Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: a review of the hydrogen futures literature.

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Title: 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 has been 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 the 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 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**

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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 timescales each type of study tends to operate.

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; Arnasson & Sigfusson 2000; Australian Government 2003; Fuel Cells Canada; 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 looked only at 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 & 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.

Table 1: A typology of hydrogen futures

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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.

3.1 Forecasts

Table 2. Studies classified as ‘Forecasts’

Two ‘roadmaps’ also included market forecasts as part of the study (Fuel Cells Canada 2003; HyNet 2004).

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 & 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 1996-2003 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 & Hertin 2002; Smil 2000), 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 may be of limited use in helping us to understand the complex processes by which large technological systems are transformed.

3.2 Exploratory scenarios

Table 3. Studies classified as 'Exploratory Scenarios'

Rather than extrapolating from existing trends, 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 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 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 stakeholders in their development.

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 2002; used by Andersen et al. 2004 and 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 2002; 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. (below) outlines the dimensions chosen by the eight exploratory scenario studies, such as rate of technological change, or type of governance.

Table 4: Major drivers in exploratory scenarios

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

Table 5. Studies classified as ‘Technical Scenarios’

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 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, 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.

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; 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

Table 6. Studies classified as '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'.

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. 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).

While some see technological transitions as manageable through R&D investment, demonstration projects, taxes, and strong government leadership (Dunn 2001; Lovins & Williams 1999), others invoke a need for major shifts in social values (Goltsov & 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

Table 7. Studies classified as ‘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).

Typical timescales 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 (2002).

3.6 Roadmaps

Table 8. Studies classified as '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.

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 technology's future (Geels & 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 aims 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 later 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 & Williams 1999; Goltsov & 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 & 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 & 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 eighteen made no mention of energy security at all. Of the studies that emphasise energy security (Arnasson & Sigfusson 2000; Australian Government 2003; DTI 2004; Dunn 2001; 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 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 & 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.

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 & Gordon 2002; Mima & 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.

1) Decentralised architectures

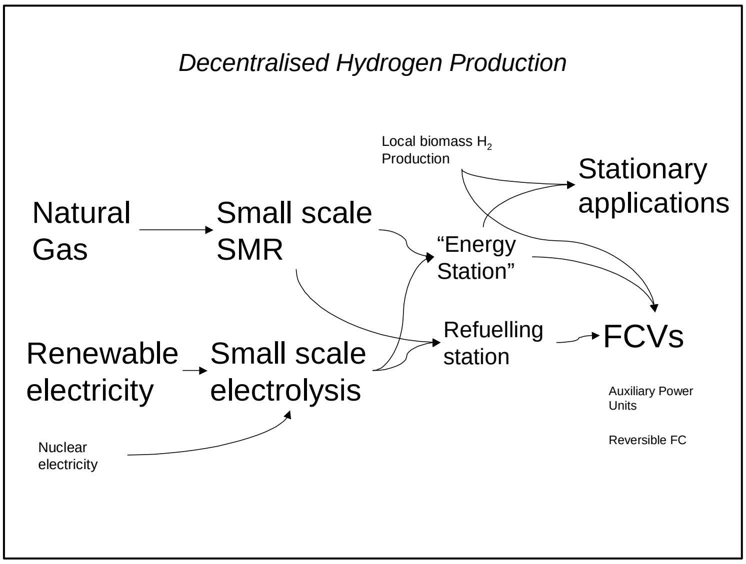

Figure 1. Shows common building blocks of a decentralised hydrogen production systems. Text size of each building block indicates the number of studies that envisage a role for it.

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

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 many of the infrastructural barriers facing a transition to hydrogen.

Some studies (Foley 2001; 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 fuel cell vehicles (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 & Williams 1999).

2) Centralised architectures

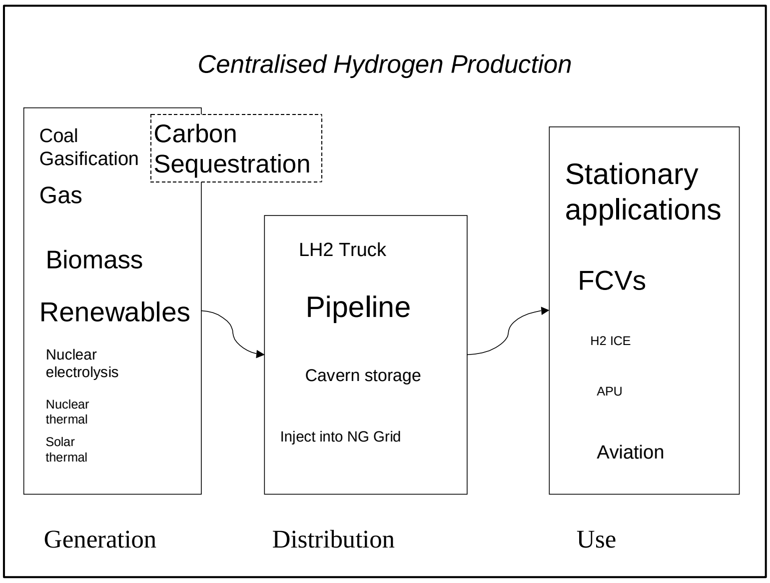

Figure 2. Shows common building blocks of a centralised hydrogen production systems. Text size of each building block indicates the number of studies that envisage a role for it.

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

A 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.

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 (Arnasson & Sigfusson 2000), or biomass (Bossel et al. 2003).

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.

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 & 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 & Williams 1999, 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, e.g.

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 & 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 & 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 (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) 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.

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 (Andersen et al. 2004)

7) 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.

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?

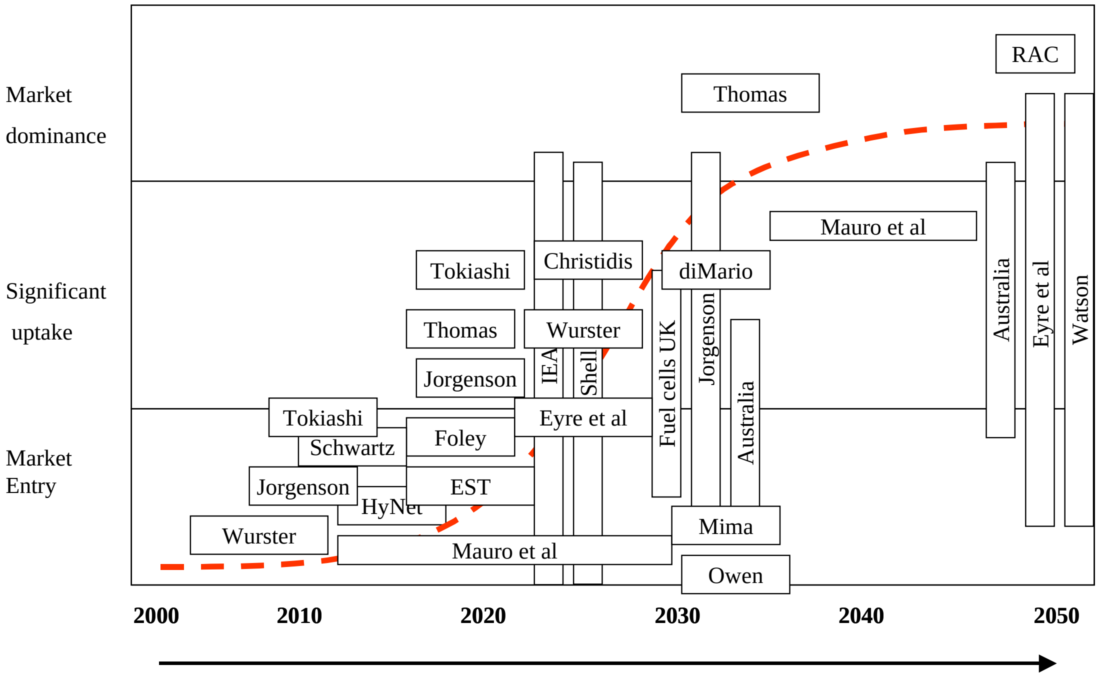

Figure 3. Shows estimated dates for a transition to a fuel cell based transport system.

Figure 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 & 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 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 & 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; and Hart et al. 2003; Owen & 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

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)

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 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 lifecycle 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 of ‘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 balance this against the limited predictive utility of current theoretical approaches to these issues.

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.

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 & 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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Table 1.

Caption:

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.

Caption:

Table 3. Studies classified as ‘Exploratory Scenarios’

	Study	Brief description
Forecasts	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 & 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.

Table 3.

Caption:

Table 3.

	Study	Brief description
Exploratory scenarios	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 2002	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.

Table 4.

Caption:

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 2002	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.

Caption:

Table 5. Studies classified as ‘Technical Scenarios’

	Study	Brief description
Technical Scenarios	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 & 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.

Table 6

Caption:

Table 6. Studies classified as ‘Visions’

	Study	Brief description
Visions	Arnason & 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 & Veziroglu 2001	Presents a vision of the ‘hydrogen civilisation’, a future world posed as the only alternative to continued dependence on fossil fuels.
	Lovins & 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 & 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.

Table 7.

Caption:

Table 7. Studies classified as ‘Backcasts & Pathways’

	Study	Brief description
Backcasts & Pathways	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 & 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.

Table 8.

Caption:

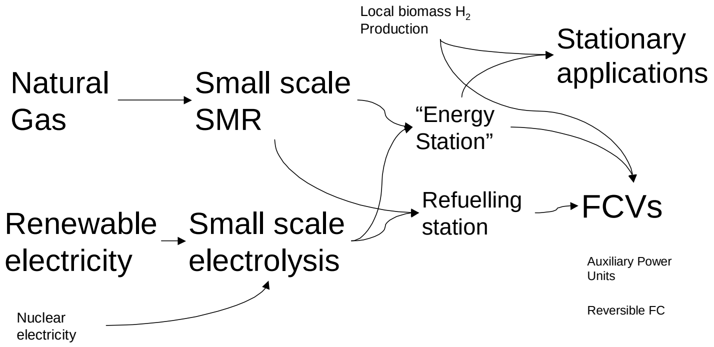
Table 8. Studies classified as ‘Roadmaps’

	Study	Brief description
Roadmaps	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.
	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.

Captions to Illustrations

Figure 1.	Shows common building blocks of a 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, Fuel Cell Vehicles (FCVs).
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.
Figure 3.	Shows estimated dates for a transition to a fuel cell based transport system.

Decentralised Hydrogen Production



Local biomass H_2 Production

Stationary applications

Natural Gas

Small scale SMR

“Energy Station”

Refuelling station

FCVs

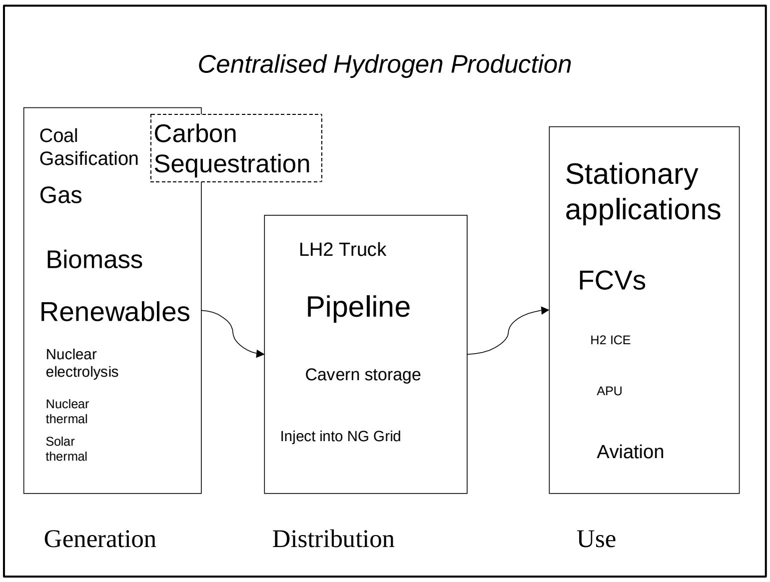
Renewable electricity

Small scale electrolysis

Auxiliary Power Units

Reversible FC

Nuclear electricity


Centralised Hydrogen Production
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Carbon
Sequestration
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Biomass
Renewables
Nuclear
electrolysis
Nuclear
thermal
Solar
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Pipeline
Cavern storage
Inject into NG Grid
Stationary
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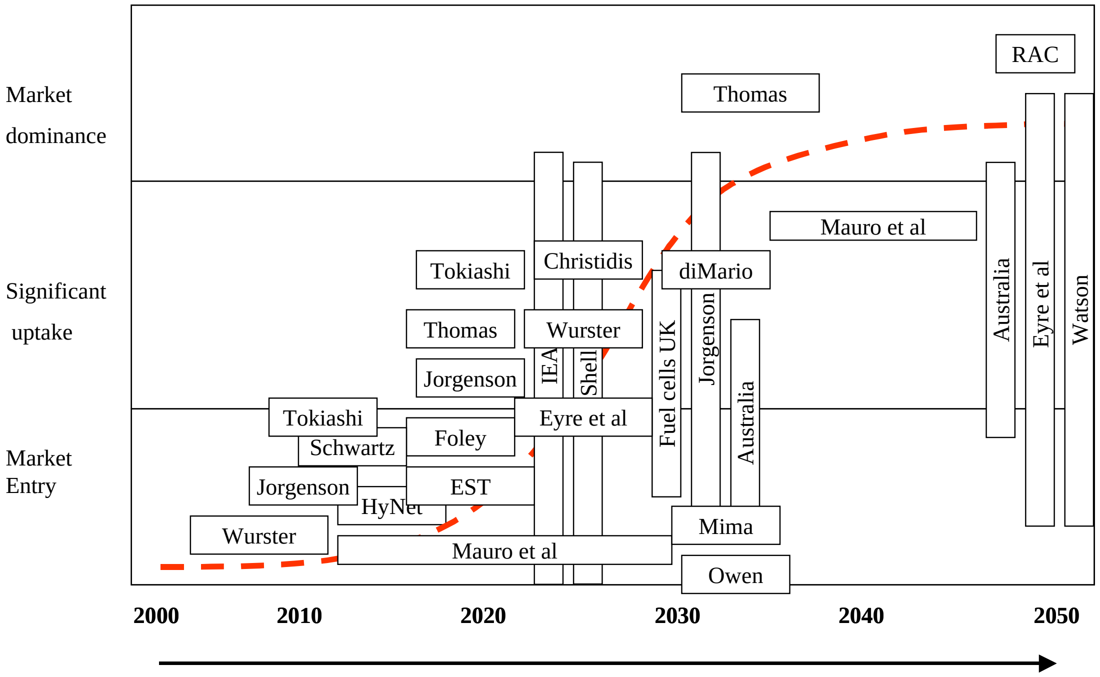
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