rapid uptake in 2040 and beyond. In the real world, the market entry date in the narrative of 2025 might be necessary to achieve sufficient initial sales and infrastructure build-up to enable mass deployment in the 2030s as depicted in the modelling results.

Scenario 2. "Horses for courses" 2010–2050

Headline summary

This scenario is a **reconfiguration**. The new regime grows out of the old regime, picking up lots of innovations, with substantial changes to the regime's basic architecture. This scenario argues that structural changes and social innovation, alongside technological substitution, are a likely response to the pressures of decarbonisation and the emergence of new technologies.

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[5] "Perfect foresight" in this context, means that the model optimises across all time periods simultaneously. That is, the optimisation algorithm 'knows' all the input data (future costs, future demands, etc.), and optimises the entire time period (2010–2050) with that knowledge.

Key branching point: Breakdown of current paradigm of vehicle ownership and operation, rapid growth of car-clubs and ownership of BEVs as second-cars, with disruptive companies entering the automotive sector.

How key areas of uncertainty play out in the scenario:

- **Technological uncertainties**. Hydrogen technologies do not progress more rapidly than competing low-carbon vehicle technologies, but continue to show strong development in terms of performance, durability and cost.
- **Behavioural Uncertainties**. Consumer behaviour evolves with the introduction of new technologies, and the emergence of social innovations in car ownership, particularly car clubs.
- **Business strategies and government policy in the transport regime**. Uptake of battery electric vehicles as second cars; growth of car clubs using FCVs, although they remain a small overall portion of the market in early years, these clubs act as a key niche for the establishment of hydrogen infrastructure. Urban emissions standards are important in converting taxis to hydrogen.
- **Energy system**. Similar to car of the future scenario.

In this scenario, globally heterogeneous approaches emerge to low carbon vehicle policies, with some countries placing more emphasis on electric vehicles, biofuels or hydrogen, in response to national industrial strengths, differing policy approaches to fostering innovation, and different policy priorities. Automotive firms continue to back diverse portfolios and continue to develop EV, PHEV and FCV technologies. Car markets become increasingly complex, with different fuels and drivetrains common, unlike the current dominance of internal combustion engines with either petrol or diesel. Technological advancements are forthcoming in all powertrain technologies, with no powertrain achieving a breakthrough that enables it to dominate all parts of the car market.

Social innovation is a key feature of this scenario: car clubs and new ownership models enable more efficient use of cars as capital goods. That is, changes in normative and cognitive rules around ‘ownership’. This facilitates a growing differentiation of vehicle markets, with consumers either owning or accessing different vehicle types for different purposes. Uptake of electric vehicles is strong in this scenario, with hydrogen FCVs and diesel PHEVs competing in the market for larger vehicles. Policy emphasis is on emissions reduction rather than supporting the development of a particular industrial choice, implying a shift away from technology-specific support mechanisms such as the RTFO and grants for plug-in vehicles. Hydrogen emerges more strongly only in the longer term (i.e. from 2035).

This scenario highlights an emerging debate in the recent literature around the idea of a portfolio of complementary options across the transportation fleet. The concept has attracted both advocates (McKinsey, 2010) and critics (Bakker & Van der Vooren, 2011).

4.2.2. Insights from modelling in UK MARKAL

Many aspects of this scenario are not suitable for analysis within the MARKAL modelling paradigm. Indeed, this exercise highlighted the limits of an energy system model framework for understanding transport technology choice in scenarios in which social innovation and flexible consumer preferences play a prominent role. The process reveals the implicit and conservative assumptions in such models concerning market structure and user behaviour. Though increasingly prominent in stakeholder opinion (see, e.g. KPMG, 2012), scenarios in which new business models, social innovation and new powertrain types disrupt established patterns of vehicle ownership have been poorly integrated into the energy system modelling frameworks most prominent in major strategic energy policy decisions.

Models examining hydrogen energy transitions have tended to build-in the assumption that a single technology will dominate road transport vehicle demand. Bottom-up energy system optimisation models, including the UK MARKAL model used in this analysis, follow this approach, with vehicle technologies competing to fulfil consumer demand for car-based transport. This scenario prompted a revision of the model to examine whether a differentiation of vehicle demands, such that large and small vehicle technologies compete to fulfil distinct demands, makes a different to technology choice in the model. The assumptions behind the modelling, as well as results, are reported in detail in (Ekins, Anandarajah, McDowall, & Usher, 2011) and (Dodds & McDowall, 2014). Contrary to the scenario storyline, the modelling suggests that technology choice is similar across vehicle classes in most model runs. The modelling suggests relatively minor differences in adoption timing and rates within different market segments, but in general model outcomes did not vary substantially between the model version in which vehicles markets are assumed to be homogenous vs. that in which technologies compete in semi-distinct market segments (such as smaller cars vs. larger cars). Here, model and storyline disagree. While the linear optimisation formulation of the model does not envisage differentiated vehicle markets resulting in greater heterogeneity of vehicle technology, the weaknesses of the model representation of consumer behaviour suggest that the storyline remains a valid possibility.

Scenario 3. “Hybrid fuels”

Headline summary

The storyline explores a future in which hydrogen plays a limited role in transportation to 2050, but is involved in a **de-alignment/re-alignment** within the heat and power regime, leading to a shift in the energy system context for decarbonising transport fuels. This de-alignment/re-alignment is caused by a rapid loss of confidence in the early 2020s in the direction of development in power and heat regimes, as a result of disappointing uptake of efficiency measures, slower than anticipated power grid upgrades, and resulting cost escalation associated with the penetration of high levels of intermittent renewables.

Key branching point: This scenario explores the possibility that commitment to existing gas infrastructure results in a redirection of decarbonisation efforts away from the focus on electrification in the reference case, to include decarbonisation of gas. This has a wider effect on the availability of hydrogen, and ultimately its use in transport. A second key branching point is technology choice in CCS, with pre-combustion gasification emerging as the key CCS technology. This enables the flexible production of hydrogen and electricity.

How key areas of uncertainty play out in the scenario:

- **Technological uncertainties**. Hydrogen technologies do not progress more rapidly than competing low-carbon vehicle technologies. Hydrogen remains confined to niches, some of which gradually grow, but which do not represent an important role within the energy system.
- **Behavioural uncertainties**. Consumers maintain similar characteristics as today. There is a general reluctance to embrace new vehicle technologies unless they represent significant personal benefits. Electric vehicles make progress as second cars, and hybrids and eventually PHEVs are the incremental route to transport decarbonisation.
- **Business strategies and government policy in the transport regime**. There is a system failure: despite evidence that a hydrogen system would probably work well, there is a failure to overcome the barriers to it. Some efforts are made, but these are insufficiently strong in the near term.
- **Energy system dynamics**. Two major developments distinguish energy system developments in this scenario. First, significant deployments of renewables and nuclear during the 2010s and early 2020s create a looming ‘balancing crisis’, with significant costs associated with natural gas balancing plant, and particularly associated with the very significant seasonal variations in energy demand, resulting in very low capacity factors for some dispatchable plant. Second, the gas industry is increasingly active in promoting decarbonisation of the gas grid, exploring biogas and hydrogen injection.

Scenario narrative

In many countries, gas companies begin strategic activities to resist the ‘all-electric’ low carbon future presented in many long-term decarbonisation scenarios: lobbying emphasises the inter-seasonal and strategic storage benefits of gas, investments in biogas, hydrogen and CHP. Globally, there is growing interest in hydrogen in gas grids, with increasing R&D dedicated to end use applications and infrastructure issues. This was led by Germany and the Netherlands. Hydrogen plays a role in transport only in the long-term. In the 2020–2030 timeframe, progress with hydrogen fuel cell vehicles is still too slow to justify major infrastructure investments. Some vehicle niches do exist: buses, various military applications, and niches in which zero emissions and fast refuelling are required.

Strong development of renewables takes place in the UK, in particular the offshore wind energy grid. However, uptake of domestic efficiency measures is disappointing, and the seasonal variation in heating demand exceeds the capacity of the low-carbon power network. There is some interest in storage projects, various models of demand-side management and smart grid technology are attempted, and there is investment in biogas. The UK government closely watches attempts to introduce hydrogen vehicles elsewhere, but decides not to intervene in markets to promote FCVs above other ultra-low emission vehicles. Instead, biofuels, PHEVs and EVs are seen as sufficient, alongside renewed investments in commuter rail and other alternatives to cars. In the long-term, roles for hydrogen throughout the energy system enable further decarbonisation of transport, but hydrogen vehicles do not enter the transport market until 2035, and are not widespread until the 2040s.

4.2.3. Insights from modelling in UK MARKAL

Previous work with UK MARKAL had assumed that the natural gas grid would start being retired from 2020 onwards. In line with the ‘hybrid fuels’ scenario, Dodds and McDowall (2013) revisited the representation of gas grids in UK MARKAL, and tested the importance of current investment programmes and decarbonisation options for the future of the grid. This work provides at least some support for the notion in this scenario that the gas grid may provide a route for hydrogen to become established as a part of the energy system, through injection of hydrogen into gas distribution networks, or wholesale conversion of some (or ultimately all) of the network.

In this case, the modelling informed a change in the scenario storyline. A previous version of the storyline emphasised the UK Government decision to require the replacement of all iron gas distribution pipes with safer polyethylene pipes by 2030 (the Iron Mains Replacement Programme). However, the modelling suggested that, despite the significant sunk investments this programme represents, it was not itself a decisive development that represents a branching point. This is because despite the large scale of the investments, they are dwarfed by both the value of the existing assets, and by the value of energy flowing through the network (and the costs associated with carbon emissions under a strict decarbonisation target). Thus the significance of the iron mains replacement programme, which an intuitive approach had suggested might be important, appears less decisive when examined in a formal quantitative framework.

5. Discussion and conclusions

5.1. Key insights for hydrogen transitions:

The analysis makes clear that there are many possible routes by which hydrogen may play a role in a low-carbon UK energy system. In particular, the scenarios highlight three key important key uncertainties and knowledge gaps for hydrogen transitions:

- The ‘car of the future’ scenario posits a case in which a high degree of alignment and collaboration between various industry sectors and government takes place. This is effectively the implicit assumption within many system models, since the co-ordination failures that would prevent this from occurring are not represented in most model frameworks. Yet the plausibility of this scenario must be confronted by the limited and partial nature of historical precedents for this kind of transition (with none a perfect analogy). The uncertainties associated with the transition governance capacity of key actors are enormous.
- Conventional analytic techniques and scenarios may have underestimated the potential importance of innovation in car ownership models, and more broadly in social innovation with respect to transport needs. It seems plausible that these could influence adoption and patterns of use of both conventional and alternative vehicle types, though understanding (and particularly modelling) how this might work in practice is highly uncertain.
- Roles for hydrogen outside transport may be valuable in themselves as renewables gain market share, and this could facilitate infrastructure transitions: assumptions about the dynamics of the rest of the energy system are highly relevant for the future of hydrogen in transport, yet are often excluded from hydrogen transition analysis in order to focus on more analytically tractable issues. In particular, the potential for hydrogen to play a role in decarbonising gas networks appears promising in both the storyline and the modelling.

5.2. *Reflections on method*

The work reported in this paper has illustrated the value of using both narrative storylines informed by participatory scenario approaches and formal quantitative models in exploring possible long-term transitions. The qualitative storyline scenarios resulted in both tests of model structure that showed sensitivity to tacit assumptions, and also revisions to model structure that demonstrated the importance of issues that have been of interest to stakeholders but neglected in the literature modelling possible transitions. At the same time, the quantitative modelling revealed areas in which scenarios placed too much emphasis on issues that appear to be techno-economically less important.

Previous work with socio-technical scenario approaches (with notable exceptions, such as the UK’s Transition Pathways project) has arguably tended to neglect the quantitative dimensions, such as the rates of transition that are plausible, or the relative techno-economic significance of different investments and scenario elements. At the same time, analysis of hydrogen with energy system models has tended to focus on a relatively narrow range of uncertainties and possibilities, and model structures have tended to obscure issues around implications of behavioural change or systemic energy system change.

The point is that thinking about radically alternative futures is necessarily an exercise that can only be informed in a limited way by changing the parameters of a given model. While it has been useful to use scenarios as structures for developing a set of input parameters to modelling exercises, it is perhaps unfortunate that fewer studies use qualitative scenarios informed by stakeholder participation to highlight different possible structural issues in the models that are applied to a given problem.

In conclusion, bringing narrative socio-technical storylines into ‘dialogue’ with quantitative energy systems modelling can yield insights that could be missed if these tools are used independently. This analysis has focused attention on key branching points and uncertainties analysed within the UKSHEC II project. However, it does not represent a comprehensive analysis of conceivable transition pathways, and should not be seen as attempting to do so.

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