



# Transitions to a UK Hydrogen Economy

**Professor Malcolm Eames  
William McDowall**

**UKSHEC Social Science Working Paper No. 19**

**July 2006**



**psi**

**Authors contact details:**

**Professor Malcolm Eames**

**Brunel Research in Enterprise, Innovation, Sustainability and Ethics  
(BRESE)**

**Brunel Business School**

**Brunel University**

**Uxbridge**

**UB8 3PH**

**Email: [malcolm.eames@brunel.ac.uk](mailto:malcolm.eames@brunel.ac.uk)**

**William McDowall**

**Email: [willmcdowall@gmail.com](mailto:willmcdowall@gmail.com)**

## Table of Contents

<b>Introduction .....</b>	<b>4</b>
Summary of the UKSHEC Scenarios.....	5
<b>Using the Scenarios .....</b>	<b>8</b>
Scenario Structure and Dimensions .....	8
Multi-Level Perspective .....	9
Drivers of the Hydrogen Economy.....	10
<b>Transitions to a UK Hydrogen Economy: the UKSHEC Scenarios .....</b>	<b>11</b>
Structural Shift → Electricity Store .....	11
Corporate Race → Ubiquitous Hydrogen .....	14
Government Mission → Centralised Hydrogen for Transport.....	17
Disruptive Innovation → Synthetic Liquid Fuel: An Alternative Scenario .....	20
<b>Competitors to Hydrogen and “Showstoppers” .....</b>	<b>23</b>
<b>Key Insights and Messages from the UKSHEC Transition Scenarios .....</b>	<b>24</b>
<b>Annex I: Developing Visions of a UK Hydrogen Future .....</b>	<b>26</b>
<b>Annex II: Technological Transitions &amp; Transition Contexts.....</b>	<b>27</b>
<b>References .....</b>	<b>34</b>

## Introduction

The future of hydrogen energy in the UK is highly uncertain: it is not clear that a transition to a hydrogen energy system will ever occur, and even less clear how such a transition might unfold. In the face of those overwhelming uncertainties, policies must attempt to be robust against a range of possible futures.

This report describes four scenarios. Each comprises a distinctive transition pathway to a different hydrogen future or end 'vision'. Both the transition pathways and end visions have been developed and informed through an extensive series of workshops and consultations with expert stakeholders, including an innovative expert-led multi-criteria sustainability appraisal of a range of prospective hydrogen futures undertaken as part of the UKSHEC scenarios building process.

The scenarios are not intended to be predictive. Rather they seek to illustrate different ways in which the large-scale socio-technological changes required for the establishment of a hydrogen economy might come about, and so highlight the choices and policy options facing the research community, business, policymakers and civil society alike on the road to a sustainable hydrogen economy. Indeed if a hydrogen economy does emerge it is perhaps most likely to resemble a blend of different elements of these transition scenarios, rather than any individual one of them.

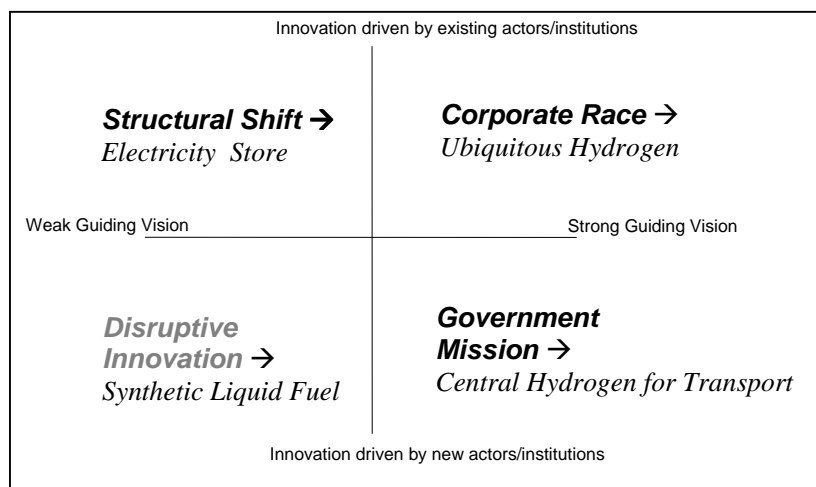
This working paper forms part of a wider package of socio-economic research, funded by the EPSRC's SUPERGEN programme, that is developing a set of 'backcasting' scenarios, illustrating how the UK might move to a sustainable hydrogen energy system. The work aims to:

- ❑ Identify a small number of credible futures for a sustainable hydrogen economy
- ❑ Drawing upon the knowledge of expert stakeholders, construct a set of technically-defined, plausible and internally-consistent scenarios, or pathways, describing how these futures might be achieved
- ❑ Use these scenarios to generate a 'road map' identifying critical decision points when action may be needed

Further details of this work can be found via the UKSHEC social science website (<http://www.psi.org.uk/ukshec>)

The paper first provides headline summaries of the four UKSHEC transition scenarios. Section two briefly describes how the scenarios were developed and how they should be used. The full scenario descriptions are presented in section three, and finally section four draws out some conclusions and insights for policy and research.

## Summary of the UKSHEC Scenarios



### Structural Shift → *Electricity Store*

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

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

This pathway results largely from a ‘**re-orientation of trajectories**’, where radical innovation within the energy sector, and later transport, emerges as a result of an ‘external’ shock in the form of restructuring of the electricity supply market to promote low carbon generation and energy efficiency.

***Electricity Store:*** Hydrogen is not only the dominant road transport fuel, it also plays a vital role providing distributed energy storage to overcoming the intermittency problems of renewable electricity generation. Hydrogen is produced locally in small scale electrolysis units for forecourt refuelling and onsite storage for use in domestic and commercial CHP units at times of peak electricity demand/limited supply. A full description of the *Electricity Store* vision can be found in the UKSHEC Hydrogen Visions working paper (Eames & McDowall 2005)

### Corporate Race → *Ubiquitous Hydrogen*

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

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

gas prices rise, fuel providers use the natural gas grid to supply hydrogen, ultimately moving to an integrated hydrogen grid, with decentralised as well as centralised hydrogen production.

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

***Ubiquitous Hydrogen:*** Gaseous hydrogen is not only the dominant road transport fuel. Many buildings also use fuel cell CHP systems running on hydrogen. Distributed renewable generation predominates, reducing need for long distance transmission and distribution, and allowing hydrogen to compete directly with electricity as the main energy vector for the provision of domestic and commercial heat and power. Regional grids of hydrogen pipelines connect (predominantly local) hydrogen supplies with local needs. A full description of the *Ubiquitous Hydrogen* vision can be found in the UKSHEC Hydrogen Visions working paper (Eames & McDowall 2005).

### **Government Mission → *Central Hydrogen for Transport***

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

Problems of climate change and energy security are increasingly seen as too pressing to be left to the market and as warranting more direct government intervention. National governments in the leading advanced and rapidly industrialising economies (US, Japan, China, India) and EU take strategic decisions to prioritise the rapid development of hydrogen transport. Partnerships are established with national industry champions. Regulation, subsidies and public procurement are all used to push hydrogen making extensive use of near-term technologies and large centralised supply routes.

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

***Centralised Hydrogen for Transport:*** Hydrogen has become the dominant transport fuel, and is produced centrally from a mixture of sources. Hydrogen is distributed as a gas by dedicated pipeline and as a liquid. In some applications, liquid hydrogen is the onboard storage mechanism, while in others, compressed gaseous hydrogen is used. This vision is an amalgamation of the original *Central Pipeline* and *Liquid Hydrogen* vision, of which full descriptions can be found in the UKSHEC Hydrogen Visions working paper (Eames & McDowall 2005).

### **Disruptive Innovation → *Synthetic Liquid Fuel* – An Alternative Scenario**

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

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

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

**Synthetic Liquid Fuel:** Renewably produced hydrogen again provides the dominant transport fuel. In this case, however, it is ‘packaged’ in the form of a synthetic liquid hydrocarbon, such as methanol, to overcome the difficulties of hydrogen storage and distribution. The carbon for fuel synthesis comes from biomass and from the flue gases of carbon-intensive industries. A full description of the *Synthetic Liquid Fuel* vision can be found in the UKSHEC Hydrogen Visions working paper (Eames & McDowall 2005).

**Summary table for the four UKSHEC Transition Scenarios**

	<b>Structural Shift</b>	<b>Corporate Race</b>	<b>Government Mission</b>	<b>Disruptive Innovation</b>
<b>Dimensions</b>	Innovation driven by existing actors/ institutions  Weak guiding vision	Innovation driven by existing actors/ institutions  Strong guiding vision	Innovation driven by new actors/ institutions  Strong guiding vision	Innovation driven by new actors/ institutions  Weak guiding vision
<b>Drivers</b>	Strong UK Government and social concern for climate change and energy security  Greater social awareness of need for demand reductions  Societal rejection of nuclear and carbon capture and storage	Strategic positioning by big auto and big oil in the face of climate change and energy security concerns  High demand and volatile supplies for oil and gas lead to increasing prices	Strong UK/EU government concerns over climate and energy security  Societal acceptance of nuclear and carbon capture and storage, and greater social trust in science and technology	Emerging climate and energy concerns  Emphasis on building competitive markets and high innovation  Social preference for liberalised markets and consumer economy
<b>Key technologies</b>	<ul style="list-style-type: none"> <li>• Fuel cells</li> <li>• Storage &amp; handling</li> <li>• Electricity grid updates</li> <li>• Smart metering</li> <li>• Renewables</li> </ul>	<ul style="list-style-type: none"> <li>• Gas separation</li> <li>• Fuel cells</li> <li>• Onboard storage</li> <li>• Gasification</li> <li>• Pipelines &amp; metering</li> <li>• Carbon capture and storage</li> <li>• Waste, biomass gasification</li> <li>• Renewables</li> </ul>	<ul style="list-style-type: none"> <li>• Storage &amp; handling</li> <li>• Fuel cells</li> <li>• High temperature nuclear</li> <li>• Pipelines &amp; liquefaction</li> <li>• Gasification technologies</li> <li>• Carbon capture &amp; storage (CCS)</li> <li>• New nuclear power</li> </ul>	<ul style="list-style-type: none"> <li>• Direct Methanol Fuel Cells (DMFC)</li> <li>• Synthetic liquid fuel synthesis</li> <li>• Fuel reformers or scale up of DMFC</li> <li>• Renewables</li> <li>• Carbon capture</li> </ul>
<b>Decision points and milestones</b>	Renewables reach a high enough proportion of grid electricity to require buffering of supply and demand	Nuclear & CCS go/no-go decisions  Commercialisation decisions of big auto  Hydrogen injected into natural gas grids  Collapse of Kyoto?	‘Go’ decision on major hydrogen programme, and on nuclear	‘No-go’ decision on major government hydrogen programme
<b>End vision</b>	<i>Electricity Store</i>	<i>Ubiquitous Hydrogen</i>	<i>Central Hydrogen for Transport</i>	<i>Synthetic Liquid Fuel</i>

## Using the Scenarios

The UKSHEC scenarios are not predictions. They are intended to shed light on possible innovation processes and transition pathways by which a future hydrogen economy might be achieved. They seek to illustrate different ways in which the large-scale socio-technological changes required for the establishment of a hydrogen economy might come about, and so highlight the choices and policy options facing the research community, business, policymakers and civil society alike on the road to a sustainable hydrogen economy. Whilst the scenarios have a UK focus, they seek to place the prospective developments they describe in a broader European and global context. In terms of time scales, the intention is to imagine the final visions far enough into the future that substantial infrastructural changes are conceivable, but not so far into the future that the technologies envisaged today will be obsolete. The visions have therefore not been constructed around an exact future date, but might nevertheless be thought of as located somewhere around the 2040-2050 mark.

**Backcasting:** The UKSHEC scenarios have been developed through a participatory stakeholder-driven backcasting process. Backcasting is a normative scenario building tool used to provide insights into how long-term goals might be reached. Backcasting entails “*looking back from a desirable ...situation in the far future to the present, in order to make steps towards the future now.*” (Vergragt & Green, 2001). Through focusing on distant goals the backcasting perspective is intended to help decision-makers move beyond immediate and everyday barriers to see opportunities for longer-term strategic action.

## Scenario Structure and Dimensions

The structure and key dimensions of the UKSHEC scenarios have been informed by recent academic research on systems innovation and technological transitions. This seeks to provide a better understanding of how large-scale socio-technological changes take place: for example, the transition from sail to steam ships; from a coal to an oil based economy; the development of the automobile as the dominant form of passenger transport; or the rise of information and communication technologies (ICTs) and the internet. In doing so, the scenarios draw heavily on the multi-level perspective on systems innovation originally developed by Frank Geels and his colleagues in the Netherlands (e.g. Geels 2002), together with more recent work by researchers from SPRU (Berkhout *et al* 2004) on the dynamics of technological transitions, and IVM on governance paradigms (Hisschemoller *et al* 2006).

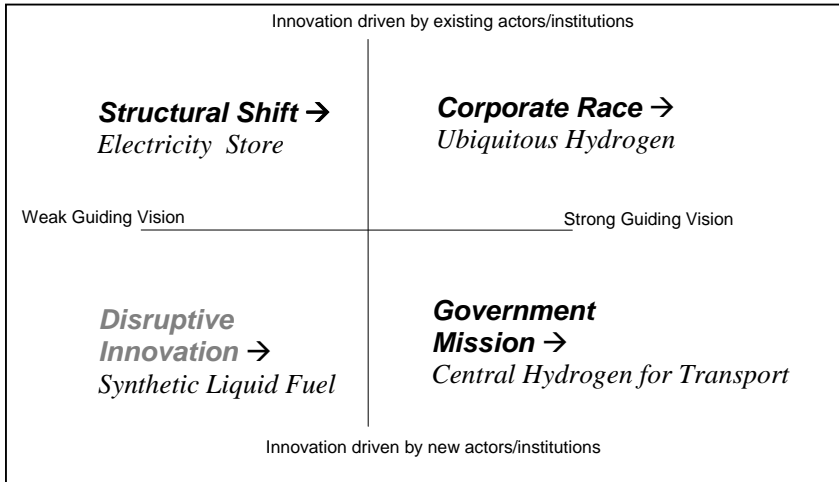
Each of the four scenarios comprises: i) a short description of a distinctive hydrogen future (or end vision); ii) a ‘storyline’ summary; iii) a set of qualitative indicators; iv) a detailed ‘multi-level’ narrative describing the transition pathway in terms of landscape, niche and systems changes; v) a ‘transition diagram’ providing a visual representation of the innovation dynamics and key developments along the individual pathway

The UKSHEC Transition Scenarios are framed by two key dimensions of change, adapted from work by Berkhout *et al* (2004), which developed a quasi-evolutionary model of systems innovation: These dimensions are:

- i. The degree to which innovation is shaped by a shared normative guiding vision. In the past, large scale transitions of energy and transport infrastructures have usually occurred as an emergent result of interacting drivers and activities, rather than as the outcome of a managed transition. This axis allows us to explore how hydrogen might emerge without a coherent action plan, as well as through concerted efforts to bring about a hydrogen future.
- ii. The extent to which innovation is driven by existing or new actors and institutions, or through existing actors taking on new roles. This axis invites us to think through the various possible roles of the different actors and institutions that will be involved in any possible transition: local, regional, and national governments; major industries; new entrants and entrepreneurs, and so on. The axis helps us to consider the interplay of different interests and agendas, and avoid assuming that any particular actor alone holds the key to the development of hydrogen energy.

Each quadrant was also associated with one of the four governance paradigms developed by Hisschemoller *et al* (2006), in order to help enrich the institutional and policy dimensions of the narrative storylines developed for each scenario.

The UKSHEC four transition scenarios are shown below mapped onto a 2x2 grid formed by the intersection of these two dimensions.



Note: Disruptive Innovation → *Synthetic Liquid Fuel* is shown in the diagram in lighter text to highlight its status as an alternative or ‘wild card’ scenario.

Of course the mapping of the transition pathways to the end visions presented in this report is only one possibility. There will be many other ways in which a transition to any particular hydrogen future could play out. Our purpose is not prediction, but to stimulate imaginative and critically informed thinking about how the future might unfold.

### Multi-Level Perspective

The four quadrants provide a useful way to distinguish different types of transition pathway. As noted above each scenario is also described in terms of a second, multi-level, structure. During a transition, developments take place on the three levels: niches, landscapes and systems. New technologies first enter use in ‘niches’: demonstration projects, niche markets, and among enthusiasts. For the technology to enter the mainstream, the conditions must be right at higher levels – both within the industries and mainstream markets that make up the middle ‘systems’ level, and at the ‘landscape level’ of long term social and economic context. Most of the time, the conditions are not right, and existing systems resist the entry of newcomers. But there are times when windows of opportunity emerge for new technological systems to develop: particularly when innovations at the niche level combine with pressures of shifting landscape conditions, such as concerns about energy supplies; or when firms look to radical new technologies to provide competitive edge.

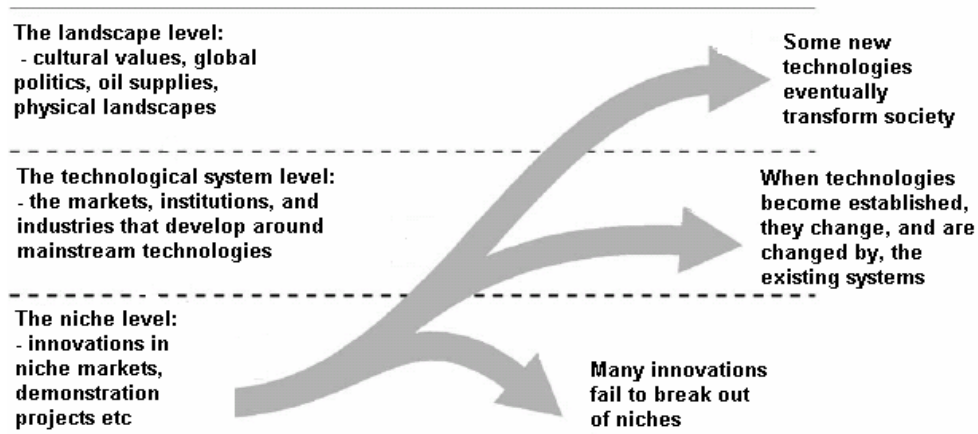


Figure showing multi-level perspective. Adapted from Geels 2002<sup>1</sup>

The diagram represents the path of a new technology as it first develops in niches, and later diffuses into mainstream markets. By simultaneously focusing on how technologies develop in niches; on the dynamics of the incumbent systems; and on the wider changes for society, we can get a better insight into the possible future for hydrogen. All of the UKSHEC transitions scenarios are therefore described in terms of developments at the niche, landscape and systems level.

### Drivers of the Hydrogen Economy

The major drivers for hydrogen at a landscape level are well established:

- ❑ Climate Change, and the potential for hydrogen to be part of a zero or low carbon transport system
- ❑ Security of primary energy supplies, and the potential for hydrogen to enable a shift from dependence on oil and gas imports, which are both unstable and, in the long term, depleting.

To a lesser extent local air quality and regional or national competitiveness also provide drivers for policy-makers to consider support for the development and diffusion of hydrogen technologies. In addition, landscape level drivers for the energy system more broadly include rates of economic growth (and hence of energy demand), and the social values that prevail.

In addition to these landscape level policy drivers, it is important to consider drivers at the systems and niche level, that influence the dynamics of change by either articulating, or responding to, changes at the landscape level, for example:

- ❑ Strategic activities of firms and industries
- ❑ Energy and transport policies (e.g. carbon trading, Zero Emissions Mandates, etc)
- ❑ Lobbying by hydrogen and fuel cell associations, activists, NGOs
- ❑ The activities of scientists and engineers in advancing the state of hydrogen and fuel cell technologies
- ❑ Growth in portable and on-vehicle power demands, leading to funding, support, and the creation of niche markets for fuel cell products
- ❑ Etc.

These drivers interact in different ways in the four transition scenarios.

<sup>1</sup> Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy*, 31(8-9): p. 1257-1274.

# Transitions to a UK Hydrogen Economy: the UKSHEC Scenarios

## **Structural Shift → Electricity Store**

### **1. The scenario “storyline”**

Driven by concerns about climate change and energy security, government acts to tackle energy-sector emissions, while maintaining emphasis on liberalised markets. In the face of stalling growth of renewables, and with a new nuclear build struggling in the face of economic difficulties and societal opposition, the UK government restructures the wholesale and domestic electricity markets to provide stronger economic incentives for renewables. This includes guaranteed feed in tariffs for a portfolio of renewables and measures at the regional and local level to facilitate distributed generation.

Renewables grow rapidly, with two sectors showing particularly strong growth: offshore wind, and small-scale and microgeneration (including CHP). Local authorities increasingly adopt local energy planning guidelines that involve on-site energy generation, following the examples of Merton and Croydon. The growth in distributed energy helps drive public engagement with efficiency and renewables support, with consumers increasingly aware of their energy choices, and less likely to oppose renewable energy developments. NGOs work to promote this trend, and some form joint initiatives with energy companies to provide energy service contracts and innovative financing for the installation of renewables, in the same way that NGOs and utilities provided 100% renewable contracts over the last few years.

Hydrogen shows slow progress in transport in the medium term, partly because of difficulties related to refuelling infrastructure. However, fuel cells find markets in some niche stationary applications, for back-up and premium power, and in off-grid applications. However, in the long term, as intermittent renewables become an increasingly important part of the electricity supply mix, niches in demand-side management and load-balancing emerge. This opportunity allows the rapid development of a hydrogen fuelling infrastructure, as hydrogen energy stations provide fuel, are demand-side flexible, and can provide back-up power services. Policies support the diffusion of hydrogen into transport, with high taxes on carbon fuels. In the long term, this allows the development of a system much like that described in *Electricity Store*, in which renewable electricity is used to generate hydrogen where it is needed, at times when electricity supply exceeds demand.

### **2. Table of Key Indicators**

Structural Shift → <i>Electricity Store</i>	
Dimensions	<ul style="list-style-type: none"> <li>• Innovation driven by existing actors/ institutions</li> <li>• Weak guiding vision</li> </ul>
Transition Dynamics	<ul style="list-style-type: none"> <li>• Re-shaping of energy regulation</li> <li>• Re-orientation and restructuring of broader energy system creates opportunities for transport infrastructure</li> </ul>
Drivers of change	<ul style="list-style-type: none"> <li>• Strong UK Government and social concern for climate change and energy security</li> <li>• Greater social awareness of need for demand reductions</li> <li>• Societal rejection of nuclear and carbon capture and storage</li> </ul>
Key Technologies	<p>Hydrogen Technologies</p> <ul style="list-style-type: none"> <li>• Fuel cells</li> <li>• Storage &amp; handling</li> </ul> <p>Complementary Technologies</p> <ul style="list-style-type: none"> <li>• Electricity grid updates</li> <li>• Smart metering</li> <li>• Renewables</li> </ul>
Decision points and Milestones	Renewables reach a high enough proportion of grid electricity to require buffering of supply and demand

### 3. Multi-level perspective

#### *Landscape*

In this scenario, liberalised, competitive markets remain an important policy goal, and political ends are achieved through a policy-networking approach, rather than through unilateral government action. There are strong concerns about both climate change and energy security, and increasingly high fossil fuel prices. This is also a society that is increasingly environmentally conscious, and wary of nuclear power and carbon sequestration.

#### *Technologies, niches and early markets*

Early markets for hydrogen in this scenario arise as a result of growing demands for premium, uninterrupted and back-up power. A niche market for hydrogen fuel cell systems also develops for off-grid applications, and community energy co-operatives or local authority-run energy schemes make use of fuel cells in CHP systems. However, more significant opportunities are created by increasing levels of intermittent renewables in electricity generation, as markets develop for demand side management and peak generation.

Key actors involved in the establishment of early markets and opportunities include the legislative and regulatory bodies that enable the shift in energy markets; the local authorities involved in developing community energy schemes; the activities of existing energy companies, many of whom move towards renewables and ESCO models of service provision; fuel cell developers; and NGOs.

This scenario relies on advances in stationary applications for fuel cells, on smart metering and grid technologies, and on substantial expansions of renewables.

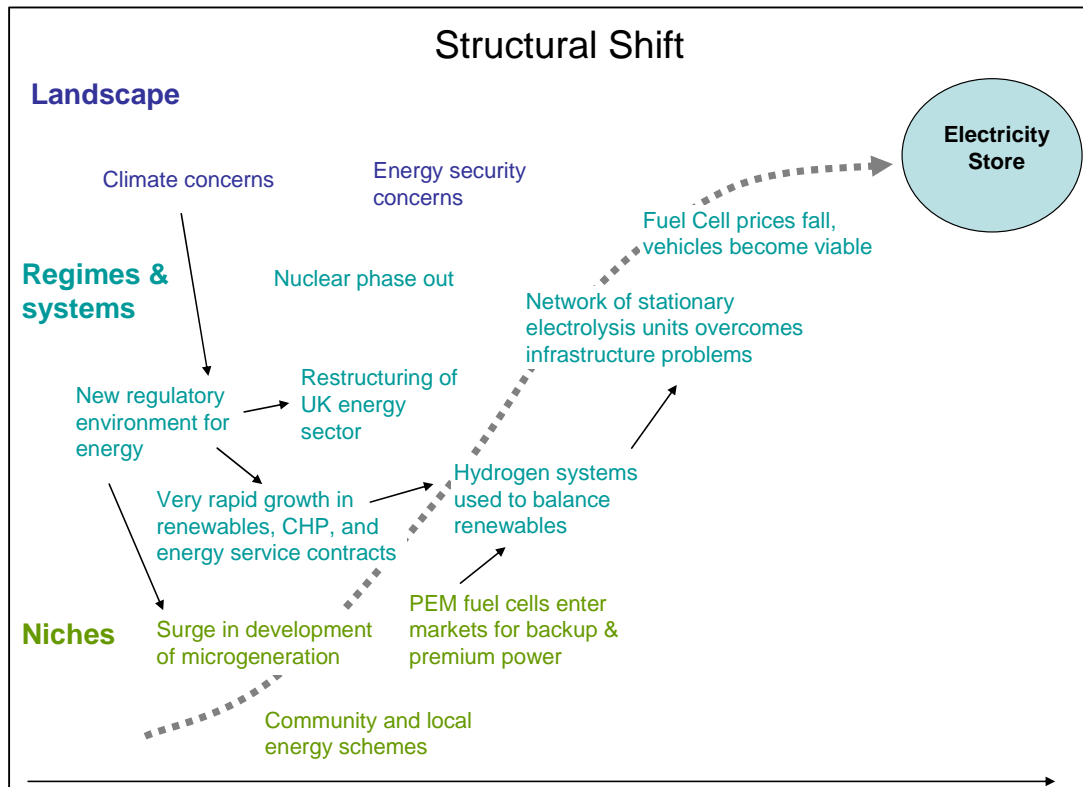
#### *Market Growth and Systems Change*

As a result of changes to regulatory frameworks around energy, there is a major restructuring of the UK energy sector, with new models of generation, distribution and supply becoming important. In particular, distributed generation, energy service contracts, and community energy schemes emerge as important. However, in the short to medium term, there is little impact on the transport sector, where hydrogen makes slow progress. The success of hybrids, and for a time the increased use of biofuels, mean that policy pressure for hydrogen in transport are insufficient to overcome the challenges of infrastructure development. It is only later, once fuel cell prices have fallen and a nascent infrastructure has become established that hydrogen vehicles start to make progress.

The important policies in this transition are those that restructure the energy market, which later creates a window of opportunity for the transition to hydrogen use in vehicles. These include the establishment of strong renewables and emissions targets; re-establishment of the fuel tax escalator; and a wholesale restructuring of the energy regulatory system to enable renewables, distributed generation and efficiency, combined with changes to planning guidelines to enable renewables.

Infrastructure for hydrogen in transport develops from a network of fuel cells and hydrogen back-up systems that provide buffering for intermittent renewables, and co-produce heat, power and fuel for transport. It is the development of a high efficiency, renewables-based energy system that creates a window of opportunity for the introduction of hydrogen, and as a result, almost all hydrogen in this scenario is generated from renewable electricity.

#### 4. Transition Diagram



## Corporate Race → Ubiquitous Hydrogen

### 1. The scenario “storyline”

In this transition, the large automotive and oil companies start to see oil depletion and climate change as major strategic challenges to their core business. As a result, a strategic race develops to gain market leadership in the hydrogen technologies that increasingly look like being part of the solution. Large automotive firms plough resources into R&D and commercialisation programmes, setting up new joint ventures and strategic partnerships to develop fuel cell vehicles (FCVs), while the major energy companies start to invest in hydrogen production and infrastructure. The existing players in both industries take action to drive hydrogen into transport.

Inter-governmental frameworks to take action on climate change fail. However, regional governments interested in both environmental concerns and in regional competitiveness form partnerships with large global corporations to create early centres of hydrogen development and deployment. These regional attempts to attract the big players are important niches in the development of hydrogen systems, as are low emission zones in big cities, providing policies to enable hydrogen in the absence of national level policy action.

The investments in R&D drive down costs in both hydrogen production and in fuel cell vehicles. At first sales are restricted to high-end markets, but as prices fall fuel cell vehicles become increasingly adopted in the mainstream. Those companies with successful hydrogen vehicle programmes seek to exploit their first mover advantage by lobbying tougher vehicle emissions and other regulatory measures to support the introduction of FCVs. Major energy companies develop infrastructure, at first through distributed natural gas reforming and through trucked liquid hydrogen, and hydrogen becomes the dominant transport fuel.

The success of hydrogen fuel in transport opens up possibilities for change in the wider energy system. As natural gas prices rise, gas companies, which have been increasingly profiting from the growing market in hydrogen vehicles, start to look for alternatives to dependence on finite natural gas reserves. Biogas and hydrogen from gasified waste and coal start to be injected into the natural gas network, after health and safety regulations are changed to allow the use of alternative gas sources in the network. Advances in gas separation technologies allow hydrogen and natural gas to be efficiently separated, and for a while, the natural gas network carries a mix of hydrogen and methane. As natural gas prices continue to rise, and shortages emerge, the proportion of hydrogen increases, and policy-makers concerned about emissions and energy security introduce a non-fossil gas obligation to encourage the use of biogas and hydrogen in gas grids. Ultimately a system much like that described in *Ubiquitous Hydrogen* emerges.

### 2. Table of Key Indicators

Corporate Race → Ubiquitous Hydrogen	
Dimensions	<ul style="list-style-type: none"> <li>• Innovation driven by existing actors/ institutions</li> <li>• Strong guiding vision</li> </ul>
Transition Dynamics	<ul style="list-style-type: none"> <li>• Big business moves ahead of government, with clear end goal of hydrogen transportation system directing developments.</li> <li>• Developments in transport create opportunities for later developments in wider energy systems.</li> </ul>
Drivers of change	<ul style="list-style-type: none"> <li>• Strategic positioning by big auto and big oil in the face of climate change and energy security concerns</li> <li>• High demand and volatile supplies for oil and gas lead to increasing prices</li> </ul>
Key Technologies	Hydrogen technologies <ul style="list-style-type: none"> <li>• Gas separation</li> <li>• Fuel cells</li> <li>• Onboard storage</li> <li>• Gasification</li> <li>• Pipelines &amp; metering</li> </ul>

	Complementary <ul style="list-style-type: none"> <li>• Carbon capture and storage</li> <li>• Waste, biomass gasification</li> <li>• Renewables</li> </ul>
Decision points and Milestones	Nuclear & CCS go/no-go decisions Commercialisation decisions of big auto Hydrogen injected into natural gas grids Collapse of Kyoto?

### 3. Multi-level perspective

#### *Landscape*

The backdrop for this transition is provided by the failure of inter-governmental action on climate change, and by mounting concerns about climate change and oil depletion within the oil and auto sectors, where they are seen as long-term strategic challenges. It is also a scenario that occurs in the context of high demands for natural gas, and increasingly volatile and insecure gas supplies over time, with real constraints on affordable gas supplies by mid-century. Regardless of government decisions around nuclear power, there is resistance to new nuclear, and eventually little, if any, is built. In this scenario, there is a continued emphasis on the importance of liberalised markets, and society accepts that major corporations alone have the competence and power to enact large scale technological change.

#### *Technologies, niches and early markets*

In this scenario, big corporate players create and expand strategic R&D units developing hydrogen vehicle and infrastructure technologies. These “skunk works” are to some extent protected from immediate market priorities by long-term strategic concerns. Early markets are established through projects linking major global energy and auto companies and local and regional authorities to create large scale demonstration and deployment projects. These innovation and deployment activities are developed and protected by the dominant players, rather than through the emergence of new players and new systems on the periphery of the mainstream.

At the centre of this scenario are a number of key technologies and technological developments. Rapid progress in automotive fuel cell systems, including the fuel cell itself and onboard storage, are achieved through the substantial investments of auto industry. Pipeline and metering technology is important for the build-up of infrastructure. As natural gas becomes increasingly expensive, gasification and gas separation technologies become important, allowing hydrogen to be used in the natural gas grid. Waste, biomass, and renewable technologies, and carbon capture and storage, are all increasingly important as the hydrogen supply is decarbonised.

The key actors in the establishment of early markets and protected niche developments are the major oil and auto firms, local governments competing to attract global companies to set up demonstration projects, and the industrial gases companies with expertise in hydrogen handling and supply.

#### *Market Growth and Systems Change*

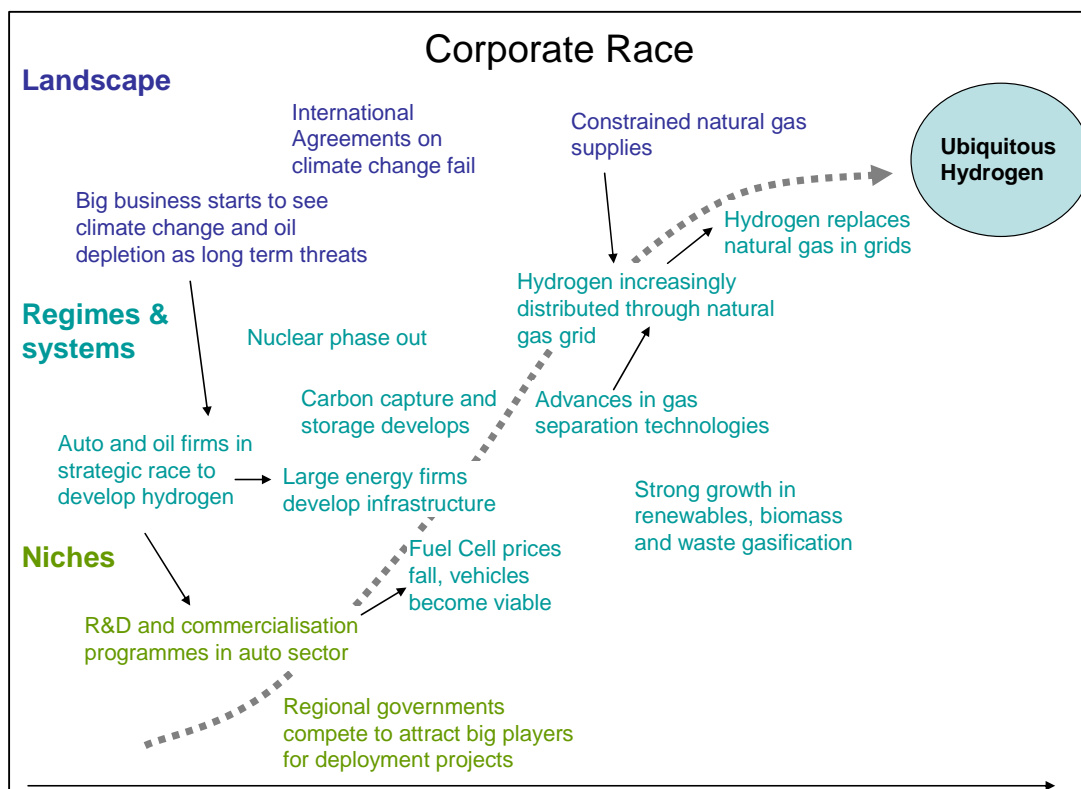
As R&D and the learning and development experience within deployment projects lead to decreased costs, hydrogen vehicles enter commercial markets, at first in high status and luxury car sectors. Those companies with successful hydrogen vehicle programmes seek to exploit their first mover advantage and increasingly lobby government for the introduction of tougher vehicle emissions standards, zero emissions mandates, zoning and market transformation programmes. Infrastructure is developed by large energy firms, principally from the existing oil sector, in collaboration with the large automotive companies, and as hydrogen fuel becomes more widely available, hydrogen vehicles diffuse into more markets. The infrastructure is developed heterogeneously, with both centralised and decentralised hydrogen production, to suit local circumstances. Hydrogen is initially

supplied from natural gas, much of it reformed at the refuelling station. As gas prices rise, gas distribution companies seek to maintain and grow their new transport-oriented market, injecting pure hydrogen directly into the grid in increasing concentrations. As concerns about climate grow, hydrogen is increasingly produced from gasified biomass and waste, and from coal with carbon sequestration. A non-fossil gas obligation is introduced, increasing the percentage of biogas and hydrogen in gas grids. Renewables, particularly distributed renewables, also contribute.

The role of governments in this scenario is relatively weak, although there is some strengthening of regional innovation policies, and strengthening of green policies as leading firms lobby for high environmental standards. Health and safety standards play an important role, in particular in enabling the use of hydrogen in natural gas grids.

The major industries involved in transport and energy adapt in the face of the substantial pressures of oil depletion, climate change and the emergence of new technologies, managing to fight off newcomers and maintain their dominant positions.

#### 4. Transition Diagram



## **Government Mission → Centralised Hydrogen for Transport**

### **1. The scenario “storyline”**

This scenario sees governments putting their full weight into steering a transition towards a hydrogen transport system, driven by concerns about climate change and energy security. The approach has a clear vision for the kind of hydrogen future that must be delivered, and there is a strong sense of ‘mission’ driving developments. With market mechanisms alone increasingly seen as unable to deliver a transition, emphasis turns to the development of national or EU level industry champions to work with government. Publics accept the need for firm government action, and accept that technologies such as nuclear and carbon sequestration are necessary to avoid dangerous climate change.

Governments promote the development of a market for hydrogen through public procurement of fleet vehicles, and encourage private fleet vehicles to move to hydrogen fuel. Many of these early vehicles have internal combustion engines and are bivalent fuelled, able to run on both petrol and hydrogen, allowing consumers to avoid concerns about limited hydrogen refuelling opportunities. European and national governments review state aids rules, to enable governments to underwrite national nuclear industries and new industries for carbon capture and storage. Changes in competition regulation encourage mergers and partnerships among major European energy and engineering firms, creating national and European champions to develop a hydrogen production and distribution infrastructure. European government also forces European automotive and energy firms to agree on common industry standards, preventing costly ‘standard wars’, and enabling more rapid diffusion of hydrogen vehicles into markets. Strong consumer uptake policies are introduced, with hypothecated taxes on carbon used to subsidise hydrogen fuel. Governments consider very stringent approaches, such as eventually banning sales of non-hydrogen vehicles, or placing limits on petrol and diesel sales.

At first, hydrogen is mainly provided through natural gas reforming. However, as a pipeline infrastructure is built where transport demand is high, and liquid hydrogen facilities provided for remoter sites, centralised hydrogen production becomes more important. Nuclear, coal with carbon capture and storage, and centralised renewable installations are all important supply sources. These new players enter transport fuel markets, helping to transform the system to look similar to *Central hydrogen for Transport*.<sup>2</sup>

### **2. Table of Key Indicators**

<b>Government Mission → Centralised Hydrogen for Transport</b>	
Dimensions	<ul style="list-style-type: none"> <li>• Innovation driven by new actors/ institutions</li> <li>• Strong guiding vision</li> </ul>
Transition Dynamics	<ul style="list-style-type: none"> <li>• Strong sense of ‘mission’</li> <li>• Driven by government, with national champion industries</li> <li>• Emphasis on the use of near-term technologies &amp; hybridisation</li> </ul>
Drivers of change	<ul style="list-style-type: none"> <li>• Strong UK/EU government concerns over climate and energy security</li> <li>• Societal acceptance of nuclear and carbon capture and storage, and greater social trust in science and technology</li> </ul>
Key Technologies	<p>Hydrogen technologies</p> <ul style="list-style-type: none"> <li>• Storage &amp; handling</li> <li>• Fuel cells</li> <li>• High temperature nuclear</li> <li>• Pipelines &amp; liquefaction</li> <li>• Gasification technologies</li> <li>• Short term small scale Steam Methane Reforming (SMR)</li> </ul> <p>Complementary technologies</p> <ul style="list-style-type: none"> <li>• Carbon capture &amp; storage</li> </ul>

<sup>2</sup> *Central Hydrogen for Transport* is an amalgamation of two of the UKSHEC Hydrogen Visions: *Central Pipeline* and *Liquid Hydrogen*

	<ul style="list-style-type: none"> <li>• New nuclear power</li> </ul>
Timescales and Milestones	'Go' decision on major hydrogen programme, and on nuclear

### 3. Multi-level perspective

#### *Landscape*

This scenario occurs in the context of a shift in governance style. It becomes widely recognised that only the State has the power to effect large scale change for the public interest, and current models of governance emphasising liberalised markets are increasingly seen as only a partial solution. Strong government is needed, because the challenges of climate change and energy security are too important to leave to the market. There is a clear strategic vision of replacing the oil-based transportation system with hydrogen, and an acceptance on behalf of the wider public that this is necessary, and that nuclear power is part of the solution. This scenario sees an increase in levels of public trust in science and technology, as publics increasingly recognise the challenges of climate change, and support government measures to tackle it.

#### *Technologies, niches and early markets*

In this scenario, governments create early opportunities for hydrogen vehicles through public procurement of fleet vehicles. These early deployments help reduce costs, and establish the first hydrogen refuelling stations. The early markets are created and protected through the activities of government, in partnership with UK and European engineering and energy companies, and with large automotive firms.

The technological emphasis in the early stages of this transition is on incremental, low cost steps, including bivalent fuelled hydrogen internal combustion engine vehicles. Hydrogen storage and handling technologies are important, as are small scale steam methane reforming. As hydrogen develops, hydrogen production shifts increasingly to new, high temperature nuclear power and gasification technologies. Pipeline and liquefaction technologies also are central for distribution and storage.

#### *Market Growth and Systems Change*

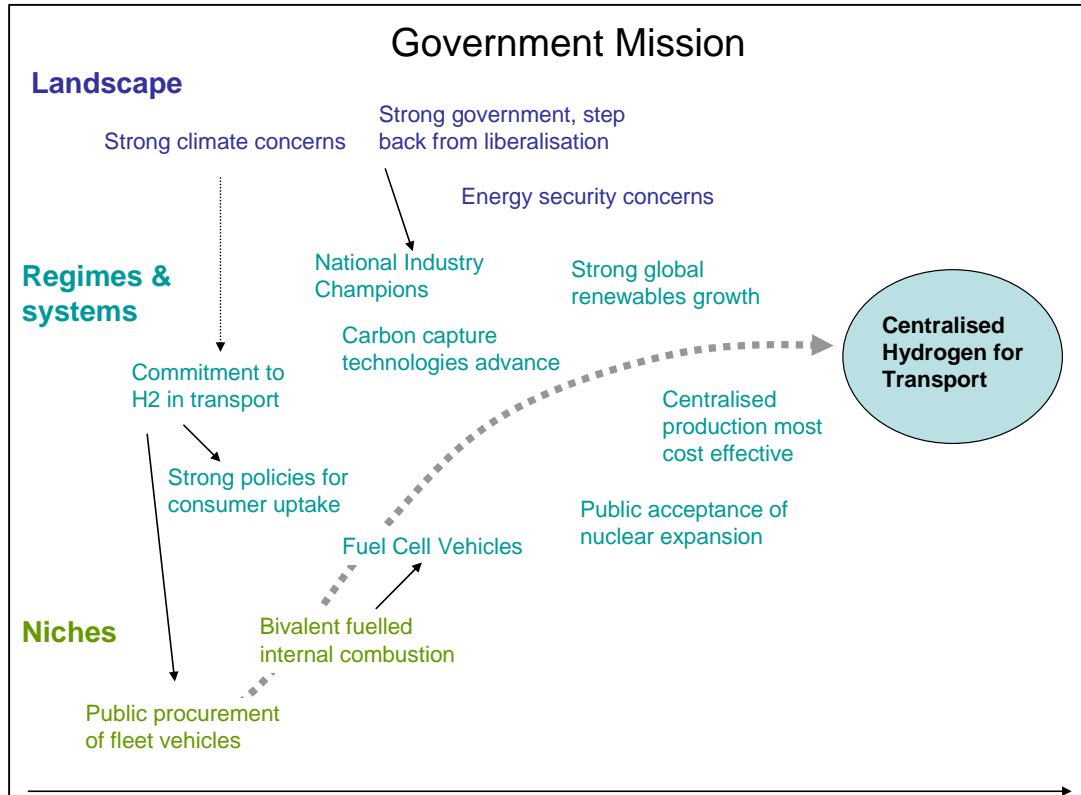
Public procurement for captive fleets (such as buses) expands from the early government-sponsored deployments, and this, combined with strong policies to encourage consumer uptake and supply-side investment in infrastructure, pushes hydrogen into wider markets. The emphasis remains on incremental changes and hybrid systems, with infrastructure developing off the natural gas grid with small scale reforming where appropriate, and with bivalent fuelled internal combustion vehicles much more common than fuel cells in the near term.

The scenario sees a restructuring of the EU energy and transport sectors, driven by government interventions. New actors and new institutions are created, though government stops short of nationalising major industries. Major shifts in policy include changes to EU State Aid rules, to allow governments to underwrite the financial risks of nuclear power and carbon capture and storage, and changes in competition regulation, encouraging mergers between large firms to re-establish national or supra-national (European) champions. Changes to planning systems enable the development of a hydrogen infrastructure, and EU government works with the champion industries to set technology standards, in a bid to promote rapid adoption (avoiding costly 'standard wars') and to help provide European industry with an advantage internationally. As the transition proceeds, governments may consider strong command-and-control policies, such as capping sales of non-hydrogen vehicles, or of petrol and diesel.

Government underwrites the development of infrastructure, using private finance initiatives and granting captive markets to champion industries. Early infrastructure is based on local steam methane reforming, but increasingly pipelines are built from centralised production facilities, and liquid

hydrogen tankers are used where pipelines are not feasible or economic. Hydrogen is produced in new nuclear power plants, a range of centralised renewable plant (including some substantial off-shore developments), and from gasified coal, with the carbon captured and stored in depleted North Sea oil and gas reservoirs.

#### 4. Transition Diagram



## **Disruptive Innovation → Synthetic Liquid Fuel: An Alternative Scenario**

### **1. The scenario “storyline”**

In this alternative scenario, hydrogen in its pure form fails to take off as a major fuel. Governments focus their attention on competitiveness and innovation, and there is antipathy towards supporting any one technology. The focus of carbon reductions is on the energy sector, and after the stalling of nuclear power, renewables and carbon capture and storage become the major growth areas.

Fuel cells, running directly on liquid hydrocarbons such as methanol, find large and expanding markets in the portable power sector, including laptops, mobile phones, military power packs, and a range of consumer electronics and portable electrical equipment. Fuel cell prices fall through this deployment, and a dominant design emerges around the direct hydrocarbon fuel cell. As users become increasingly accustomed to mobile power, their needs adapt and change, with higher mobile power demands becoming the norm. The infrastructure of fuel cartridges that this industry creates also serves a growing market for fuel cell scooters, again fuelled with a synthetic hydrocarbon. As technological developments continue, and consumers increasingly expect mobile power from their vehicles, fuel cell companies enter automotive supply chains, providing fuel cells for auxiliary power or for propulsion. Developments in fuel cell technology then ultimately lead to dominance of the synthetic hydrocarbon in transport markets, both in fuel cells and in internal combustion engines.

At first, fuel is supplied from natural gas, but as gas prices rise, and as governments increasingly enforce emissions reductions, fuel suppliers look for alternatives. Governments change regulations, such as the Biofuels Directive, to enable to use of synthetic renewable fuels. A variety of routes emerge, but by the middle of the century, electrolytic hydrogen from renewables has become a primary feedstock, along with carbon from biomass and from the flue-gases of carbon intensive industries, and the transport fuel system looks much like that described in *Synthetic Liquid Fuel*.

### **2. Table of Key Indicators**

Disruptive Innovation → <i>Synthetic Liquid Fuel</i>	
Dimensions	<ul style="list-style-type: none"> <li>• Innovation driven by new actors/ institutions</li> <li>• Weak guiding vision</li> </ul>
Transition Dynamics	<ul style="list-style-type: none"> <li>• Government emphasis on fostering innovation, breaking monopolies</li> <li>• Emergence of new industries and players, driven by expansion of new markets for portable power</li> </ul>
Drivers of change	<ul style="list-style-type: none"> <li>• Emerging climate and energy concerns</li> <li>• Emphasis on building competitive markets and high innovation</li> <li>• Social preference for liberalised markets and consumer economy</li> </ul>
Key Technologies	<p>“Hydrogen” technologies</p> <ul style="list-style-type: none"> <li>• DMFC</li> <li>• Synthetic liquid fuel synthesis</li> <li>• Fuel reformers or scale up of DMFC</li> </ul> <p>Complementary</p> <ul style="list-style-type: none"> <li>• Renewables</li> <li>• Carbon capture</li> </ul>
Decision points and Milestones	‘No-go’ decision on major government hydrogen programme

### **3. Multi-level perspective**

#### *Landscape*

This alternative scenario takes place in a world with increasing climate and energy concerns, but with an antipathy to ‘picking technological winners’, and an emphasis on innovation and competitiveness. It is believed that government should not aspire to direct change, but to create the conditions for competitive, innovative markets. Efforts are made to remove barriers to the entry of new technologies

and entrepreneurs into markets, and an anti-trust approach aims to keep competition and innovation at the forefront of change. There is an emphasis on liberalised markets, and a consumer economy, but governments do create incentive structures to reduce carbon emissions. This scenario also occurs against a background of steadily rising gas prices.

#### *Technologies, niches and early markets*

This scenario is driven by market demands, and the important early developments are in niche markets for portable power, auxiliary power onboard vehicles, and on niche vehicles (such as forklifts). Fuel cells enter use in laptops and portable electronic appliances, mostly running on methanol or a similar liquid hydrocarbon fuel. The military is an important 'protected space' for the development of portable fuel cell technologies, as portable power, and 'engine-off' power on vehicles, is highly valuable in military operations. This sees the military put significant investment into portable applications, and leads to developments with spill-out benefits to the civilian sector. Fuel cell scooters are also an important early market, particularly in East Asia, where electric scooters and bicycles are already common.

The early markets and niches are created and developed by companies largely outside the automotive and energy sectors, with electronics and battery firms playing an important role. This scenario is driven by the mobile power demands of end users – consumers who want mobile power to enjoy the full benefits of mobile communications and IT.

Unlike the other scenarios, Direct Methanol Fuel Cell or fuel reformer technologies are at the heart of this transition. Synthetic fuel synthesis, renewables, and carbon capture technology are also key.

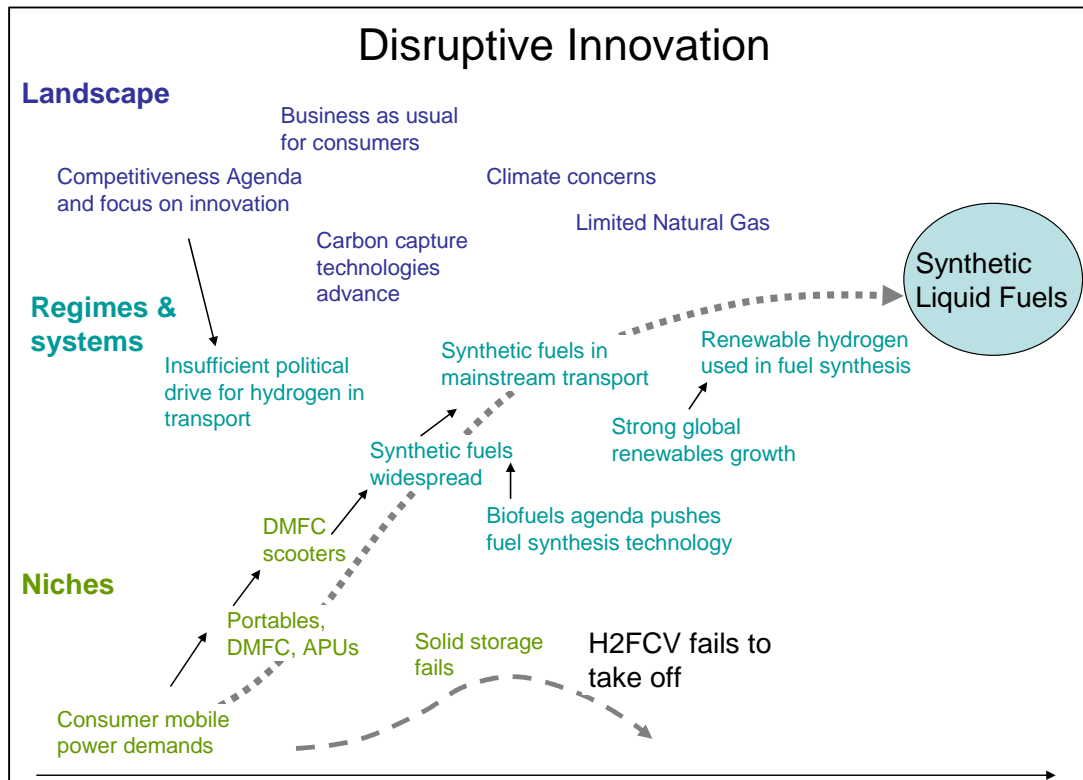
#### *Market Growth and Systems Change*

The early markets in portable electronics, the military, niche vehicles and scooters allow high volume fuel cell production, and subsequent cost reductions. A distribution infrastructure of liquid fuel cartridges becomes established, enabling greater expansion of fuel cells into portable applications and on-board auxiliary power. As consumers become accustomed to on-demand mobile power, there is a growing market of complementary products, providing mobile entertainment, communications and IT. Cost reductions, and changes in user preferences towards maximising the on-board power potential of vehicles leads to the entry of synthetic fuel vehicles into transportation. Carbon reduction policies steadily decarbonise fuel synthesis.

The scenario sees rapid growth and restructuring in the electronics and battery industries, as new players emerge and disrupt supply chains in the automotive industry. The fuel supply industry undergoes radical change, with battery firms dominating early markets, and with fuel synthesis becoming a major business. The infrastructure for fuel is initially based on the distribution of cartridges, but as markets expand in transport applications, refuelling stations increasingly provide synthetic fuel, in a pattern similar to today.

Two areas of policy enable this transition to take place. The first area concerns removing barriers to innovation, strengthening anti-trust legislation, and encouraging entrepreneurs. A second key area of policy is focused on decarbonisation, leading ultimately to the use of recycled or biomass-derived carbon in the synthetic liquid fuel. This enables a transition from the initially natural gas or coal-derived synthetic fuel to a low-carbon alternative.

## 4. Transition Diagram



## **Competitors to Hydrogen and “Showstoppers”**

One of the potential shortcomings of a backcasting approach is that it can neglect the competing and alternative developments that would close off the vision or transition pathway described. This section briefly reminds us of the competing technologies, and potential barriers, that could lead away from hydrogen and fuel cells. Several of these are common across all the transitions.

In technological terms, there are competitors in all potential hydrogen applications: e.g. transport, stationary power, grid buffering, and portables. These include for example:

- ❑ Battery electric vehicles (including vehicles with super or ‘ultra’ capacitors)
- ❑ Plug-in hybrids
- ❑ Biofuels
- ❑ Alternative energy storage and demand side management technologies to deal with intermittent electricity generation
- ❑ Advances in battery technologies for portable power

Major developments in these technologies could forestall the transition pathways described.

In addition to these direct technological competitors, it is also possible that hydrogen technologies will themselves simply fail to be developed as rapidly as expected or that they will never overcome some of the current problems and constraints preventing them entering widespread use. Such ‘showstoppers’ might include:

- ❑ Failure to develop adequate onboard storage technologies
- ❑ Difficulties with fuel cells (cost, fuel purity questions, durability)
- ❑ Limitations in raw materials (such as platinum)

Finally of course, as with many new technologies, public and consumer acceptance will be critical: an early disaster with hydrogen could have a major impact on perceptions and serve to set back developments for many years,.

## Key Insights and Messages from the UKSHEC Transition Scenarios

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

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

**Government Mission** → *Central Hydrogen for Transport*: Despite the scale of the challenge posed the climate and energy security drivers of a hydrogen economy, much of the policy discussion about hydrogen is constrained by current assumptions about the dominance of the market, the limits of government and antipathy to ‘picking winners’. This scenario reminds us that stronger government intervention may be required for a rapid transition to hydrogen, and challenges us to critically reconsider the ability of liberalised markets to deliver the purposive, large-scale socio-technological and infrastructural developments that may be required in an increasingly unstable and hostile world.

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

### Lessons across all scenarios

Despite very different governance structures and policies across the scenarios, all contain at least some attempts by policy-makers to reduce carbon emissions and enhance primary energy security. This reminds us of the importance of the policies and regulatory processes that embody society’s desire to maintain a secure and sustainable energy system for the future.

Although the scenarios envisage the use and deployment of a range of technologies, there is a portfolio of technologies that is common across the scenarios. This includes:

- ❑ A range of fuel cell technologies (principally low temperature fuel cells for vehicles, but also fuel cells for stationary use, or running on fuels other than pure hydrogen);
- ❑ Hydrogen production technologies,
- ❑ Hydrogen storage and handling technologies;
- ❑ Hydrogen purification and clean-up.

However, some of the technologies envisaged do not fit across all the scenarios. The development and widespread use of stationary hydrogen ‘energy stations’, nuclear power, gasification, methanol fuel cells, carbon capture and storage, and pipeline technologies would fit into some pathways but lead others elsewhere. Decisions to support some but not others of these would clearly influence the direction of technological change, and create a different set of choices in the future. Picking a

'winning' set of technologies is impossible given the uncertainties inherent in their development, and the market alone or 'business as usual' may not deliver the technologies that make a transition possible. Instead, support for portfolios of promising technologies may be the most robust approach.

The scenarios also highlight a number of broader strategic decision points, for government, business and wider society, which are likely to prove influential in shaping the direction of future technological developments with respect to hydrogen. These include decisions over:

- ❑ Primary energy production and options for the replacement of the UK's aging nuclear and coal plant (e.g. decisions on new nuclear build, carbon capture and storage, and large scale renewables policies).
- ❑ Whether it is viable to distribute hydrogen through natural gas pipelines
- ❑ The commercialisation decisions of major automotive firms, and a UK decision point similar to the US Department of Energy's 2015 'go/ no-go' commercialisation decision on support for FCVs.

## **Annex I: Developing Visions of a UK Hydrogen Future**

The challenge in putting together a set of hydrogen futures was to create a small number of credible, transparent and internally consistent end points that strike a balance between the specificity of the future visions on the one hand, and coverage of hydrogen ‘possibility space’ on the other. The visions are not predictions, but should be seen as tools for understanding about how the range of possibilities might come about.

In differentiating a set of futures that aim to map out a possibility space, a number of approaches are possible. Previous exercises have frequently focused on the social and economic worlds (and drivers) in which alternative technological systems are thought to be more or less likely to evolve (e.g. Watson et al 2004). However, in order to appraise the relative sustainability of the choices facing us with respect to hydrogen, the UKSHEC visions are defined in terms of technologies, so that the appraisal will reflect views on technological systems, rather than on the desirability of particular social worlds.

In September 2004, the research team convened the UKSHEC Hydrogen Vision Workshop, which brought together more than 40 stakeholders from government, industry and academia to develop visions of what a sustainable hydrogen economy might look like (McDowall & Eames 2004).

The team then drew on the outputs of the workshop, along with insights from the literature, to develop a set of visions which sought to capture the range of prevalent views about what a hydrogen future might or should look like. These visions comprised:

- ❑ Structured narrative storylines describing ‘archetypal’ configurations of hydrogen production, infrastructure (storage and distribution) and end-use technologies
- ❑ Indicative quantitative indicators to provide a sense of the scale of technological deployment implied, and
- ❑ Systems diagrams providing pictorial representations of each vision

The credibility, transparent and internal consistency of the visions was then tested through consultation with our stakeholders, and the visions refined. This consultation was also designed to ensure that the visions covered a broad enough range of possible hydrogen futures and that no relevant future was excluded from the subsequent analysis.

## **Annex II: Technological Transitions & Transition Contexts**

The academic literature on processes of technological change is broad and wide ranging, with approaches from a wide variety of disciplinary backgrounds. A recent body of work from the Netherlands has made progress in pulling together the many strands of research into a synthesis framework that is useful for describing how large scale technological transitions occur. This section outlines the technological transitions approach, and characterises the current energy and transport systems in terms of this framework.

The term ‘technological transition’ refers to a large scale change in the way that a particular social function (heat, light, transport, food, etc) is fulfilled, with classic examples being the transition from sail to steam in shipping, or from gas to electric lighting. The framework attempts to make sense of these transitions by providing a structure through which to consider the simultaneous and co-evolutionary processes that occur over different scales. This section introduces the three levels at which change occurs, and then explores attempts to develop a typology of different possible transition paths.

### *Three related levels for understanding change*

1. *The landscape*, the deep-rooted structures that set the context for change, including long-lived physical infrastructures, culture and social values, availability of natural resources and so on.
2. *The socio-technical regime* – the configuration of artefacts (e.g. cars), institutions (e.g. Traffic police, Highways Agency, and ‘soft’ social institutions such as opprobrium about drink driving), users (motorists), manufacturers and so on that keep the technological system operating.
3. *Niches* – spaces in which novelties and innovations are found, on the periphery of the mainstream regime. This includes both niche markets, in which users value particular attributes and functionalities, and ‘technological niches’ a concept describing the multitude of spaces in which technologies are nurtured and protected (for example, enthusiasts and activists, strategic spin-out companies in firms, local experiments and demonstration projects and so on).

Very simply, the framework seeks to understand the processes of large scale change with reference to the way that changes at the landscape level, or emerging tensions within the regime, create opportunities for innovations to emerge from niches and enter, or replace, the mainstream technologies. The framework is perhaps best illustrated graphically, as in figure 1. below.

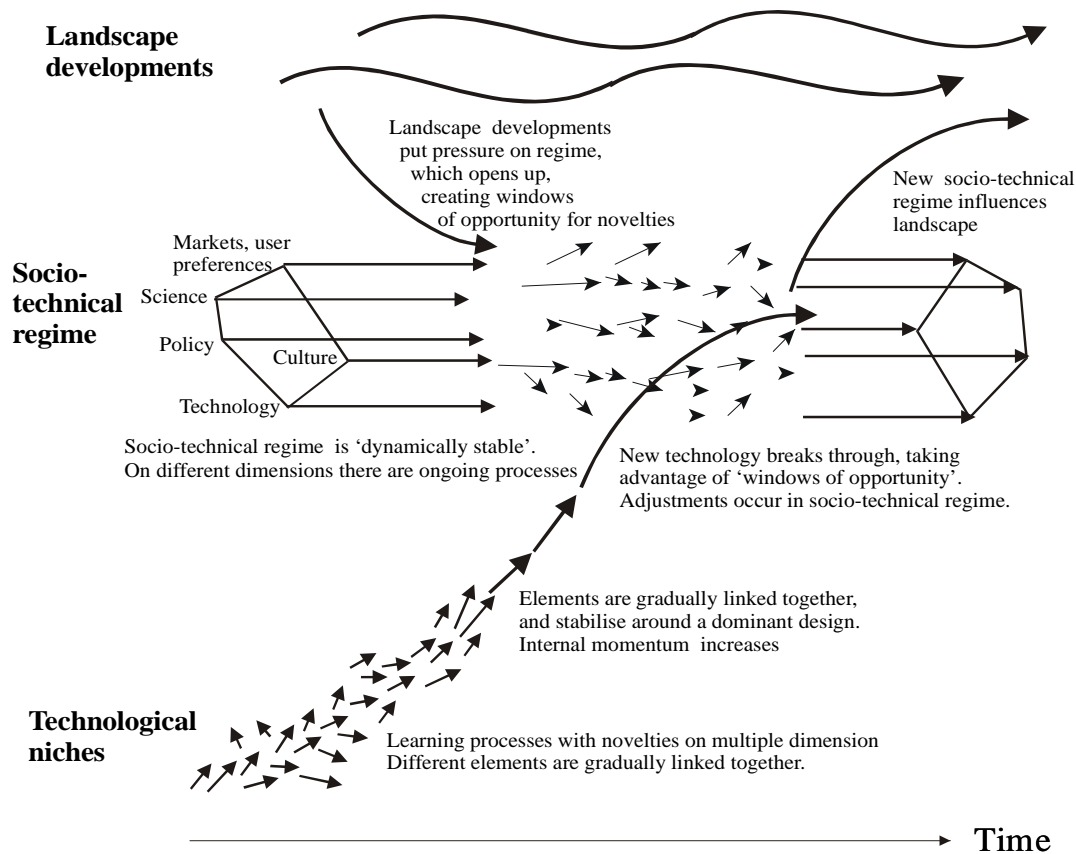


Figure reproduced from Geels 2005

### Socio-technical Landscape

The landscape sets the conditions in which all technological systems operate. This includes the long-lived physical infrastructures and patterns of demographics, the political and social philosophies of a people, and the state of the wider economy. The overall landscape conditions for energy and transport are familiar to us all. Important recent 'landscape' level trends include:

- ❑ globalisation and global economic growth;
- ❑ the collapse of communism;
- ❑ the rise of ecological modernisation and sustainable development as dominant paradigms for understanding the challenges of environmental change;
- ❑ dependence on fossil fuels
- ❑ suburbia and urban sprawl
- ❑ move away from nationalised industries towards liberalised market

It is in the nature of landscape conditions that they are taken for granted, and frequently go unchallenged in futures thinking. But history demonstrates repeatedly that the current belief systems and political priorities (such as the importance of markets), technologies, and 'ways of doing things' are flexible, and co-evolve as new socio-technical systems emerge. It is an important aim of scenario studies to prompt thinking about the nature of long-term change, and while many fail to do this, or focus on some 'received wisdom uncertainties', it is clear that the landscape conditions may change over time.

Key uncertainties at a landscape level can be summed up below:

- ❑ Social values regarding the environment, and the trade-offs between material wealth, environmental integrity, and social equity. This includes how political processes respond to problems, through attempting to set the 'rules of the game' for market systems, through direct regulation, or through the direct provision of services through nationalised industries. It also

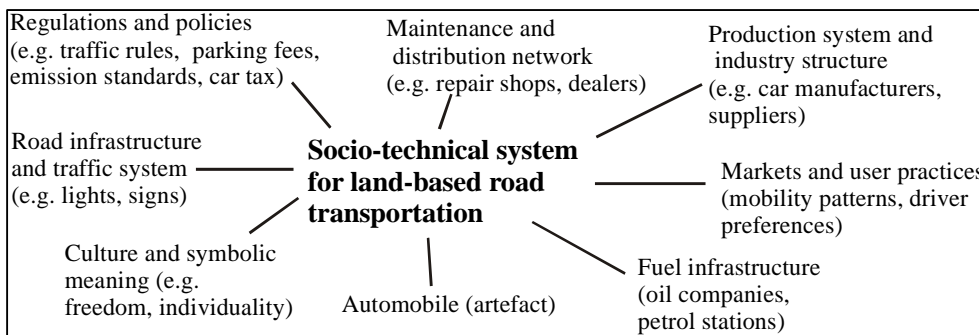
includes how citizens in their daily lives choose to live: alone or in multi-occupancy households? In small communities or in sprawled suburbia? Choosing to consume material goods or leisure time?

- ❑ Rate of economic growth, and relationship of growth to demand
- ❑ Population and demographics
- ❑ Availability of existing fuels, and political stability in their delivery
- ❑ Rate of climate change, and the political and social responses to it.

The scenario set includes a variety of directions of change in these uncertainties. However, unlike in many previous scenario studies, the nature of each scenario is not defined according to landscape conditions using a two-axis grid. This attempts to reflect the insight that technological transitions are not simply top-down processes, pre-determined by the landscape conditions that pertain. They rather co-evolve along with landscape conditions.

### Socio-technical Regimes: Transport & Energy

The concept of the socio-technical system describes the configuration of technologies, systems, actors, and institutions that together provide a 'societal function', such as transport. The diagram below illustrates the concept with reference to the automobile.



From Geels, 2005.

The energy system underpins and enables almost all human activity, and is thus intimately connected with developments in all socio-technical systems. Here we focus on the ways in which energy and transport services are provided in our society.

Following the attempt of Anderson et al (2005) to understand the current state of the UK energy system with respect to the MLP, the UK energy and transport system can be characterised by:

- ❑ A dependency on fossil fuel based energy supply
- ❑ An oil, gas and coal extraction, processing and transportation infrastructure
- ❑ Large-scale electricity generation technologies (coal, gas and nuclear plant)
- ❑ Connection to a centralised national grid, with comprehensive regional and local electricity grids
- ❑ A reasonably comprehensive natural gas grid
- ❑ A national network of petrol and diesel distribution
- ❑ A privatised set of operators who are regulated by government bodies
- ❑ An extensive road network
- ❑ Moderately comprehensive rail and aviation infrastructure.

This has, of course, not always been the case. In the transport system, the second half of the twentieth century saw the private car establish itself as the dominant transport mode despite the oil shocks of the 1970s. In 1986 Margaret Thatcher crowned the car unquestionable king of the transport pecking order, with her proclamation that "A man who, beyond the age of 26, finds himself on a bus can count himself as a failure". Concerns about local air pollution have led to shifts in technology

(introduction of catalytic converters, removal of lead from petrol), and recently pressure on climate has created accelerated improvements in vehicle efficiency (for example, through the EU agreements with ACEA). However, attempts to break the domination of the internal combustion petroleum vehicle, through ‘modal shifting’ policies, and the 1990s experiments with electric vehicles, have largely failed.

In the heat and power sectors, the UK has been historically dependent on coal, not only for the generation of electricity, but for many years for heating fuel in the form of town gas, and as solid coal itself. Natural gas use was limited until the development of the UK oil and gas fields in the North Sea, when town gas was eliminated. The collapse of the domestic coal-mining industry, stricter emissions standards forcing the closure of old coal plant, the stalling of nationalised nuclear power, and the liberalisation of energy markets led to the rapid expansion of gas use in electricity generation during the 1990s. More recently, the UK’s transition to a net gas importer has set the stage for current concerns over energy security, while rising concerns about the implications of climate change have put carbon emissions at the top of the energy policy agenda.

Looking to the future, it is possible to identify a range of key developments and uncertainties within the energy and transport systems that will be important for the development or otherwise of a hydrogen energy.

- ❑ Direction of technological change in primary energy (nuclear, renewables, CCS, microgeneration) and in transport (hydrogen, biofuels, batteries, ultracapacitors). Breakthroughs or substantial progress in any of these fields could lead to widespread change, either helping or hindering the development of hydrogen. The development of solutions to intermittent electricity supplies from renewables could also be important.
- ❑ Developments in energy demand: efficiency and decoupling. Changes in energy demand trends would have important knock-on effects on the ways in which systems could change.
- ❑ The evolution of consumer transport and energy behaviour. This might include increases in the use of mobile power, the steady rise of aviation, the development of new ‘needs’; or substantial modal shifts away from automobiles towards mass-transit systems)
- ❑ Energy and transport policy: both the policy priorities (such as the relative importance of air pollution, congestion, carbon, security of supply, cost, keeping markets competitive), and the preferred policy instruments (emissions trading, taxes, R&D funding) are important. An important question in the context of hydrogen will be the extent to which governments adopt integrated strategies for the development of hydrogen, or if there are more general ‘low carbon’ policies.
- ❑ Responses of industry – the extent to which industries will oppose or enable change will be important. At this stage, it is unclear which industries will be losers from a transition to hydrogen, as all potentially can see a future for themselves. But as this becomes clear, industries will fight back.
- ❑ Expectations are important – hydrogen is currently seen as an important future technology, but this could change. The phenomenon of ‘hype-backlash’ in expectations about technology is well known, and could well effect hydrogen.

### **Niches and the Periphery**

The multi-level perspective highlights the role of niches – spaces in which technologies are developed and incubated before reaching maturity. From niches, technologies emerge into mainstream applications and markets, where they may enter into existing regimes, or even create entirely new ones.

There has been some confusion in the literature as to what exactly is meant by the 'niche'. Two concepts are key: the technological niche and market niche.

By the time a technology has reached its first market, it has undergone a substantial phase of development, involving scientists, engineers, financiers, entrepreneurs, and frequently activists. These actors form a loose social network around the emerging technology, advocating on its behalf, and mobilising investment and support for its development. In brief, the activities of these actors create a 'protected space', in which the technology can develop, and this protected space is the 'technological niche'. In physical terms, the niche is often embodied through research centres, demonstration and deployment projects, while the social network that creates the niche is formalised through the development of partnerships and industry associations (such as the London Hydrogen Partnership). The technological niche can be very broad, for example there is a wide niche developing and promoting hydrogen and fuel cell technologies. This includes the activities of large firms developing hydrogen for long-term strategic reasons, the military R&D centres, groups of technological activists (such as the Campaign for a Hydrogen Economy) and scientists working on hydrogen technologies. The activities and motives of these social groups will be an important factor in the dynamics of any transition.

The second 'niche' concept relates to the first products developed around the new technology to enter markets, in niche markets. These niches are defined by a set of functionalities desired by a small and specialised set of consumers, such as those with unusually high portable power needs for example. Market niches that may be important are not solely those confined to hydrogen and fuel cell technologies. The experiments with battery electric vehicles in the 1990s were an important niche for the development of electric drive train technology. Similarly, the development of biofuels and other alternative vehicles have provided institutional and policy lessons that are likely to be relevant to companies and policy-makers addressing a potential transition to hydrogen.

However, there are several small markets in which fuel cell and hydrogen technologies are clearly much closer to market than the mainstream propulsion and power markets:

- ❑ Portable power
- ❑ Back-up & premium power;
- ❑ Off-grid installations
- ❑ Auxiliary power units (on board cars, boats and aeroplanes)
- ❑ Niche vehicles

The diffusion of hydrogen and fuel cell technologies into any of these niches could have implications for the development trajectory of the technologies, through learning, scale economies, user familiarity and a range of other processes. The choice of technology (for example, Direct Methanol Fuel Cells vs. PEM fuel cells in portable applications) could have important implications for the direction that these developments take (see Agnolucci & McDowall).

### **Transition Contexts and Governance Paradigms**

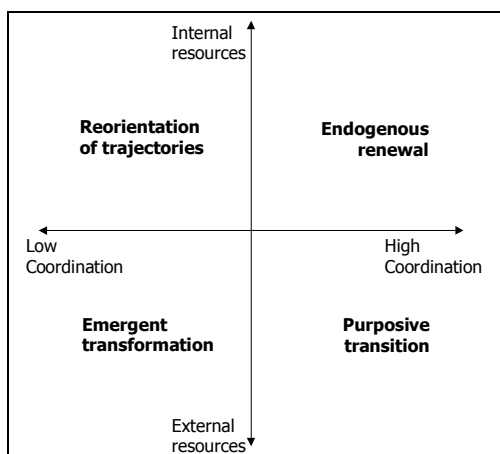
Attempts have been made to develop typologies of different kinds of large scale transition. Berkhout et al argue that the Multi-Level Perspective puts too much emphasis on a single kind of technological transition: one in which novelties emerge outside the existing regime, and ultimately supplant it, as an emergent and evolutionary process. They argue that this ignores other possible transition dynamics, such as transitions in which developments are consciously driven by coalitions of actors with a vision of what the transition is leading towards.

Geels and Schot have developed a taxonomy of five archetypal transition pathways. These have been applied to the future of the UK energy system by Anderson et al., and describe the way in which elements at the niche, landscape and regime level interact. However, we agree with the critique of Berkhout et al that this typology treats too lightly issues of agency, power and governance. In particular, in the context of discussions around hydrogen, the Geels framework pays little attention to whether or not a transition is actively envisaged by the actors involved, or whether it is the emergent result of contingent processes.

The ‘transition contexts’ typology developed by Berkhout, Smith and Stirling argued that regimes are constantly facing competition from alternative regimes and new socio-technical configurations in niches. The ability of regimes to respond to those pressures is termed their ‘adaptive capacity’.

The second element in Berkhout et al’s analysis is the exploration of different forms of pressure that create the conditions for change. The selection pressures they identify act on different levels – top-down, bottom-up, and as a result of competitive pressures between alternative regimes, or future orientations within the regime. Secondly, they explore how selection pressures can be targeted at a regime transformation, or can emerge contingently.

They then develop a two-fold axis: the first dimension explores the degree to which change (both the response of the regime to pressure, but also the degree to which pressure is co-ordinated in a particular direction) is co-ordinated and intended. The second explores the degree to which the resources deployed to respond to those pressures are external or internal to the regime.



This typology sees two possible roles for governance: as either articulating selection pressures (for example, by internalising environmental costs through green taxation) or as facilitating adaptive capacity (for example, with R&D funding to a particular industry or socio-technical regime).

This focus on governance relates to work on ‘governance paradigms’ in technological transitions. Elzen & Wiecek, and Hisschemoller et al, both argue that different transitions types might be understood in terms of the type of governance structure. Hisschemoller et al explore the relationships between political institutions and processes and transition trajectories to a hydrogen economy. In doing so, they outline four archetypal ‘governance paradigms’ that are applied to technological change.

- i) Governance by government
- ii) Governance by policy networking
- iii) Governance by corporate business
- iv) Governance by challenge

These four modes of governance can be related to the SPRU transition contexts.

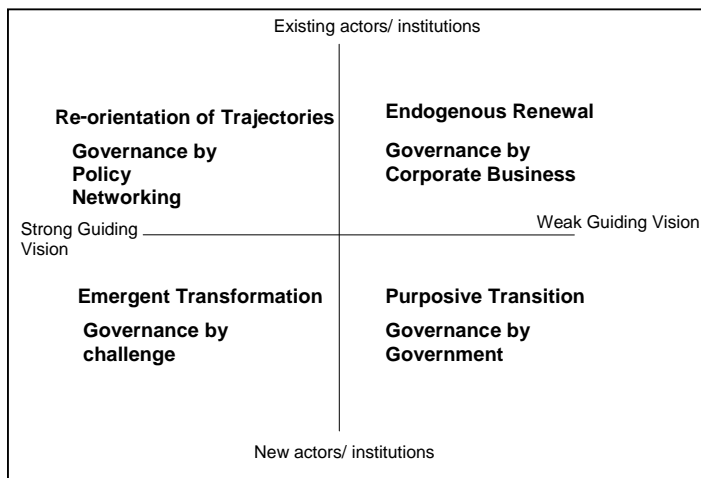
*Endogenous Renewal* describes situations in which selection pressures are clearly articulated in a particular direction, and there is a highly co-ordinated response based on resources originating within the regime. This relates to *Governance by Corporate Business*, where the actors within the dominant regime are able to recognise long term threats and identify possible solutions, and have the capacity to steer their activities in a direction that protects their long-term interests. Large companies are continually investing in R&D to protect their leading positions, and have the capacity to direct it in a particular direction.

*Re-orientation of trajectories* describes a situation in which the pressure for change is not articulated clearly within the regime, and there is no clear sense of a new direction in which to move. However, the regime does possess the adaptive capacity to accommodate new pressures and priorities, and re-orient itself accordingly. As an emergent result of a range of pressures from the niche, regime and landscape level, which are articulated through the networks making up the regime, a re-orientation occurs that leads to an un-planned for outcome. This relates to *Governance by Policy Networking*, in which governments have modest ambitions with respect to direction change, and engage a network of stakeholders to facilitate and modulate, rather than direct and plan. Governance here focuses on creating a regulatory environment that enables the adaptive capacity of the network to break out of locked-in trajectories.

*Emergent Transformation* describes transitions in which the direction of change is not anticipated or planned. The pressures that induce change are not co-ordinated or clearly articulated in any particular direction, but create the conditions for novelties to develop in unexpected ways from outside the existing dominant regimes. This broadly corresponds to situations governed by Hisschemoller *et al.*'s notion of '*Governance by Challenge*' in which emphasis is on the removal of barriers that prevent innovation, and the promotion of policies that prevent 'lock-in' to any one technological regime. This includes strong anti-trust policies that break up monopoly power within industry, and enable breakthrough of new firms, technologies and networks.

*Purposive Transition* describes a transition lead by a clear vision. Pressures are clearly articulated, and resources are intentionally directed at reaching a pre-defined goal. Resources have to be brought from outside the existing regime to enable change to take place, for the processes of articulating pressure, defining goals, and enacting the transition. The clearest historical examples of these sorts of transitions involve *Governance by Government*, in which only the State has the resources, vision and authority to direct change. This includes the development of close links between government and key 'national champion' industries, direct involvement in the development of infrastructures, and the power to coerce change where necessary.

This mapping of Hisschemoller *et al.*'s Governance Paradigms onto the SPRU transitions framework is pictured below:



By exploring four possible transitions based on each of these archetypal transition dynamics, we can illustrate the patterns and processes likely to be important for a transition to hydrogen, and expand thinking about the possible mechanisms of change.

## References

- Agnolucci & McDowall (unpublished) Technological change in niches: the auxiliary power unit and the hydrogen economy. Paper submitted to *Technological Forecasting and Social Change*, June 2006. Policy Studies Institute, London.
- Anderson et al 2005. Decarbonising the UK: Energy for a climate conscious future. Report of the Tyndall for Climate Change Research, UK.
- Berkhout, F., Smith, A., and Stirling, A. (2004). Socio-technical regimes and transition contexts, in Elzen, Geels and Green (Eds), *System innovation and the transition to sustainability: Theory, evidence and policy*. Camberley, Edward Elgar.
- Eames, M. and McDowall, W. (2005) UKSHEC Hydrogen Visions. UKSHEC Social Science Working Paper No. 10. Policy Studies Institute, London.
- Elzen and Wieczorek (2005). Transitions towards sustainability through system innovation. *Technological Forecasting and Social Change* **72**: 651-661.
- Geels, F.W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy* **31**(8-9): 1257-1274.
- Geels, F.W. (2005). Processes and patterns in transitions and system innovations: Refining the co-evolutionary multi-level perspective. *Technological Forecasting and Social Change* **72**(6): 681-696.
- Geels, F.W. and Schot, J. (2005). Taxonomy of transition pathways in socio-technical systems. ESRC Sustainable Technologies Programme Transitions workshop, London.
- Hisschemoller, Bode, Van der Kerkhof (2006). What governs the transition to a sustainable hydrogen economy? Articulating the relationship between technologies and political institutions. *Energy Policy* **34** (11): 1227-1235.
- McDowall & Eames (2004) *Report of the September 2004 UKSHEC hydrogen visions workshop*. UKSHEC Social Science Working Paper No. 9, Policy Studies Institute, London.
- Vergragt, P., and Green, K. (2001). "The SusHouse methodology: Design orienting scenarios for sustainable solutions." *The Journal of Design Research* **1**(2).
- Watson, Tetteh, et al. (2004). "Hydrogen Futures to 2050." Tyndall Working Paper **46**. Tyndall Centre for Climate Change Research.