



FORECASTS, SCENARIOS, VISIONS,
BACKCASTS AND ROADMAPS TO THE
HYDROGEN ECONOMY:

A REVIEW OF THE HYDROGEN FUTURES
LITERATURE FOR UK-SHEC

**William McDowall
Dr Malcolm Eames**

**Policy Studies Institute
100 Park Village East
London
NW1 3SR**

www.psi.org.uk

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1. Introduction

Scenarios, roadmaps and similar foresight methods are increasingly used by both academic researchers and policymakers from government and industry as a means of coping with uncertainty in areas with long planning horizons, such as energy or transport policy. Research into the future of hydrogen as a component of the energy system and the putative hydrogen economy has been no exception. As will become clear from the below, 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.

Such 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. Indeed, one of the specific tasks identified in the social science component of the UK Sustainable Hydrogen Energy Consortium (UK-SHEC) work programme is to “*construct a small number of credible hydrogen futures, roadmaps and pathways to them; and to identify critical decision points along these pathways when action may be needed.*”

This paper represents the first stage of that work. In reviewing the literature on hydrogen futures, we have sought to map the current state of the art of scenario construction in this area and to explore how the future of hydrogen is perceived and framed by different actors.

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 (English language) 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 timescales each type of study tends to operate, and what they tell us about the future of hydrogen.

This working paper is structured as follows. Section 2 briefly describes the search strategies and standardised template used to identify and analyse the hydrogen futures literature considered within this review. As will become apparent a wide range of different approaches and types of futures studies were located. Section 3 therefore 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 on this work.

2. Review Methodology

Studies were identified with searches, using two electronic journal databases (Web of Knowledge and Sciencedirect), and the internet search engine Google. Search terms used were: '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 some studies specific to other countries were also included (Arnasson & Sigfusson 2000; US Department of Energy 2002; Jørgensen et al. 2003; Australian Government 2003; Canadian Fuel Cells). A total of 40 studies, published between 1996 and 2004, were reviewed (see bibliography attached).

Of these 11 focus on hydrogen or fuel cells in road transport, whilst a handful looked only at stationary fuel cell applications or hydrogen/wind energy systems. 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 (see Appendix 1) to ensure that the same elements of each were captured and compared in a rigorous and efficient manner.

3. A Typology of Hydrogen Futures

Our analysis identified six distinct, though overlapping, types of study (see table below), based on the tools used to describe the future of hydrogen energy. These six types can be further grouped into ‘descriptive’ and ‘normative’ approaches:

- **Descriptive studies** (forecasts, exploratory scenarios, and technical scenarios): aim to describe either ‘likely’ or plausible futures based upon existing trends or drivers. They are not normative, and do not seek to present a picture of a necessarily desirable future.
- **Normative studies** (visions, backcasts, and roadmaps): aim to produce a picture of a desired future, or to elaborate possible routes towards such a future.

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 storylines must progress.
	Technical Scenarios explore possible future technological systems based on hydrogen. They emphasise the technical feasibility and implications of different options, rather than exploring 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 by defining a desirable and plausible future end point. 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 five groups, or elements of these groups, sometimes form the basis for the identification of specific measures.

3.1 Forecasts

Five of the studies reviewed were classified under this heading (Mima & Criqui 2003; Christidis et al. 2003; Thomas et al. 1998; Fukushima et al. 2004; Kosugi et al. 2004). Two ‘roadmaps’ also included market forecasts as part of the study (HyNet 2004; Fuel Cells Canada 2003).

These studies are characterised by the use of quantitative methods to predict likely futures based on current trends, or based on surveys of expert opinion (e.g. Kosugi et al. 2004). They tend to explore shorter time scales than other types of study (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 (Fukushima et al. 2004; Mima & Criqui 2003; Christidis et al. 2003; Thomas et al. 1998). Some of these studies 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, in contrast to the relatively sophisticated models above, simply extrapolates sales figures from 1996-2003 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, in all of these studies, 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).

Forecasts, particularly over long time-horizons, have been criticised for an overly deterministic view of the future (Smil 2000, Berkhout & Hertin 2002), and of technological change (Geels & Smit 2000). Such 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 are therefore likely to be of limited use in helping us to understand the complex processes by which large technological systems are transformed.

3.2 Exploratory scenarios

Eight of the studies reviewed were classified under this heading (Ohi 2002; Watson et al. 2004; Australian Government 2003; Barreto et al. 2003; Di Mario et al. 2003; Jørgensen et al. 2003; Shell 2001; Kurani et al. 2003).

Rather than assuming that the future will largely follow existing trends or patterns, exploratory scenarios seek to inform policymaking by illuminating underlying drivers of

change, often drawing upon tacit knowledge and expertise, to build internally consistent storylines describing a number of possible futures.

The approach has a substantial intellectual pedigree and was developed as an alternative to deterministic forecasts. The scenarios reviewed here follow in this tradition, usually exploring longer-term (2030 – 2100) futures and trend-breaking developments. However, it is worth noting that whilst the possibility of including ‘surprise’ elements is thought to be a key strength of the exploratory approach (van Notten et al. 2004), this possibility was discussed in only two of the hydrogen scenario studies reviewed (Ohi 2002, 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 & Hertin 2002), only the studies by Ohi (2002), Watson et al. (2004) and the Australian Government (2003) appear to have involved stakeholder participation in their development.

Unlike most of the other futures 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 2002; used by Watson et al 2004 and Jørgensen et al. 2003).

Three of the exploratory scenario studies reviewed use scenario frameworks developed by others, including 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 develop storylines to explore the potential for hydrogen in the contexts set by those ‘parent’ scenarios, and use those storylines to feed into a quantitative model (such as MESSAGE-MACRO, POLES, or the purpose-built THESIS) to enrich and help quantify the scenario outputs.

The other exploratory scenario studies develop new scenarios and storylines to explore the conditions under which a hydrogen future might be expected to unfold (Jørgensen et al. 2003; Ohi 2002; Shell 2001; Kurani et al. 2003; Australian Government 2003). This involves identifying sets of drivers and relationships between them that are likely to be important in the future development of the hydrogen industry, 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 (Jørgensen et al. 2003).

The exploratory scenarios stand out as having more structured approaches to thinking about drivers, and, as attempts to address the future contexts in which hydrogen technologies will or will not develop, they have an emphasis on drivers at the ‘landscape’ level. These are frequently expressed as dimensions, across which the broad range of possible futures can be mapped. Though this approach has been criticised as being overly ‘top-down’ (Geels 2002b), over long time periods it may represent the most suitable way of capturing the broad dimensions of change. The table below outlines the dimensions chosen by the eight exploratory scenario studies. Typical dimensions used to frame such scenarios, and drive the development of alternative futures, include the rate of technological change, type of governance, or the strength of a society’s social or ecological values.

Study	Dimensions	Assumed correlations
Australian Government 2003	Economic growth: fast-slow Environmental values: strong-weak Technological change: fast-slow Conventional energy price: high-low	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 2002	Environmental & Social activism: strong-weak Technological change: fast-slow	Strong social values can make increased R&D funding politically acceptable, driving faster technological change
Jørgensen et al. 2003	Not expressed as ‘dimensions for change’ in the study itself – these are inferred. Balance of power: market vs. state Climate change impacts: apparent-invisible Oil supplies: secure-volatile.	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: Environmental values: Strong-weak Governance systems: 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.

An important feature of exploratory scenario building is that the storylines are not supposed to be driven by a preconceived desirable end-point. However, it is notable that many of the exploratory scenario studies reviewed here include a ‘happy ending’ storyline, in which CO₂ is dramatically reduced and society is reasonably well off and secure. These ‘happy ending’ scenarios tend to involve rapid technological change integrated with a socially responsible and globally co-ordinated society – with a significant role for hydrogen. This may represent a tendency of such exercises to come up with an unconscious ‘favourite’ – one that, in this case, is usually decidedly pro-hydrogen.

3.3 Technical Scenarios

Five of the studies were classified under this heading (Winebrake & Creswick 2003; Hart et al 2004; Sørensen et al. 2004; Ogden 1999; Eyre et al 2002)

The approach of these studies is best summed by Hart et al (2004):

“...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 future hydrogen-based technological systems, that would constitute all or part of a hydrogen economy, and assess the implications of these against a range of criteria, such as carbon emissions, cost, and technical feasibility. 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 2004; Sørensen et al. 2004; Ogden 1999) 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 transition pathways to the modelled systems, and therefore do not explore the broader factors that would promote or inhibit particular futures developing.

3.4 Visions

Nine of the studies reviewed were classified under this heading (Lovins et al. 1999; Foley 2001; Bockris 1999; Goltsov & Veziroglu 2001; Bossel et al 2003; Dunn 2001; Arnason & Sigfusson 2000; Schwartz & Randall 2003; Rifkin 2002).

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 how a hydrogen future could look. The second type 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’.

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, and are often based on a single individual’s opinions, expectations or interpretation of the literature.

Timescales 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).

None of them take a clearly defined approach towards technological change. While some see technological transitions as manageable through R&D investment, demonstration projects, taxes, and strong government leadership (Foley 2001; Dunn 2001; Lovins et al 1999), others invoke a need for major shifts in social values (Goltsov & Veziroglu 2001), or revolutionary technological breakthroughs (Bockris 1999).

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.

One striking feature of the visions reviewed is the degree of commonality amongst them, not least because they tend to gloss over 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.

3.5 Backcasts & Pathways

Six of the studies reviewed were classified under this heading (California Fuel Cell Partnership 2001; Farrel et al. 2001; Mauro et al. 1996; Wurster 2002; Owen & Gordon 2002; Fuel Cells UK 2003).

These studies all start with the assumption that some form of hydrogen economy is desirable, and they investigate possible paths by which the transition to that hydrogen future might be attained. 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. 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).

Typical timescales range from 2020 to 2050. Only the California study considers the possible effects of ‘surprise’ and discontinuities. 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 (2002).

Another interesting feature of these studies is the wide variety of opinions they offer regarding how close a hydrogen economy might be in the future, based on very different interpretations of the market readiness of the key technologies.

3.6 Roadmaps

Eight of the studies reviewed were classified under this heading (EC 2003/Hynet 2004; US Department of Energy 2002; Greater London Authority 2002; DTI 2004; NHA 2004; Fuel Cells Canada 2003; EST 2002; Toshiaki 2003).

Like backcasts, roadmaps assume the desirability of hydrogen, often defining a 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.

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 major aspects of a future world, or describing storylines. The future is treated as a ‘policy problem’, and emphasis is not on what will happen, but on what might be achieved.

Most of these roadmaps combine three important aims. Firstly, they identify barriers to the emergence of a hydrogen future and 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, having been produced to demonstrate and convince others of the potential of hydrogen. As a result it has been suggested that many roadmaps create unrealistically rosy expectations of the technology’s future (Geels & Smit 2000).

Lastly, the roadmapping process seeks to bring together key stakeholders to develop a shared vision of the future and shared strategies for success: 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 one of the explicit aims of many roadmapping initiatives.

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, looking at measures that can be implemented now to move towards set goals, and to overcome identified barriers. Policies are usually identified for the short term (5-10 years), with targets mapped out over the longer term (up to 2050 and beyond).

There is little discussion of formal ideas of technological change, and the studies are dominated by 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 about the future of the hydrogen economy, by examining the answers it provides to a series of questions. Specifically: 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?

4.1 What are the drivers of a hydrogen economy?

The literature revealed divergent views on the sorts of factor 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.

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

Meanwhile, 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; Rifkin 2002; Lovins et al. 1999; Goltsov & Veziroglu 2001). These studies frame the hydrogen economy as an issue of politics – held back only by the inability of governments to take a lead.

As well as this diversity of opinion on the sort of factor that is important in shaping change, the literature included 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 increased concerns for backup power.

More broadly, four overarching problems or policy objectives are consistently cited 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 The term energy security 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 eighteen made no mention of energy security at all. Of the studies that emphasise energy security (Australian Government 2003; Dunn 2001; Arnasson & Sigfusson 2000; NHA 2004; DTI 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 a few studies gave this factor particular emphasis. Air pollution featured most prominently in the more regionally focussed studies, such as those from London and especially California (Ogden 1999; Thomas et al 1998; California Fuel Cell Partnership 2001).

Competitiveness: Seven studies refer to international competitiveness as an important driver in the transition towards a hydrogen economy, a driver that is premised on the belief that such a transition is very likely or inevitable (Owen & Gordon 2002; Fuel Cells UK 2003; EC 2003/HyNet 2004; Fuel Cells Canada 2003; Australian Government 2003; Greater London Authority 2002; US Department of Energy 2002).

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

Of course, there are a range of other potential technological solutions that might contribute to achieve these objectives. The literature therefore sets out the attributes that are seen as setting hydrogen and fuel cells apart from these other potential solutions. These include the:

- ❑ High efficiency of fuel cells, and recent advances in fuel cell technology.
- ❑ Quiet running of fuel cells.
- ❑ Flexibility of hydrogen, in terms of the range of energy sources and technologies which can be used to generate it.
- ❑ Cleanliness of hydrogen at the point of use, particularly the potential to achieve zero toxic emissions from the combination of hydrogen and fuels cells.
- ❑ Potential to use hydrogen to store energy produced from intermittent renewable sources.

- The ability of hydrogen-fuel cell systems to provide a solution to the increasing demand for onboard electrical power in vehicles, an attribute which, along with quiet operation, is particularly valued in military applications.

4.2 Barriers & Challenges

The literature also recognises barriers to the development a hydrogen economy, and, as with the drivers, a variety of approaches are taken. In spite of that diversity, three barriers stand apart as the most clearly recognised:

- The absence of a hydrogen refuelling infrastructure, and the difficulty of establishing a market for FCVs in the absence of a refuelling infrastructure, and vice versa.
- The high costs of hydrogen technologies, particularly of fuel cells and of ‘green’ (low-carbon) hydrogen production.
- Technological immaturity: particularly of on-board storage and consequent limited current driving range of hydrogen vehicles; and, the 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 potential public acceptability and safety concerns (e.g. Greater London Authority 2002; US Department of Energy 2002), and the current lack of codes and standards (7 studies).

There are also many barriers that are picked up by only a few studies, including: the absence of surplus renewable electricity (Eyre et al. 2002; Hart et al. 2004); social values that disregard the environment (Goltsov & Veziroglu 2001); a regulatory framework that currently supports fossil fuels (Rifkin 2002; Dunn 2001); ability of incumbent technologies to adapt in the face of competition from hydrogen; limited skills base (Fuel Cells UK 2003; Fuel Cells Canada 2003); absence of global co-operation or plan of action (Mauro et al 1996); limited availability of fuel cell materials and components, particularly platinum (Ohi 2001); difficulty of technological developers in accessing capital (Fuel Cells Canada 2003); social opposition to carbon sequestration (Ohi 2001); and, uncertainty over the viability and costs of carbon sequestration (Jørgenson et al 2003; US Department of Energy 2002).

4.3 In what kinds of future does hydrogen become important?

Having examined the drivers, barriers and challenges recognised by the literature, we can ask what the literature says about the conditions necessary for hydrogen to have a major role in energy systems. 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.

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 (Owen & Gordon 2002; Mima & Criqui 2003; Australian Government 2003; Jørgensen et al. 2003; Di Mario et al. 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: Di Mario et al. 2003; Jørgensen et al. 2003), or major ‘discontinuities’, such as shifts in social values (Ohi 2001, Di Mario et al. 2003), technological breakthroughs that radically reduce costs (Ohi 2001), shifts in the relative price of oil (Jørgensen et al. 2003), or increases in the speed and intensity of climate change.

4.4 What does the Hydrogen economy look like?

Most of the studies consider the role of hydrogen and fuel cells in a variety of applications, both mobile and stationary, but some studies have a narrower focus. In particular, 11 studies concentrate solely on hydrogen and fuel cells in transportation. Only one study (Fukushima et al 2004) focuses exclusively on the possible role of fuel cells in electricity generation.

The drivers, barriers and challenges outlined above shape a wide range of possible hydrogen economies, involving different ‘technological architectures’, and a variety of trajectories that lead to those architectures. 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.

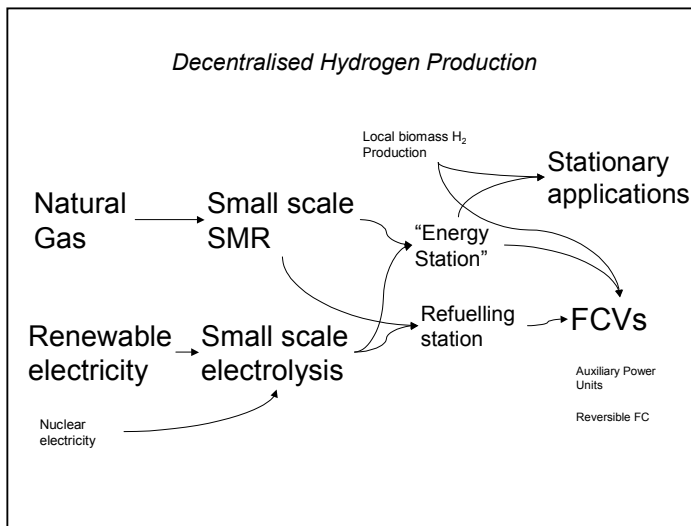


Figure 1. Shows common building blocks of decentralised hydrogen production systems. Text size of each building block indicates the number of studies that envisage a role for it.

Key technologies: Small scale electrolysis and Steam Methane Reforming of natural gas (SMR), renewables, ‘energy station’ stationary systems, FCVs

1) Decentralised architectures

These architectures are based on the local production of hydrogen, either from electrolysis, biomass processes, or the steam reforming of natural gas. Some decentralised systems envisage hydrogen production from locally available energy sources (such as small-scale biomass conversion, or local renewable electricity–hydrogen installations) while others see energy production as remaining centralised, with energy transferred to hydrogen production units either as electricity or natural gas. Decentralised hydrogen production overcomes many of the infrastructure issues associated with a transition to hydrogen, making use as it does of existing energy infrastructures. Many of the decentralised architectures involve the ‘energy station’ concept – small scale hydrogen electrolysers or gas reformers (either on a domestic or large commercial/service building scale), that provide hydrogen fuel for both heat and power co-generation, and for vehicle refuelling. Other studies envisage ‘forecourt’ production of hydrogen, for vehicle refuelling at depots and petrol stations.

Some studies (Foley 2001; NHA 2004), particularly those with a focus on road transport, see on-site hydrogen production as a predominantly 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 providing mobile power, and often selling power to the grid at times of peak demand (Barreto et al. 2003; Australian Government 2003; Lovins et al. 1999; Dunn 2001).

2) Centralised architectures

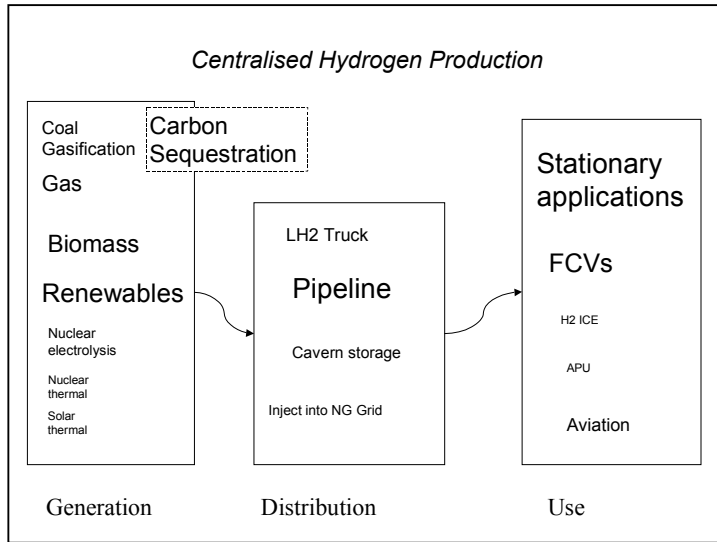


Figure 2. Shows common building blocks of a centralised hydrogen production systems. Text size of each building block indicates the number of studies that envisage a role for it.

Key Technologies: Carbon sequestration, Pipelines, renewables, biomass, FCVs, Stationary fuel cells

A system in which hydrogen is centrally produced 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.

A third technological architecture, described by Bossel et al (2003) and Arnasson & 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, in the case of Arnasson & Sigfusson (2000), or from biomass, in the case of Bossel et al (2003).

Other very different technological architectures are possible, for example the Shell scenarios envisage hydrogen sold ‘in a box’ as a fuel cartridge, at least in the early stages of hydrogen uptake, 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.

Each architecture is dependent on key technological building blocks.

If government or industry makes a decision to support a particular architecture, or simply expect a particular architecture to emerge, R&D efforts will be directed to the solution of specific key technological problems, 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 can help determine the likelihood of a particular architecture becoming dominant. For example, the development of low-cost liquid hydrogen storage, or a (perceived) failure of solid storage and high-compression tanks, could rule out decentralised systems at least in the short term, given the technological difficulties of small-scale liquefaction. Similarly, a breakthrough in on-board reforming of methanol could make the synthetic liquid hydrocarbon route more attractive, obviating the need for on-board hydrogen storage. Breakthroughs in these key technological building blocks can thus produce ‘emerging irreversibilities’, leading to ‘lock-in’ or ‘path dependency’ (see David 1985, Arthur 1989, Rip & Schot 2003), a phenomenon cited as a reason to avoid R&D in particular technologies, such as on-board methanol refuelling (Lovins et al. 1999, NHA 2004).

For decentralised systems, the major technological challenge is the expense of hydrogen from small-scale natural gas reformers and electrolyzers, 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.

Further key technologies are necessary for the envisaged hydrogen economies to be low-carbon. There is broad agreement in the literature that fossil fuels will be the major source of hydrogen in the short to medium term, and many studies see a role for fossil fuels in the long term. For such a system to be low-carbon, carbon sequestration technology must be proven and acceptable. For decentralised systems based on the natural gas grid, carbon sequestration is not feasible, and often these are therefore seen as a transition towards either more centralised systems with sequestration, or to systems based on small-scale electrolyzers. The alternative major source of low-carbon hydrogen is nuclear power. In the longer term, most of the studies envisage a system based entirely on hydrogen produced electrolytically from renewable resources. For the Australian and US plans, the combination of coal gasification technology and carbon sequestration are important in meeting both climate and security goals.

Key technologies for all pathways include improved fuel cell power density & 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 by some studies, in some cases as a transitional form.

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, particularly in terms of the energy sources (nuclear energy, extended use of fossil fuels), and the scale at which energy is produced and distributed. 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 debate and uncertainty. The basis on which different elements, or ‘building blocks’, are included or rejected varies, but there are also shared elements. All include fuel cell vehicles, and most include strong roles for renewable resources, either electricity or biomass. 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 future role for fuel cells in distributed electricity generation, but do not specify the type of fuel cell, or the fuel on which the cells will run.

4.5 Evolution of hydrogen economies – how does the system change?

The hydrogen futures envisaged in the literature often are not static, but adapt as resources, demands and energy systems change. This is clearest in those studies that present some sort of ‘transition path’ towards a ‘final’ hydrogen economy. There is considerably more consensus in the literature over the ‘final’ hydrogen economy than there is over transition paths, which vary greatly. What patterns are there?

1) From decentralised to centralised? Most see the decentralised route as the key to bypassing 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 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’.

And what disagreements are there about system change?

There is broad agreement that fleet vehicles, refuelled only at predictable times at a depot, 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 & Rodgers 2004). However, there is marked disagreement about the types of vehicle that will be the most likely or suitable early targets for conversion to fuel cells. 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 et al. 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 (Arnasson & 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, Schot & Hoogma 1998).

1) H₂ 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. However, Hydrogen fuelled ICEs are likely to use liquid hydrogen (their lower efficiency exacerbates driving range problems), with attendant infrastructural implications.

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.

6) 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 (Jørgensen et al. 2003)

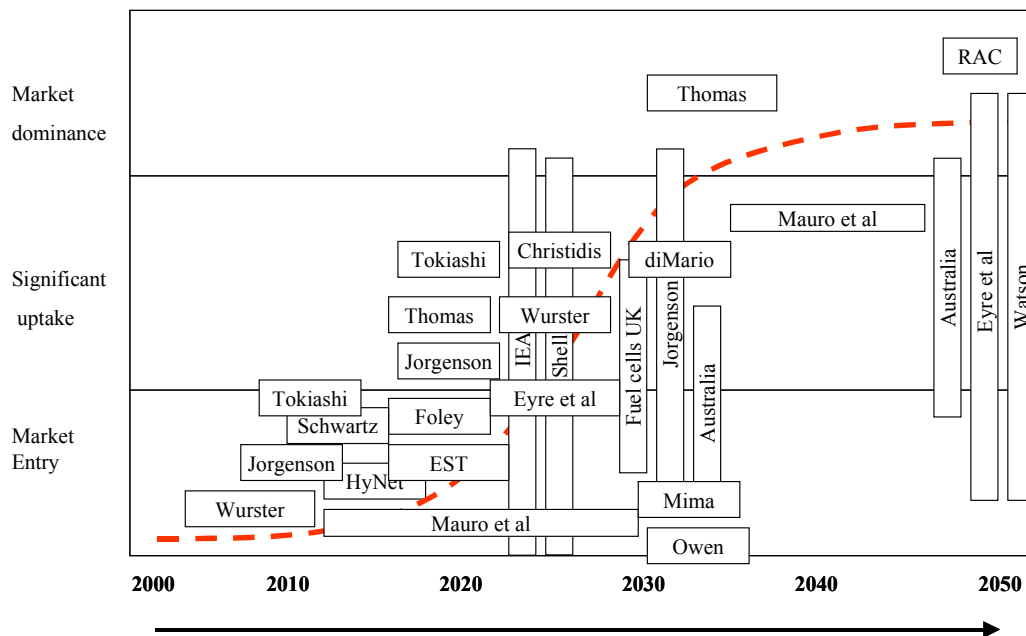
7) Auxiliary power units (APUs) for vehicles – APUs would provide electricity in vehicles while the engine is off, making them attractive to the military and long-haul trucks in particular (Lutsey et al. 2003). The cost challenges for small (5kW) APUs are less

daunting than for automotive cells. APUs currently under development run on either diesel, with a reformer, or with direct hydrogen, which could be supplied in the form of a fuel cartridge.

8) 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?



The above chart 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 & 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.

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 policy-oriented 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 CO₂ emissions (Di Mario et al. 2003; Barreto et al. 2003; Watson et al. 2004; Owen & Gordon 2002; Eyre et al. 2002; Hart 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 (Owen & Gordon 2002; Eyre et al. 2002; and Hart et al. 2004) 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

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)

As hydrogen futures practitioners, what is useful in 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. Only one technology is found in all futures: the fuel cell vehicle. However, there are widely divergent views on the likely dates of 'market entry' for fuel cell vehicles.

- ❑ 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.
- ❑ There are significant disagreements over what, in terms of greenhouse gas emissions, a transition to hydrogen energy would achieve in the short to medium term.

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 & 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 stakeholder 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 (e.g. the London Hydrogen Action Plan picks up targets from the Japanese Vision), and targets tend to be recycled as predictions.
- ❑ Little attempt to deal with waste/de-commissioning issues – for example, possible toxicity of fuel cell components or hydrogen storage materials. This means that the pictures of the future are incomplete.
- ❑ 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’.

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 (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, 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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Appendix 1: Review Template

Bibliographic information	
Title	
Author	
Year	
Publication	
Funding/affiliations	
Summary information	
What is the explicitly stated aim of the study? Are there any implicit aims?	
The study involves:	<ul style="list-style-type: none"> a) Forecasting the future from current trends b) Exploring possible futures c) Elaborating a vision of a desirable future d) Backcasting or exploring routes to a defined future. e) Outlining a roadmap
Brief description of method	
Does the study generate new scenarios, or build on pre-existing 'Global' scenarios?	
How many distinct scenarios are considered?	
Nature of outputs: Qualitative or Quantitative. Are quantitative results base on numerical inputs?	
Was the process based on the input of a variety of stakeholders? On the opinion of experts?	
Degree of transparency – is it easy to see how the scenarios were arrived at, and who took part in the creation of them?	
On what theoretical background, if any, does it draw?	
Content	
Timescales	
Is there an emphasis on particular technologies or sectors (e.g. fuel cells, transport)	
What are the major perceived benefits of hydrogen/fuel cells?	
What key drivers shape the envisaged hydrogen future(s)?	
What key barriers or hurdles are identified as needing to be overcome for the realisation of a hydrogen economy?	
Does the study identify measures to bring about the changes necessary to realise a hydrogen future?	
What is the geographical scope?	
Notes & Comments; major assumptions.	

Scenario		
Name		
Main Drivers/ Dimensions		
Fuel chain for hydrogen		
Short Synopsis		