



Towards a Sustainable Hydrogen Economy:

A multi-criteria mapping of the UKSHEC hydrogen futures

FULL REPORT

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Executive Summary

Hydrogen has the potential to provide a sustainable and secure energy system. However, there is no consensus on what a hydrogen future should look like, and deep disagreements are emerging over the energy sources and types of infrastructure that should be included or rejected.

This report presents the results of an exercise in developing a set of visions of possible hydrogen futures for the UK, and subjecting those visions to a participatory multi-criteria sustainability appraisal, with a view to exploring the broader dimensions of sustainability around hydrogen systems. The work is part of a backcasting scenario project, which aims to develop visions of a sustainable hydrogen future, and then explore the pathways by which those visions might be achieved.

This report aims to:

- ❑ Present the six UKSHEC Hydrogen Visions, representing possible hydrogen futures for the UK
- ❑ Report the findings of a multi-criteria sustainability appraisal of those six visions
- ❑ Draw conclusions about the uncertainties, different perspectives, and key issues that are important in considering how hydrogen energy might contribute to sustainability
- ❑ Highlight lessons for research and policy

What does vision appraisal tell us?

Visions of the future are important in technological change, helping to create a shared sense of purpose about priorities and policies. However, visions are often contested, and hydrogen is no exception: there is no single agreed vision of a sustainable hydrogen economy. This work is based on an understanding that where uncertainties are large, and where there are different social priorities involved, it is not possible to identify a single best or ‘optimal’ solution. The six future visions in this study are not intended as predictions. The technologies they comprise could be configured into a wide range of possible future hydrogen systems, and hybrid systems, involving some components of a number of visions, may be much more likely. Instead, the visions are intended to cover the broad range of possibilities in a manageable number of visions. This means that the results cannot be seen as advocating or endorsing any one of the visions alone, but as a way of learning about the important perspectives, issues, and uncertainties that surround the hydrogen debate. The aim is to promote thinking about the sort of systems that are desirable and achievable in the long term, and to use the visions to open up discussion around how different hydrogen systems might meet sustainability objectives.

How were the visions developed and appraised?

The six UKSHEC visions were developed through a review of the hydrogen futures literature, and on the basis of a workshop bringing together 40 UK hydrogen stakeholders. Each vision consists of a description and diagram of a technological system, including the production, distribution and end-use of hydrogen. The six visions were appraised by a panel of 15 expert stakeholders, with backgrounds in government, research, industry, and environmental campaigning, using a Multi-Criteria Mapping method.

Headline Results from the Appraisal

- ❑ Hydrogen is not automatically a sustainable option. Participants recognised a range of circumstances in which hydrogen energy might be less sustainable than the current system or some non-hydrogen business as usual futures. However, hydrogen was perceived as having the potential to deliver substantial sustainability benefits over a wide range of issues.
- ❑ The panel identified carbon emissions as the single most important dimension of sustainability with respect to the hydrogen futures.
- ❑ Even for issues with relatively well characterised data sources (such as wells-to-wheels carbon studies) there were debates about how well technological systems could be expected to perform in real world applications.
- ❑ There is significant uncertainty over the future costs and performance of the technologies, and these uncertainties have important impacts on the likely sustainability of the different futures. In particular, there are uncertainties concerning: the performance and costs of carbon capture and storage, nuclear power, pipelines, small scale steam methane reformers, fuel cells and hydrogen storage technologies.
- ❑ There is a wide range of rationales for ranking different futures (e.g. political implications vs. technical appraisals of likely system performance). Some of these issues are amenable to further research, others are based on normative value judgements about the way in which society should operate, and are therefore likely to be a continuing source of disagreement and dissent. Nuclear power, the degree of decentralisation, and feasibility were key areas dividing participants' appraisals.
- ❑ For those concerned about nuclear power, opposition was as much to do with social and political aspects as environmental concerns.
- ❑ Assumptions about technological change are important – do some routes mean that we close off others? This is an area that further research might cast some light on.
- ❑ 'Business as usual' or the market alone are thought to be unlikely to deliver any of the visions, at least in the short term.

Recommendations for Policy

- ❑ While carbon emissions were recognised to be the most important single determinant of the sustainability of a hydrogen energy system, there are a wide range of other criteria that are seen as important. Issues other than carbon and cost need to be considered if the introduction of hydrogen is truly to deliver greater sustainability.
- ❑ Hydrogen policy must also be robust in the face of uncertainties about future context conditions, such as future availability and price of natural gas, and public attitudes to technology. The future of political frameworks around carbon and climate change is a key uncertainty affecting the perceived feasibility of the visions.
- ❑ The broad interest coalition promoting hydrogen is fragile. If hydrogen systems develop, there is significant potential for future social conflict over the shape and direction that those systems take.

- ❑ Robust research policy should address ‘backstop’ technologies – for example, that explore the possibility that hydrogen storage technologies fail to improve significantly.

Recommendations for Research

- ❑ Public acceptability research needs to take a whole systems approach, including primary energy as well as just the use of hydrogen as a fuel. Studies that only examine the public’s attitudes to the safety or end-use of hydrogen in isolation are likely to be of little use in understanding future conflicts.
- ❑ Research into social issues must move beyond narrow questions of public acceptance: control, state intervention, access, and consumer choice may all be important. While public acceptability is important, there appear to be broader concerns about the potential social impacts of hydrogen systems.
- ❑ Combining scenario approaches with multi-criteria appraisal provides a valuable tool for exploring and mapping the perspectives, issues and uncertainties involved in long-term strategic technology choice. The approach could be fruitfully explored in other contexts. In particular, many of the issues raised as important for hydrogen would not have been discussed and explored with reliance on a more narrowly framed approach.

1. Introduction

A 'hydrogen economy' has the potential to provide the basis for a sustainable and secure energy system. The wide and growing attention that it has received has led to a rich literature of studies, promoting and exploring different possible hydrogen futures, and suggesting strategies for how a hydrogen economy might be achieved.

However, despite broad agreement that hydrogen has the potential to make a significant contribution to sustainable energy policy goals, the literature suggests that the future of hydrogen is deeply contested. Visions of a hydrogen future select, combine and reconfigure individual hydrogen generation, distribution, and end-use technologies into more or less mutually compatible energy and transportation systems, which embody deeply contested and conflicting views of sustainability. There is no single, shared vision of a 'sustainable hydrogen economy'. Rather, different organisations and individuals produce visions and expectations of possible hydrogen economies that reflect their own interests and agendas (Eames et al. 2006).

For some, hydrogen is a means of maintaining current systems, structures and ways of life; for others, it has the potential to radically re-order transport and energy in ways that may facilitate broader social change. Brown et al (2000) have recently highlighted the way in which technological futures become spaces in which a variety of current social interests and agendas compete, and this appears to be true of hydrogen.

Despite the range of different possible hydrogen systems that the literature embodies, there appears to be little systematic attempt to appraise the relative sustainability or desirability of different hydrogen futures. Those few studies that do attempt to provide integrated appraisals of different hydrogen options tend to do so on the basis of few criteria (typically carbon emissions, cost, and air pollutants, e.g. Granovskii et al 2006), or with no attempt to engage different legitimate perspectives on problem framings, weightings, and criteria definition (see, for example, the studies by Afgan & Carvallo 2004; Row et al 2002).

This study aims to open up the debate about the relative sustainability of alternative possible hydrogen systems, and to explore not only the technological uncertainties around hydrogen, but also the divergent values and social priorities that are likely to make a consensus view of a 'sustainable' hydrogen economy difficult. In order to do this, a novel methodology has been developed, combining a participatory 'visioning' exercise with a multi-criteria evaluation technique, Multi-Criteria Mapping.

1.1 Aims & Objectives

The work forms initial findings from part of a wider package of socio-economic research, funded by the EPSRC's SUPERGEN programme, that is developing a set of 'backcasting' scenarios to illustrate 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

This paper first outlines the theoretical background informing the work. Section two then describes the development of the methodology used to develop and appraise a set of visions. The visions are

presented in section three, and the results of the appraisal in section 4. Section 5 then reflects on these findings, and explores what the appraisal tells us. Finally, section 6 draws out some conclusions and insights for policy.

1.2 Background and literature

Scenarios and Backcasting

Predictive forecasting approaches to studying the future are ill-suited to the long time scales, great uncertainties, and technological, social and economic change that any transition to a hydrogen economy will entail. Increasing recognition of the limitations of predictive forecasts have led to the emergence of a wide range of alternative ‘foresight’ and scenario building techniques (Smil 2000; Berkhout & Hertin 2002). These approaches avoid prediction, seeking instead to explore alternative possible futures and challenge tacit assumptions about the future, in order to promote policies that are more robust in the face of future uncertainties.

‘Backcasting’ is a normative scenario building tool used to provide insights into how long-term goals might be reached. As such, it is an appropriate form of analysis for a project tasked with investigating how a hydrogen economy might be achieved. Backcasting essentially 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). Rather than attempting to map out what might happen, the backcasting perspective emphasises what might be done, or, as Robinson puts it (1990) “*The major distinguishing characteristic of backcasting is a concern, not with what futures are likely to happen, but with how desirable futures can be attained*”.

Backcasting usually involves a number of key steps:

- ❑ Characterising relevant aspects of the current state of the world
- ❑ ‘Visioning’ a desirable future world
- ❑ Writing of scenario storylines articulating a limited number of pathways from the current state of the world to this desirable future
- ❑ Evaluating these pathways to identify key decision points and policy recommendations

Through focusing on distant goals, the backcasting perspective helps decision makers to move beyond the immediate and everyday barriers to see opportunities for long-term strategic action. The approach has informed a number of recent futures studies in a range of areas (e.g. Vergragt & Green 2001; Banister et al 2000; Tuinstra et al 2002; Van den Bosch et al 2005).

In addition to generating insights into possible transition routes, one of the aims of backcasting is to create a shared vision that unites actors and facilitates co-operation (Van den Bosch et al. 2005).

Technological Expectations

The idea that the development of a shared ‘vision’ of the future can help bring that future about is supported by the emerging literature on technological expectations, which suggests that expectations have an important role in the trajectory of technological development.

Technological expectations may be implicit assumptions shared within a more or less formal network of actors, they may be embodied in physical entities such as prototypes or demonstration projects, or they may be articulated through shared scripts and narratives, such as those provided by foresight processes. Expectations and visions can play a guiding role in technological development, as ‘guiding visions’ (Kemp et al 1998) or *Leitbilder* (Dierkes et al 1996). As Van Lente (1993) argues, “one should not think that promises are primarily an element of the tactics and PR-vocabulary of firms.... They seem to be important in the actual shaping of a technology itself”.

Van Lente and Dierkes et al. identify several ways visions and expectations influence the dynamics and direction of technological development, within the constraints of the physically possible:

- Expectations legitimate and justify actions, such as the establishment of demonstration projects or spin-out units.
- Expectations provide meaning for scientists and engineers, who define their activities with respect to social and economic goals, as well as on grounds based purely on curiosity.
- Positive expectations mobilise funds and support, both in terms of finance and investment, but also in terms of political and regulatory backing.
- Shared expectations facilitate agenda building and alignment around particular technologies, creating a technological community through the establishment of societies, user groups, industry associations and so on.
- Expectations reduce uncertainty in decision-making. Technology developers use shared ‘scripts’ of the future to understand ‘likely’ areas for development and to understand ‘the way things are going’ to structure their decisions. Within an evolutionary perspective of technological change, this implies that the ‘search space’ for innovations becomes constrained, and that the generation of new ideas and technologies is shaped by the expectations and visions of technologists.

When positive expectations and visions of a particularly technology become widespread, they can make such technological developments more likely.

Scenarios, ‘visions’ and other foresight tools do not simply describe possible futures, they can also play a performative role in creating and shaping expectations about *the* future (Weber 2004). Indeed, many, although by no means all, studies of technology futures are explicitly intended to promote or legitimate a particular future (Phaal et al. 2004). Russell and Williams talk of visions as “resources” used to mobilise and shape expectations, which in turn enlist support, and help create momentum behind the technology (Russell & Williams 2003, p. 60).

It is not surprising then, that future visions become a rhetorical space in which present social battles are fought.

Multi-Criteria Appraisal

The idea of a single, shared vision of a ‘sustainable hydrogen economy’ is problematic. We have already noted the way in which the future of hydrogen is a contested rhetorical space, in which social groups with different agendas and interests compete (see also Eames et al 2006). There is no single and agreed definition of a ‘sustainable hydrogen economy’, and the deeply contested values embodied in the debate suggest that a consensus view of a sustainable hydrogen economy may be impossible. In practical terms, this means that a study attempting to articulate a desired future hydrogen economy must take very seriously the issue of whose desires are being expressed (Robinson 2003).

This implies a need for an open and transparent process in the building of scenarios, and using participatory approaches as a route to ‘social learning’ (e.g. Robinson 2003; Brown et al 2003). However, it also suggests that there is value in challenging the sustainability of the proposed visions in a more systematic and critical fashion. With a critical approach to the construction of visions, a backcasting study can go beyond helping policy makers to think strategically about the future. In addition, the process of articulating and challenging normative visions of the future becomes an opportunity for real deliberation and debate about social priorities with respect to new technologies. As Berkhout et al. (2004) argue, “*the real value of the notion of the “guiding vision”... does not lie, as is often implied, in its apparently unproblematic normative policy credentials. Quite the contrary: by focusing on the role of guiding visions, attention is concentrated on the importance of legitimate*

and effective deliberation and learning, and on the crucial role of providing for plurality, reversibility and sustained dissent.”

The challenge, then, is to find an approach to vision appraisal that recognises both the significant uncertainties involved in long-term futures, and the differing perspectives, values, and framings of the debate.

Recent debates within the field of environmental policy appraisal have highlighted the weaknesses of traditional approaches such as cost-benefit analysis, especially where “*the facts are uncertain, values in dispute, stakes high, and decisions urgent*” (Funtowicz & Ravetz 1994). Critiques of such approaches stem from recognition that they are closed to alternative problem framings, criteria definitions, and hence different social perspectives; that there is no uniquely rational way to aggregate different dimensions of value along a single metric; and that their treatment of uncertainty is frequently insufficient (Munda 2004, Stirling 1999).

Proposed alternatives to traditional technical appraisal include a broad array of multi-criteria, participatory, and deliberative techniques, all attempting to deal with what Vatn calls the problem of ‘institutionalising social choice’ (Vatn 2005). Many of these have been applied to problems in energy policy (Pohekar & Ramachandran 2004; Stagl 2006; Giampietro et al 2006). The uncertainties and contested values embodied in debates about the future of hydrogen make such approaches appropriate to the challenges of exploring and ‘opening up’ debates around the sustainability of possible hydrogen alternatives. The next section describes how a participatory multi-criteria tool was selected and adapted for use in this study with long term technological futures.

2. Methodology and Research Design: Combining Participatory Backcasting and Multi-criteria Analysis

2.1 Overview of the approach

An overview of the project stages is provided in figure 2.1, with the project areas discussed in this paper represented in black. Project elements in oval boxes involved the participation of external stakeholders.

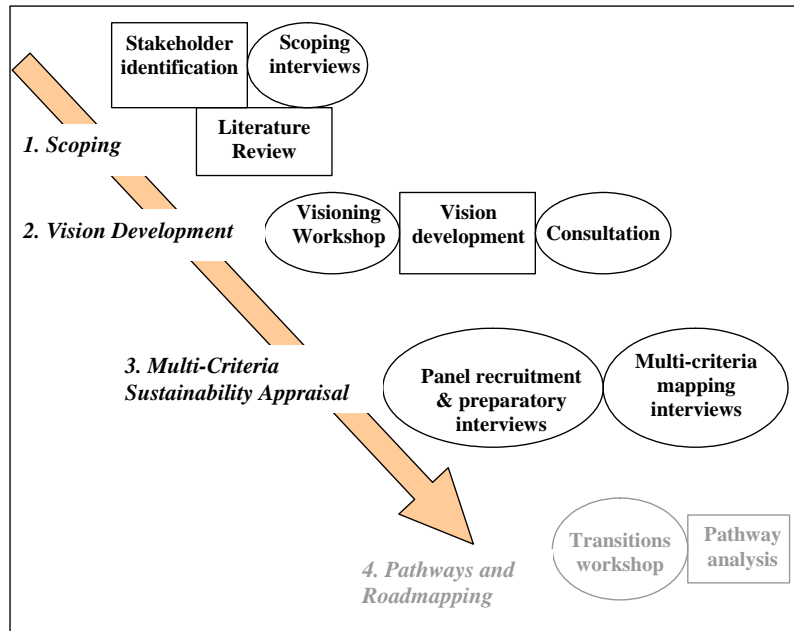


Figure 2.1 Overview of the UKSHEC Scenarios Project

2.2 Stakeholder involvement

Who takes part in a participatory process is clearly of fundamental importance to both the legitimacy and value of the outcomes. Identifying and engaging appropriate stakeholders, i.e. those with either relevant knowledge or an interest in the outcome of the appraisal process, is therefore critical. The focus of this current study has been to achieve broad transdisciplinary expert participation, rather than to involve lay citizens. Clearly wider publics have an interest in the future of hydrogen. However, resource constraints dictated a small engagement procedure, and it was felt that at this stage of opening up the debate to a range of more detailed views, expert contributions would be most relevant. Furthermore, our intention is to expose the visions to wider publics within the forthcoming social acceptability work stream of the UKSHEC project.

Stakeholders were identified through a review of membership of relevant UK steering groups, partnerships and networks associated with hydrogen energy, and through a process of ‘mapping’ the key areas of the hydrogen production, supply and end-use chains to ensure that participants from all relevant sectors were invited to take part in some form. Scoping interviews with key members of the ‘hydrogen community’ were also used to elicit views about who should be involved in the process. Efforts were made to ensure that there were sceptical, as well as enthusiastic, viewpoints represented in particular at the appraisal stage.

Different stages of the study required different levels of stakeholder engagement, commitment, and expertise. The ‘visioning’ workshop used to inform the development of the visions aimed to represent as wide a range of stakeholder opinion as possible, and involved more than 40 participants. The expert panel for appraising the sustainability of the visions was necessarily much smaller, involving 15 participants from a range of backgrounds. Participants were asked to take part as individuals with an informed background, rather than as representatives of their institutions. The purposive sampling approach used, which aimed to involve participants from a range of backgrounds, as well as the small number of participants, clearly means that the results from this work can not be extrapolated to the public at large, or even to the UK hydrogen community as a whole. Rather, the results of the appraisal provide insight into the range of arguments and perspectives, and illustrate the some of the more contentious issues at stake.

The expert panel comprised 15 individuals, all based in the UK, from a range of professional and disciplinary backgrounds.

- Nuclear Industry Expert
- Carbon Trust Analyst
- DTI Policy Maker (Department for Trade and Industry)
- Fuel Cell Industry Participant
- Sustainable Energy Consultant
- Industrial Gases Industry Participant
- Energy Technology Researcher
- Environmental Campaigner
- Health & Safety Regulator
- Energy Policy Researcher
- Senior Oil Industry Participant
- DfT Policy Maker (Department for Transport)
- Automotive Industry Participant
- Regional Government Policy Maker
- Climate Scientist

2.3 Constructing the visions

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.

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 principally defined in terms of technologies and infrastructures, so that the appraisal will reflect views on technological systems, rather than simply on the desirability of particular social worlds¹.

¹ Given what we know of the co-evolution and co-construction of socio-technical systems, this distinction is obviously problematic, as technologies and social values are inevitably and intimately intertwined. However, in terms of the scenario writing process it is a useful distinction to bear in mind.

In September 2004, the 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
- systems diagrams providing pictorial representations of each vision

The credibility, transparency 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. Clearly, the technologies making up the visions could be configured in a wide variety of ways, and not all possibilities are outlined in the vision set. Rather, the aim has been to cover the range of possibility found in debates around hydrogen. This implies a need for care in the interpretation of the results, to ensure that the inclusion of a technological component seen as unsustainable by the panel does not lead to the rejection of other components within the same vision.

Furthermore, the six future visions in this study are not intended as predictions. The technologies they comprise could be configured into a wide range of possible future hydrogen systems, and hybrid systems, involving some components of a number of visions, may be much more likely. Instead, the visions are intended to cover the broad range of possibilities in a manageable number of visions. The aim is to promote thinking about the sort of systems that are desirable and achievable in the long term, and to open up discussion around how different hydrogen systems might meet sustainability objectives. This means that the results cannot be seen as advocating or endorsing any one of the visions alone, but they are rather to be thought of as tools for learning about the important technologies, issues, and uncertainties that surround the hydrogen debate.

The full hydrogen visions are outlined in section 3.

2.4 Multi-Criteria Mapping

A wide variety of methods exists for participatory multi-criteria appraisal (for a review see DLTR 1998, or Pohekar and Ramachandran 2004 for applications to energy). Davies et al (2003; p. 31) recognise this proliferation of methods, and while noting a growing body of good practice, identify a need for 'fit-for-purpose' techniques.

The long-term and uncertain nature of the visions, the contested values underlying different perspectives, and the need for any appraisal to open up the debate beyond narrow technical concerns, implied a need for a method that allows participants the space to frame their own appraisal, rather than provide narrowly defined inputs into a pre-determined decision structure. Furthermore, an approach aimed at opening up different perspectives on the debate should not seek to create consensus where none exists, but should seek to highlight the reasons and values underlying any conflicts.

Multi-criteria mapping (MCM) is a method developed by Stirling with an emphasis on capturing alternative framings and value-based perspectives (Stirling & Mayer 1999, Stirling 1999). The

approach is based on the understanding that there is not necessarily a single ‘best’ solution, or as Stirling puts it: “*the aim is to explore the way in which different pictures of strategic choices may change, depending on the view that is taken – not to prescribe a particular ‘best choice’.*” (Stirling, 2005). Multi-Criteria Mapping thus maps the sensitivities of performance according to different perspectives, uncertainties and framing assumptions.

The MCM Process

In terms of process, MCM is conducted through a series of two to three hour, one-to-one interviews with expert stakeholders, using a dedicated software package developed at SPRU (for details of the interview procedure, see the MCM Interview Protocol, Stirling 2004). Interviews were recorded and transcribed, providing a rich source of information on participants’ deliberations, reasoning and arguments. A brief overview of the method is outlined below, and further details are available from the MCM Manual (Stirling 2004).

The interview takes the participant through a structured series of stages, as illustrated in figure 2.2.

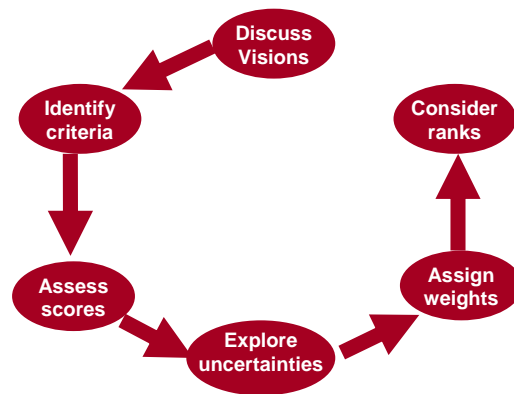


Figure 2.2 The Multi-Criteria Mapping Process

- ❑ *Discuss Visions.* At this stage, participants are invited for general comments about the set of visions, and are invited to introduce any that they feel are missing from the appraisal.
- ❑ *Define Criteria.* Participants define their own criteria, and discuss exactly what is meant by each criterion. Two kinds of criteria are possible: *criteria* under which the visions are scored relative to each other, and *principles* on the basis of which a vision is either acceptable or unacceptable.
- ❑ *Assess Scores.* Participants go through each criterion, and give each vision a performance score under that criterion. Scores are made on an arbitrary scale – it is the intervals between scores, rather than absolute values, that matters. Participants use any scale with which they feel comfortable, typically 1-10 or 1-100, with higher scores indicating better performance. It should be noted that even where good quantitative data are available, it is not possible to use these data directly, since scores represent the degree to which one vision is *preferred* to another, under a particular criterion (Stirling 2004, p. 21). This clearly involves some degree of subjective judgement.
- ❑ *Explore Uncertainty.* During scoring, participants are asked to provide not one score but two, the first on the basis of most optimistic assumptions, the second under pessimistic assumptions. This captures the degree of uncertainty and variability around the performance of particular visions under a given criterion. Participants are asked to talk about their

assumptions behind these different scores, and this qualitative data is recorded and transcribed. This captures *uncertainty* about how well the vision will actually work, *variability* within the vision (use of more or less of a particular supply option, for example), and *sensitivity* to wider context conditions, such as future natural gas prices.

- *Assign Weights.* Once scoring is complete, participants record their perceptions of the relative importance of different criteria in ranking overall vision performance.
- *Consider Ranks.* Finally, the software produces a visual ‘map’ of the rankings of the visions, using a weighted sum method. Participants can see the overall picture that their appraisal has produced, and are invited to reflect on whether this appears to conform to their initial expectations and feelings. If not, participants can make a back-up of the original appraisal, and explore other weighting schemes, or revisit their criteria and scoring. This is not an attempt to ‘fix’ the results, but to allow participants to confront possible inconsistencies in their appraisal, or areas that they feel they may have underplayed or overplayed.

For this study, the qualitative material was transcribed and explored using NVivo (a qualitative research software tool), while the quantitative outputs were analysed with MCM Analyst, a bespoke software tool developed at SPRU.

Adapting the MCM tool for use with long-term futures

Previous applications of the MCM approach have involved the appraisal of technological options, and the approach has not previously been used to appraise long-term futures in the context of a backcasting exercise. As a result, some amendments to the technique were necessary.

First, in previous MCM work the options assessed are elicited directly from the expert participants. In this exercise, the core set of visions to be assessed were the product of the extensive stakeholder consultation process set out above. However, in order to ensure that significant futures were not arbitrarily excluded, participants in the expert panel were offered the opportunity to add additional visions for assessment during their individual MCM interviews.

Second, MCM has in the past avoided imposing any sort of ex ante grouping of issues or criteria, in an attempt to keep the process of appraisal as open as possible. In the current study, which explicitly attempted to appraise sustainability, a set of ex ante criteria groupings were used to prompt participants to consider the classic elements of sustainability: environmental, economic, and social issues; as well as an important aspect of energy policy in particular: energy security. In order to avoid restricting the framing of the appraisals to these categories, participants were invited to identify criteria outside that framework (in an ‘other’ category) if they felt it appropriate, and were also invited to work outside of those putative criteria groupings if they felt it did not reflect their views.

Third, the appraised scenario set, in addition to the six visions outlined in section 3, contained a ‘status quo’ or reference scenario, describing the current systems for energy and transport in the UK. This was also appraised, as a way of providing a benchmark comparison for the different visions.

Finally, the plausibility and sustainability of different visions are inevitably contingent upon implicit framing assumptions about the wider future, e.g. framing assumptions concerning geopolitical and social stability, rates of climate change, resource availability and fuel prices, and so on. While an MCM study attempts to record such framing assumptions, these are often implicit and remain tacit. In order to more fully explore participants’ framing assumptions, at the end of the interview participants were therefore confronted with a pair of external “sideswipe” scenarios - *rapid climate change* and *sustained oil and gas crisis*, that would challenge tacit assumptions about

the wider contexts in which the hydrogen visions might sit. After reading through these, participants were asked for brief comments on how such a scenario might change their appraisal, both in terms of the criteria selected, the performance of visions under those criteria, and the relative importance of criteria. This allowed the investigators to explore, albeit it in a brief, qualitative fashion, the importance of tacit framing assumptions in the appraisal, and the robustness of the ‘desirability and plausibility’ of the visions in the light of these relevant major uncertainties. The opportunity to explore the importance of such sideswipes or surprises is often cited as one of the advantages of scenario approaches, although in practice, surprises are rarely explored (Van Notten et al 2005).

Box 2.1. Description of sideswipe scenarios

Rapid Climate Change

Draws on a scenario developed for the Pentagon by Peter Schwartz and Doug Randall (2003).

In this scenario, the most pessimistic assessments of climate scientists are borne out. By 2010, a sharp increase in ‘extreme weather events’ has become obvious. At the same time, evidence is mounting that the thermohaline cycle that powers the Gulf Stream is collapsing, bringing significant cooling to Northern Europe, along with a marked decline in precipitation. By 2015, climate scientists and forecasters are facing new challenges, as the models and simulations developed over decades are inadequate to deal with increasingly unpredictable patterns. As a result of the Gulf Stream collapse, Europe is hardest hit by climatic change, and in particular Scandinavian countries struggle to stem emigration, as life becomes increasingly difficult. Elsewhere, in Siberia and Northern Canada, warming leads to the melting of tundra, which starts to release large quantities of carbon dioxide and methane, contributing to a climatic feedback. Melting icecaps and reduced snow cover also contribute to feedback by reducing the earth’s albedo. By 2020, disruptions to food supply are causing widespread conflict and suffering.

Sustained Oil and Gas Crisis

Draws on US National Intelligence Committee scenarios for the Middle East and Eurasia (NIC 2004), and the Japanese METI’s *Critical scenario*; METI 2001).

While oil shortages per se, as predicted by some geologists (e.g. Campbell), do not occur, oil flow problems and market uncertainty arise from conflicts in oil regions, and rapidly rising demand in Asia. The US democratisation experiment in Iraq is a failure, with Iraq becoming a long-term failed state, mired in civil war. Increasing Islamic fundamentalism finally erupts into revolution in Saudi Arabia, and while conflict itself is short lived, confidence in the oil industry is severely damaged, as is oil infrastructure. In Iran, the deeply unpopular theocracy is finally toppled leading to long-term internal conflict as the new government struggles to contain fundamentalist counter-coups, creating further shocks and uncertainty in oil and gas markets. Russia continues its slide into poverty, economic stagnation, and energy resource dependence, and a xenophobic backlash in around 2015 mirrors that of Iran in 1950-1953, when the oil industry was seen as a symbol of national subjugation by foreign powers and corrupt oligarchs. Continuing instability in other oil & gas producing states, including Nigeria, Venezuela, and those in Central Asia and the Caucasus, lead to an oil price that fluctuates unpredictably around an average \$100/bl, never falling below \$40/bl between now and 2050.

3. Visions of a Hydrogen Economy for the UK

As outlined in section 2.3, the construction of the UKSHEC hydrogen visions drew on the existing hydrogen futures literature, and on a stakeholder workshop in September 2004. This section presents the six visions, with a summary in Box 3.1 followed by the full description as presented to the expert panel. Full details of the development of the visions can be found in Eames & McDowall (2005).

Box 3.1 Headline Summary of the UKSHEC hydrogen visions		
Transport Futures (hydrogen only used as a transport fuel)	Central Pipeline	Hydrogen has become the dominant transport fuel, and is produced centrally from a mixture of clean coal and fossil fuels (with C-sequestration), nuclear power, and large-scale renewables. Hydrogen is distributed as a gas by dedicated pipeline.
	Forecourt Reforming	Hydrogen produced locally from natural gas is the dominant road transport fuel. The existing natural gas network provides the delivery infrastructure, and hydrogen is generated on-site by steam methane reforming at the refuelling station.
	Liquid Hydrogen	Liquid hydrogen produced by nuclear power and large scale renewable installations has become the dominant transport fuel. There is an international market in liquid hydrogen. This is largely a scenario of substitution, with current energy and transport paradigms remaining unchanged.
	Synthetic liquid fuels	Renewably produced hydrogen again provides the dominant transport fuel. In this case, however, it is 'packaged' in the form of a synthetic liquid hydrocarbon, such as methanol, to overcome the difficulties of hydrogen storage and distribution. The carbon for fuel synthesis comes from biomass and from the flue gases of carbon-intensive industries.
Transport & Energy Services Futures	Ubiquitous Hydrogen	Gaseous hydrogen is not only the dominant road transport fuel. Many buildings also use fuel cell CHP systems running on hydrogen. Distributed renewable generation predominates, reducing need for long distance transmission and distribution, and allowing hydrogen to compete directly with electricity as the main energy vector for the provision of domestic and commercial heat and power. Regional grids of hydrogen pipelines connect (predominantly local) hydrogen supplies with local needs.
	Electricity Store	Hydrogen is not only the dominant road transport fuel, it also plays a vital role providing distributed energy storage to overcome the intermittency problems of renewable electricity generation. Hydrogen is produced locally in small scale electrolysis units for forecourt refuelling and onsite storage for use in domestic and commercial CHP units at times of peak electricity demand/limited supply.

These futures differ in relation to the end-uses of hydrogen, the means of hydrogen generation and storage, and the degree of centralisation/decentralisation of its production and supply. In terms of time scales, the intention is to imagine them far enough into the future that substantial infrastructural changes are conceivable, but not so far into the future that the technologies envisaged today will be obsolete. They have therefore not been constructed around an exact future date, but might nevertheless be thought of as located somewhere around the 2040-2050 mark.

The visions are differentiated according to the perceived role of hydrogen (as a transport fuel only, or as providing both transport and broader energy services), and the degree to which the system is centralised or decentralised.

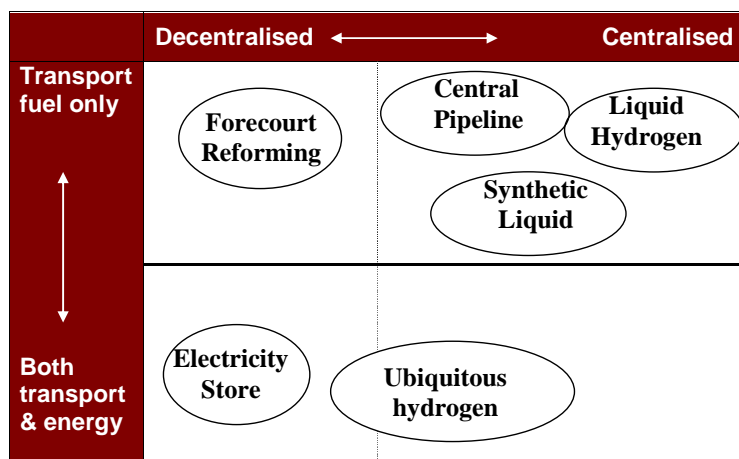


Figure 3.1 showing how the visions are differentiated

The *Synthetic Liquid Fuel* vision has been included as an ‘alternative’ type vision, exploring the possibility that renewable hydrogen can be packaged for use in a synthetic liquid fuel, that is easier to transport and store.

UKSHEC Hydrogen Visions

Vision 1. Central Pipeline

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

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

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

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

Key technologies:

- Onboard (compressed or solid state) storage
- Fuel Cell Vehicles

- Pipelines and stationary bulk storage
- Clean coal and carbon sequestration
- Thermal or thermo-chemical production of hydrogen in high temperature reactors
- Large scale electrolysis

Vision draws on: E4Tech *et al.* (2004), Ogden (1999), interviews. This centralised, gas-based future was a feature in the visions workshop, particularly from the group focused on energy security (McDowall & Eames 2004).

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

- Coal gasification: 40.6 million tonnes of coal, or 76% of UK coal consumption in 2003, *or*
- Steam methane reforming: 250TWh, or 23-25% of UK gas consumption in 2003, *or*
- 32 Sizewell B sized nuclear power plants (1.2GW; data sources assumed electrolysis rather than thermal routes), *or*
- 27,700 3MW wind turbines (compared to 1,200 wind turbines currently installed in the UK)

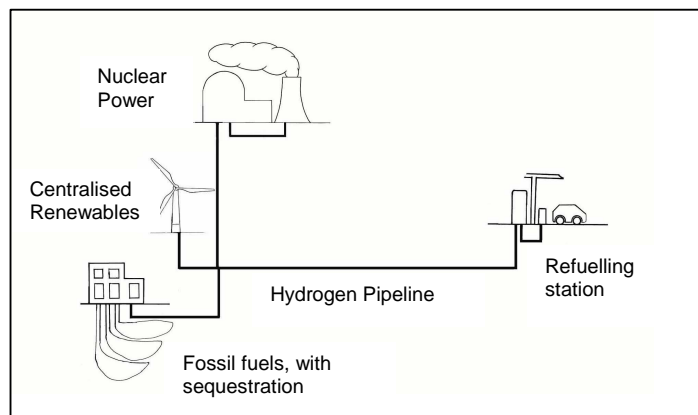


Figure 3.2 Central Pipeline

Vision 2. Forecourt Reforming

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

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

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

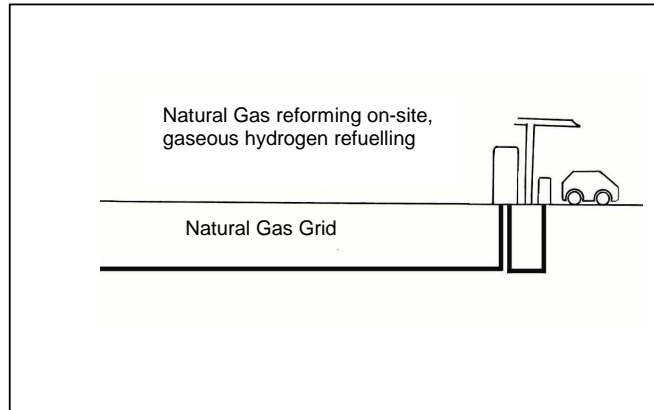


Figure 3.3 Forecourt Reforming

Key Technologies:

- Small scale natural gas reformers
- Onboard (compressed or solid state) storage
- Fuel Cell Vehicles

Vision draws on: interviews, workshop participants in the UK competitiveness group (McDowall & Eames, 2004)

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

Vision 3. Liquid Hydrogen

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

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

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

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

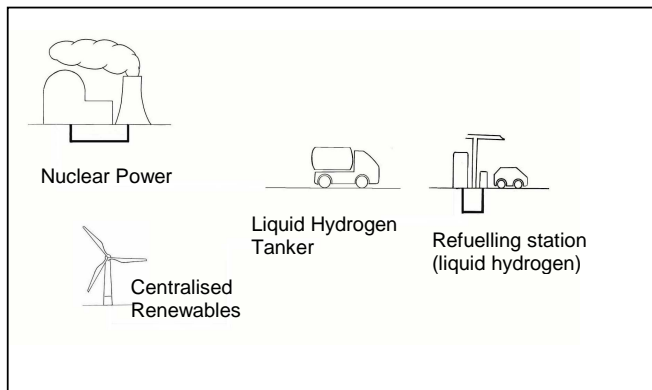


Figure 3.4 Liquid Hydrogen

Key technologies:

- Liquid hydrogen storage
- Direct solar hydrogen production
- Cryogenic technologies
- New nuclear power
- Fuel cell vehicle

Vision draws on: BMW (2004), Ogden (1999).

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

Vision 4. Synthetic Liquid Fuels

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

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

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

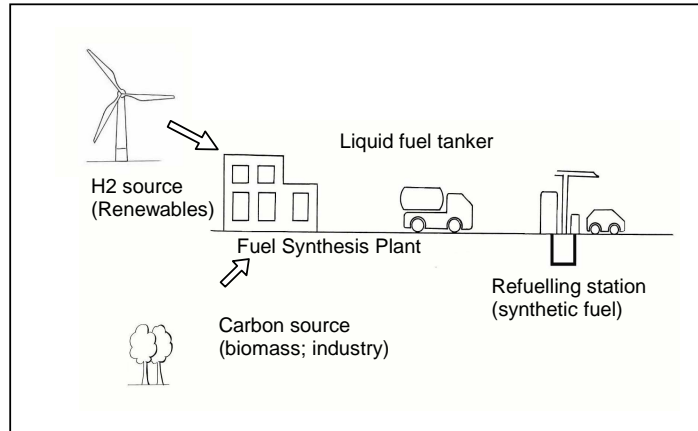


Figure 3.5 Synthetic Liquid Fuel

Key Technologies:

- synthetic liquid fuel production

Vision draws on Bossel *et al.* (2003); Arnasson & Sigfusson (2000).

No wells-to-wheels energy data were found for this pathway, though a recent feasibility study claimed that up to 62% of the renewable electricity input can be stored as methanol (Mignard et al 2003).

Vision 5. Ubiquitous Hydrogen

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

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

Hydrogen is produced both centrally and locally, using a variety of technologies, with a significant proportion from distributed renewables (such as wind turbines and building-integrated PV) and biomass (such as wood from short rotation coppice and forestry, agricultural, food industry and municipal waste streams via gasification, and from 'wet biomass' such as grasses and sewage sludge via fermentation). Large scale renewable hydrogen installations operate in renewable-rich areas (e.g. highland Scotland, and offshore zones with wind, tidal, and wave power potential), and some limited fossil fuel production of hydrogen with sequestration of CO₂.

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

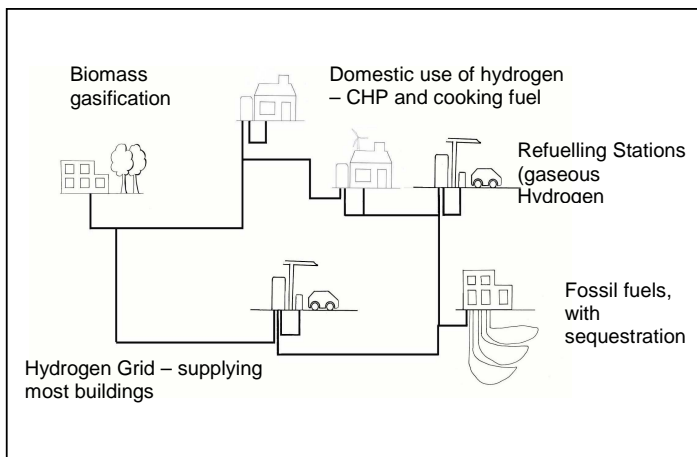


Figure 3.6 Ubiquitous Hydrogen

Key Technologies:

- Pipelines & stationary bulk storage
- ‘Smart’ networks
- Hydrogen CHP (probably SOFC)
- Onboard (compressed or solid state) storage
- Fuel Cell vehicles

Vision draws on: Rifkin 2002, Lovins & Williams (1999)

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

- 47-57 millions tonnes of dry short rotation coppice biomass, about 4.7-5.7 million hectares, assuming average yield of 10 tonnes per hectare, or between ¼-½ of the UK’s agricultural land including grazing land, *or*
- 27,700 3MW wind turbines

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

Vision 6. Electricity Store

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

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

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

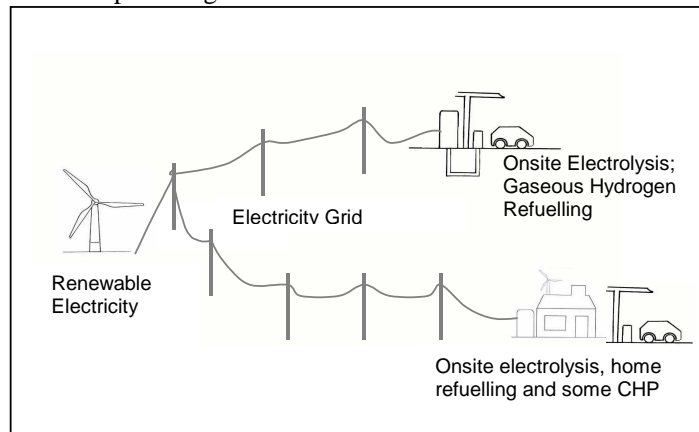


Figure 3.7 Electricity Store

Key technologies:

- Small scale electrolysis
- Onboard and small-scale stationary (compressed or solid state) storage
- ‘Smart’ networks
- Hydrogen CHP
- Reversible stationary fuel cells

Vision draws on: interviews, Sorenson *et al.* This future came through strongly from the workshop group focused on climate change (McDowall & Eames, 2004). The Energy White Paper: “*Fuel cells also have the potential to help renewables produce more stable supplies. Hydrogen can be generated when electricity demand is less than that being generated by the renewable energy source. This can then be converted to electricity via the fuel cell when electricity demand exceeds that being generated by the renewable energy source.*” P. 58

If transport demand remains much as it is today, this future would require around 27,600 3MW wind turbines, for transport alone. There are currently 1,200 wind turbines in the UK. Clearly significantly more capacity would be required for the heat and power loads envisaged in this future.

Status Quo Vision

In addition to the six visions, the following ‘status quo’ vision was included for the purposes of appraisal.

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

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

4. Results: Appraising the Sustainability of Hydrogen Futures

This section gives an overview of initial results and outputs from the multi-criteria appraisal. It is comprised of four parts, the first of which describes participants' engagement with the process, and their responses to the visions, criteria development, scoring and weighting. The second part then explores the picture of rankings that the MCM analysis has produced, and discusses rankings in terms of the major criteria and issues. Part three reports the patterns of uncertainties and dependencies on which the rankings depend. Finally, the fourth part explores how this ranking picture changes under different perspectives, by grouping participants' appraisals first in terms of their institutional backgrounds, and then in terms of the attitudes towards the dynamics and social implications of technology.

4.1 Engagement with Process

Visions

In general participants were happy to appraise the set of futures developed. None felt that major elements of a possible hydrogen future were obviously missing. One participant defined an additional vision, while a further two explored hybrids of two of the UKSHEC visions. These additional visions are described in the box below.

Box 4.1. Additions to the Six UKSHEC Visions

The *Health and Safety Regulator* introduced a vision based on the European 'Natural-HY' research project. This vision involves the use of hydrogen from a range of centralised sources, including nuclear power, natural gas reforming, and coal gasification with sequestration of the carbon dioxide. Hydrogen is then injected into natural gas grids for distribution. Natural gas-hydrogen blends are used directly in domestic boilers and gas cookers, and hydrogen is separated from natural gas to fuel vehicles. The *Carbon Trust Analyst* also raised this as relevant for the transition to one of the visions, but not as a viable vision in itself: "rather than it being a final scenario, what's the role ...in the transition"

The *Automotive Industry Participant* introduced a hybrid between *Liquid Hydrogen* and *Ubiquitous Hydrogen*. In this vision, local renewable hydrogen supplies local heat and power needs, much as in *Ubiquitous Hydrogen*, but where there is insufficient local resource, liquid hydrogen imports would satisfy transport energy demand. It was argued that alone, the *Liquid Hydrogen* vision did not adequately represent the strengths of using liquid hydrogen in vehicles, as it ignored heat and power markets.

The *Environmental Campaigner* introduced a hybrid between *Electricity Store* and *Ubiquitous Hydrogen*, to emphasise perceived synergies between the dual electricity and hybrid networks. As with both *Electricity Store* and *Ubiquitous Hydrogen*, the emphasis was on renewable sources of hydrogen.

The *Sustainable Energy Consultant* and the *Industrial Gases Industry Participant* had concerns over the apparent arbitrariness of the inclusion or exclusion of particular primary energy pathways from particular infrastructures. The *Automotive Industry Participant* also had concerns about the

consistency of comparing transport-only futures with those that saw wider roles for hydrogen. However, none felt that these constrained their ability to participate in their appraisal.

There were two common reservations about the set of futures.

- The first concerned the way in which the visions were framed, as most felt that the most likely future would be some sort of hybrid or mix of the visions presented, and that the futures were artificially parcelled up. While most participants acknowledged that this was an inevitable feature of using scenarios, at least one felt that by dividing up hydrogen futures, the project would downplay the versatility of hydrogen in a diverse energy system, which was felt to be one of its key strengths.
- The second was a general problem with considering only a ‘snapshot’ in the long-distant future, rather than considering the transition route by which a future was obtained, or the strategies through which such a future might be brought about. This may be partly because the participants are accustomed to evaluating strategies and policies, but are not so used to evaluating possible alternative goals. Several found this difficult.

The scenarios contain significant scope for interpretation. This meant that participants were not always focusing on the same elements of each of the visions, sometimes making direct comparison of their appraisals problematic. For example, under various criteria relating to local environmental impacts, some participants focused on the implications of downstream hydrogen use in transport, while others concentrated on the upstream implications of the primary energy mix. This of course reflects the dynamics of wider public debates about energy, with different interests, groups and analysts focusing on different areas of likely or plausible futures. However, it does mean that aggregation of different individuals appraisals must be conducted with caution.

Several participants clearly identified ‘favourites’ (or least favourites) during the process of talking through the details of the visions, in advance of considering criteria and scoring. The *Energy Technology Researcher*, commenting on *Forecourt Reforming*, exclaimed: “*this is what I’m afraid of*”, but saw it as potentially one of the most likely. The *Regional Government Policy-Maker*, commenting on *Central Pipeline*, said “*the cynic in me thinks we’ll end up doing that*”. This tendency for participants to bring prior prejudices to appraisal is to some extent inevitable in a participatory approach.

Specific comments on each of the visions prior to appraisal

The following provides a summary of participants initial discussion of the visions, prior to undertaking the appraisal, and reflect the general sense of the extent to which the visions were considered plausible and attractive.

Central Pipeline. All participants recognised this future as playing a well established role in hydrogen debates. For some, it is the most straightforward system, with the only difficulty being the large upfront infrastructure requirement. As the *Senior Oil Industry Participant* put it: “I think this is one of the more credible scenarios. The idea that you’re going to have a grid linking the centralised sources is, I think is absolutely right”. For others, it represents a perpetuation of the kind of ‘big energy’ solutions that have failed in the past, and have had negative social and environmental consequences. Three participants felt that, if hydrogen was being supplied by pipeline for transport, then it would probably be used for stationary power as well. The *Carbon Trust Analyst* said that “Central pipeline means that hydrogen is available at a large scale in nodes, that has an obvious fit with transport infrastructure, hydrogen stations etc. But it does actually suggest that there are other roles for hydrogen? For instance as despatchable load. So if you’ve got that much hydrogen available at that price, yes transport would be likely to be the biggest use for it, but others would be willing to pay for it”. In contrast, the *Sustainable Energy Consultant* was highly

sceptical that hydrogen fuel could be delivered at a cost that would enable it to compete with grid electricity in stationary applications.

Forecourt Reforming. Eight participants saw this as having little role as a viable ‘end-point’ vision, but spoke of it as having a valuable role to play as a transitional step in terms of infrastructure development. The *Regional Government Policy Maker* said that “I mean this is certainly something I think we should do now, but it wouldn’t be where I’d want to end up.” However, there was some support for it as an ‘end point’ vision. The *Sustainable Energy Consultant*, for example, commented that “It might even be an end stage. Well, a twenty-fifty end stage where we still have natural gas and we want to make as efficient use of it as possible”. An interesting feature of this vision was the debate over its practicality, with the panel showing sharply opposing views on the feasibility of widespread distributed natural gas reforming. This question is revisited in section 4.3.

Liquid Hydrogen. Several participants felt that this was one of the least likely, or most incomplete, visions presented in the set. While the rationale for including it was generally accepted, several felt that this vision, as presented, was not a serious candidate for a hydrogen future. This was mostly clearly summed up by the *Sustainable Energy Consultant*, who said simply “I don’t buy it”. However, the technologies within the vision were all felt to be relevant and worth exploring. The *Industrial Gases Industry Participant* felt it was not likely, but broadly plausible: “the technology’s known, it’s a current way of distributing hydrogen, ... if you can justify the investment in the plant and you know there’s a market there, then... It doesn’t seem unreasonable to me.” The feeling overall seemed to be that while liquefied hydrogen is likely to play an important role in the distribution and storage of hydrogen in some circumstances, the sole use of liquid is unlikely. The *Health and Safety Regulator* challenged the rationale for the vision, which in part was based on the possibility of a failure of gaseous or solid hydrogen onboard storage systems to improve, by arguing that the automotive industry seemed to be producing prototypes with adequate range (250 miles). The Senior Oil Industry Employee argued that the great advantage of liquid hydrogen is its purity, and that unless fuel cells can be made more resistant to poisoning, purity concerns may close off some routes.

Synthetic Liquid Fuel. Unlike the other visions, this was new to many of the participants, but in general it was thought to be an interesting addition to the overall set. The *Industrial Gases Industry Participant* and the *Regional Government Policy Maker* both felt that it was not plausible, given the apparent direction of automotive firm R&D, which was seen to have ‘turned its back’ on synthetic fuels such as methanol. The *DTI Policy Maker* had been sceptical at the scoping interview stage, but was more positive in the MCM interview: “I was sceptical because... all the vehicle manufacturers seem to be assuming gaseous hydrogen as storage or possibly solid-state hydrogen storage as being the means of introducing fuel cell vehicles. Having looked at the arguments for synthetic liquid fuels, I think there’s definitely a case to be made there.” Six participants expressed some unease at the likely carbon balance of the vision.

Ubiquitous Hydrogen. Opinion on this vision was sharply divided, and in the words of the *Carbon Trust Analyst* it was seen as the “most interesting and most complex of the [visions]”. The *Sustainable Energy Consultant* described this vision as “a pipedream”, a basically nice-looking but ultimately implausible future, because of the thermodynamic and efficiency issues around distributing energy for stationary applications as hydrogen. For others, it is the most obviously sensible and desirable system. The *Energy Technology Researcher* felt that this future required most innovation, and that it was possibly the least plausible, without a major natural gas crisis. The *Fuel Cell Industry Participant* drew parallels between *Ubiquitous Hydrogen* and the old town gas system, only with locally appropriate low-carbon resources. A common attitude to this vision summed up by the *DTI Policy Maker*, who commented that “it’s credible when there aren’t really any alternatives left”.

Electricity Store. All participants recognised this as a major part of the hydrogen debate. Most saw it as only viable in the very long term, given its reliance on renewables, and the *Industrial Gases Industry Participant* and *DfT Policy Maker* were concerned that pursuit of this vision would lead to less efficient use of limited renewable electricity supplies. Some participants (including the *Automotive Industry Participant*, the *Senior Oil Industry Participant*, the *Regional Government Policy Maker*) felt that a likely amendment would be to have some hydrogen distribution by truck or pipeline in addition to the onsite generation from electrolysis, but accepted that this was the dominant feature of the vision. The *Nuclear Industry Expert* felt that the inclusion of nuclear power in this vision would make it more robust and more feasible.

Criteria

Between them, the 15 members of the expert panel defined a total of 98 criteria, of which many seemed to be very similar across different participants (e.g. various criteria exploring carbon emissions and security of supply), reflecting the dominant concerns frequently discussed in hydrogen debates. Of all the criteria against which the visions were scored, only one was treated as a matter of principle. The *Environmental Campaigner* could not countenance any vision involving the use of nuclear power. In addition, at least two others considered ruling out nuclear power. The *Regional Government Policy Maker* considered ruling out on principle anything involving nuclear power or carbon capture and storage, but ultimately decided that the issues associated with these would come out clearly through scored criteria. The *Energy Policy Researcher* commented that “I don’t think really with climate change you can rule anything out on principle.... I think it would be very nice to say you should rule out nuclear power. I just don’t think you can”.

Under ‘social’, seven of the participants considered only social acceptability – and the way in which this was defined and scored suggested it was often seen as a feasibility barrier rather than a broader component of sustainability. This reflects assumptions about the nature of social resistance to technological change.

All participants developed a criterion that in some way reflected the performance of the visions in terms of global climate change, and all but the *Climate Scientist* also developed at least one criterion looking at other aspects of the environmental performance of the vision.

For many participants, the selection of criteria shows the extent to which the debate around hydrogen is shaped by (UK) government policy priorities; the oft-repeated ‘drivers’ for hydrogen: climate, security, and air quality; and the main barrier, cost. Indeed, some participants’ appraisals included only criteria that are included in current policy objectives related to hydrogen, unlike previous applications of MCM (e.g. Stirling & Mayer 1999), which have found that most participants include criteria that go well beyond existing policy appraisals.

Although many of the criteria appear to overlap, some of these have subtle differences in emphasis. More easily measurable criteria, such as those predominantly dealing with greenhouse gas emissions, were relatively consistently defined across participants, although even here there were some differences (between ‘global impacts’ and ‘carbon emissions’, for example). Others, such as costs and security, exhibited a wider range of criteria definitions. For example, the precise definitions of ‘energy security’ criteria included differences around the importance of diversity of supply, or the security profile of particular fuels, or the reserves of fuel available within the UK

Table 4.1 Showing full list of criteria

Participant	Criteria Group	Criteria
Nuclear Industry Expert	Environmental	GHG Emissions
		Local air quality
		Toxicity
		Visual impact
	Social	Socio-political acceptability
	Economic	Affordability of h2 fuel
	Energy Security	Security of primary supply
		Diversity of primary energy sources
Other	Quality of supply (in terms of day to day level of service)	
	Technical feasibility & potential	
Carbon Trust Analyst	Environmental	Global Impacts
		Regional Impacts
		Local Impacts
	Social	Access to energy services
		Public acceptability
	Economic	Cost of fuel
		Impact on UK Economy
	Energy Security	Degree of consumer choice
Security/diversity		
DTI Policy Maker	Environmental	Carbon Emissions
		Other environmental Issues
	Social	Social acceptability
	Economic	Impact on UK economy
		Impacts on local economy
	Energy Security	Security
Other	Health and safety	
	Feasibility	
Fuel Cell Industry Participant	Environmental	Carbon Emissions
		Local air quality
		Other environmental impacts
	Social	Social acceptability
	Economic	Fuel Cost
		Business case feasibility
Energy Security	Supply Security	
Sustainable Energy Consultant	Environmental	Cost effective Carbon Reductions
		Local environmental impact
	Economic	Upstream Energy Security
		Economic Attractiveness
Industrial Gases Industry Participant	Environmental	Carbon Emissions
		Local Air quality
	Economic	Upfront capital costs
		Ongoing fuel cost
	Energy Security	Security of supply
Energy technology researcher	Environmental	Greenhouse Gas
		Local Air Quality
		Other environmental impacts
		Biodiversity
	Social	Public Acceptability
	Economic	Cost
Energy Security		Resource Scarcity
	Diversity of supply	
Environmental Campaigner	Environmental	Greenhouse Gas
		PRINCIPLE: Nuclear Free Futures Only
	Economic	Cost
		Other
	Flexibility	
	Upheaval	
Geo-political issues		
Health and Safety Regulator	Environmental	Greenhouse gases
		Non-carbon pollution
	Social	Public acceptability
Other	Practicability/feasibility	

		Flexibility
Energy Policy Researcher	Environmental	Carbon Emissions trajectory
		Natural Environment/wilderness
		Catastrophic risk
	Social	Social Justice
	Economic	Least cost portfolio
	Energy Security	Primary supply
		Infrastructure
Other	Radioactive Waste	
	Complementarity	
Senior Oil Industry Participant	Environmental	Energy Efficiency
		Physical integrity
	Social	Physical intrusion
		Control of energy
		Usability
	Economic	Affordability
Energy Security	Diversity of sources	
DfT Policy Maker	Environmental	Carbon
		Other environmental issues
	Social	Public acceptability
	Economic	Business case feasibility
Energy Security	Security of supply	
Automotive Industry Participant	Environmental	WTW Carbon
		Utilisation of available resources
	Social	Degree of state intervention required
	Economic	Economic feasibility
Energy Security	Security/diversity	
Regional Gov. Policy Maker	Environmental	Carbon
		Air quality
		Complementarity with renewables
	Social	Acceptability/risk
	Economic	Cost
Energy Security	Compatibility with decentralised	
Climate Scientist	Environmental	Global environmental improvement
	Economic	Cost competitiveness
	Other	Scale of tech deployment

The table shows criteria as they were grouped by the participants themselves during the interview.

Furthermore, several criteria could be viewed as multi-dimensional, and did not fit into any of the category groups in a straightforward way. The *Senior Oil Industry Participant* defined an ‘Energy Efficiency’ criterion, that was explicitly economic as well as environmental. The *Energy Policy Researcher* felt strongly that a ‘Radioactive Waste’ criterion must be social, political and economic, as well as environmental, and the same was true of a ‘Social Justice’ criterion.

Scoring

Many participants found scoring difficult – not conceptually, but because of the substantial uncertainties surrounding the performance of different visions under particular criteria. In particular, participants had difficulty scoring the visions on economic criteria (and had difficulty in defining appropriate economic criteria). This applied to both narrower criteria on the likely costs of particular systems, and some broader criteria about what impact the different systems might have on the UK economy as a whole. However, this was perhaps to be expected, given the long term and highly uncertain nature of the scenarios and the future worlds in which they would exist.

During scoring, several participants chose to delete criteria that had been defined earlier, because they felt that the criterion, though important, would be of little relevance in distinguishing between

the different visions. Some deleted criteria on the basis that the issues had been dealt with under a previous criterion.

Table 4.2 Showing criteria deleted by participants during scoring

Participant	Criterion deleted during scoring
Health and Safety Regulator	'cost to the user' was removed, on the basis that the assessment of a 'practicability' criterion had borne in mind potential costs.
Automotive Industry Participant	'other environmental issues', which had largely focused on air quality, was felt to be of little use in distinguishing among visions
DfT Policy-Maker	'cost' issues were removed, as they had been considered under 'business feasibility'
	A 'resilience' criterion was deleted, as this could be bundled with upstream energy security
Regional Gov. Policy Maker	'performance of system/quality of service' was felt not to be useful in distinguishing the visions.
Energy Policy Researcher	'Environmental Justice' criterion, as this was felt to be an important framework condition, rather than a criterion on which the visions could be distinguished.
Industrial Gases Industry Participant	'impact on the UK economy' was rejected, as it was felt that the uncertainties were equally overwhelming for all visions.

There were several examples of what might be considered strategic scoring, or subjective scoring, in which participants' justifications of particular scores were clearly influenced by the overall appeal of a particular vision (e.g. "*Oh, I quite like this one. Go for seven.*" and "*Yes, but... what I'm... sort of trying to plug... is our [organisation name] concept*")

Treatment of Uncertainty and Variability

Participants showed strong personal differences in the way in which they expressed uncertainty during scoring. In the face of very great uncertainties, four participants felt unable to provide a range, feeling that the best response was a single point¹. Two participants tended to use the optimistic and pessimistic scores to point out the strengths and weaknesses of the vision, rather than to explore performance under different assumptions. In general however, participants were happy to use the variable scoring to reflect the uncertainties and dependencies of the future performance of the visions. Discussion of how these uncertainties impact the overall picture of the results is presented in section 4.3.

Weighting

The overall picture of weightings² provides an overview of the groups of issues that participants judged to be most important. There is a clear tendency for environmental issues to receive high weightings, with social issues in general receiving much less attention, and with a substantial spread of views around the importance of economic criteria. It is also interesting to note the relatively high weights given to criteria identified in the 'other' category. This perhaps suggests that participants

¹ Similar scoring behaviour has also occurred in previous uses of the method (e.g. Davies et al 2003: 142).

² Note that, during the appraisal, participants were asked to concentrate on the relative performance of the visions, rather than to use an absolute scale. As a result, the x-axis of all charts denotes relative degrees (e.g. of performance, of weighting etc.), rather than absolute figures.

only introduced criteria outside the four defined categories when they felt that these were particularly important, whereas it may be that participants were prompted to add criteria that they felt were less important by the group headings such as ‘social’. The ‘other’ group included a very wide range of criteria, such as feasibility, physical intrusion, social justice, flexibility, and the degree to which the vision was seen as facilitating the development of renewables. For some participants, the ‘other’ group included key criteria that arguably best reflected their own personal approach to the framing of the appraisal, such as ‘radioactive waste’ for the *Energy Policy Researcher*, or ‘compatibility with renewables’ for the *Regional Government Policy Maker*.

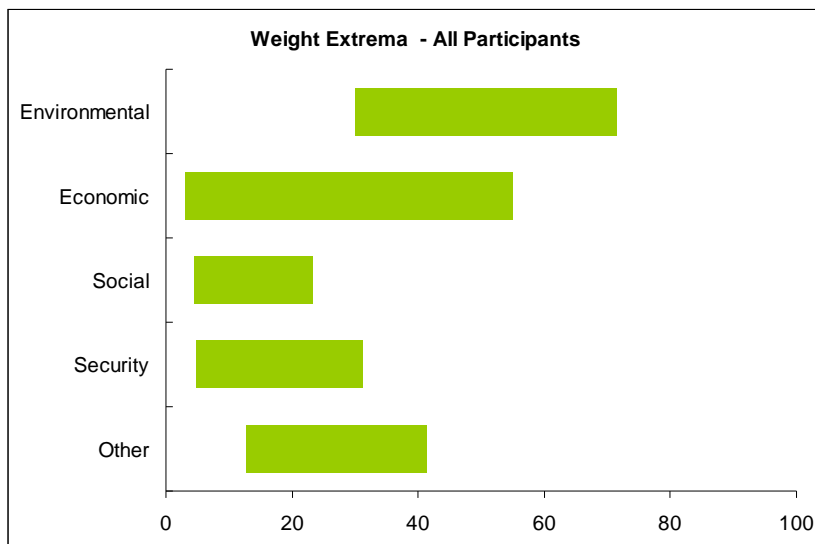


Figure 4.1 Showing criteria weightings. Bars represent the range between the lowest (furthest to the left) and highest weights given by any participant for that group of issues. Each participant distributed 100 importance ‘points’ among their criteria, to indicate relative performance.

Some participants clearly used weightings to respond to general issues, rather than to rate the importance of the criterion in question. Essentially, they used the criterion as a proxy for a whole suite of issues that had not been included during criteria definition and scoring. In one clearest example, the *Regional Government Policy Maker* was unhappy with the final ranking of visions. Looking back through the process, it became clear that the criterion ‘cost’, which in itself was not felt to be of overarching importance, was being used to represent broader economic concerns, and was thus given a high weight. This suggests a need to look carefully at how participants talked about importance and weighting issues throughout the process, as well as how they actually weight particular criteria. It also may reflect a more general tendency in appraisal – to make decisions on the basis of emblematic indices. This would represent a ‘rules-of-thumb’ approach to decision making, which may have interesting implications for appraisal.

Responses to the Sideswipes

The ‘sideswipes’ exercise was introduced as a methodological experiment and check for the robustness of the findings. Several participants commented that this was a worthwhile exercise. As the *Sustainable Energy Consultant* put it: “That was interesting. That was a useful thing to do. ‘Cos that was... outside the boundaries of the visions”.

In discussing the sideswipes, it was noteworthy that many participants felt the sideswipe scenarios were plausible, and not radically different from the futures they expected despite their somewhat extreme character. For example, one participant's response was:

Participant: "Yeah. Well, I... I sympathise strongly with the first one, the climate change one

Interviewer: For you, it's not a, not a radical surprise?

Participant: Not at all. (Laughs) unfortunately.

However, while many participants had recognised the importance of the threats embodied in the sideswipes during the appraisal, they had not taken into account the radically changed conditions that such sideswipes would imply. Rather, participants had explored future states in terms of current society's assessment of the importance of climate change and energy security. Their agreement with the sideswipes as plausible futures demonstrates their high levels of concern for these issues, but also demonstrates the difficulties of thinking through the implications of a radically altered future. Most participants felt that the sideswipes would alter the weightings that they had given to energy security and carbon emission criteria. Some noted ways in which conditions would change, for example:

Carbon Trust Analyst: I suppose the other scenario driver in this is sustained strategic intervention by governments, stockpiling, re-nationalisation, energy infrastructure, global trade patterns around things like gas, impact on historic relations between oil and gas prices...

Interviewer: Do you think that ties into willingness of governments to intervene in markets to pull through new technologies like hydrogen?

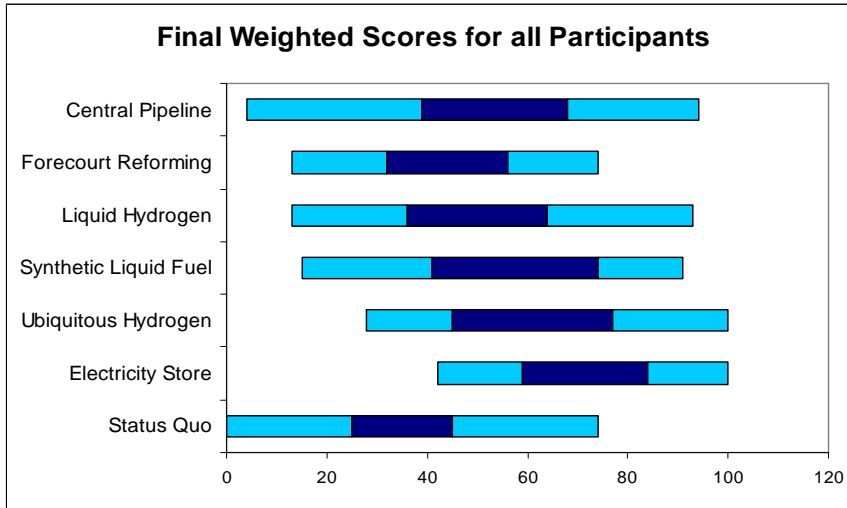
Carbon Trust Analyst: It could do. I mean its sustainability, security of supply, all become much more important under both of those [sideswipes]. Looking at these drivers, this would change the weights of that last exercise, security of supply, instead of being a '20 issue' would be an '80' issue."

Several participants felt that the sideswipes would increase the feasibility of a transition to a hydrogen future. For example, the *DfT Policy Maker* commented that at the moment the drivers for a transition are not really strong enough, but that the futures envisaged in the sideswipes represent "*a very different picture and then hydrogen becomes a lot more persuasive as an argument.*"

Some participants suggested that, while they had taken into account these radically different futures during their appraisal, other sideswipes might have had significant impacts on their approach, such as technological-breakthrough sideswipes, economic recession, or unexpectedly weak climate change. While there was not the time to explore these possibilities, the fact that they were raised suggests that the exercise did promote broader thinking about the background assumptions made in the appraisal, and that such interventions might be useful in exploring tacit expectations and framing assumptions in other futures studies.

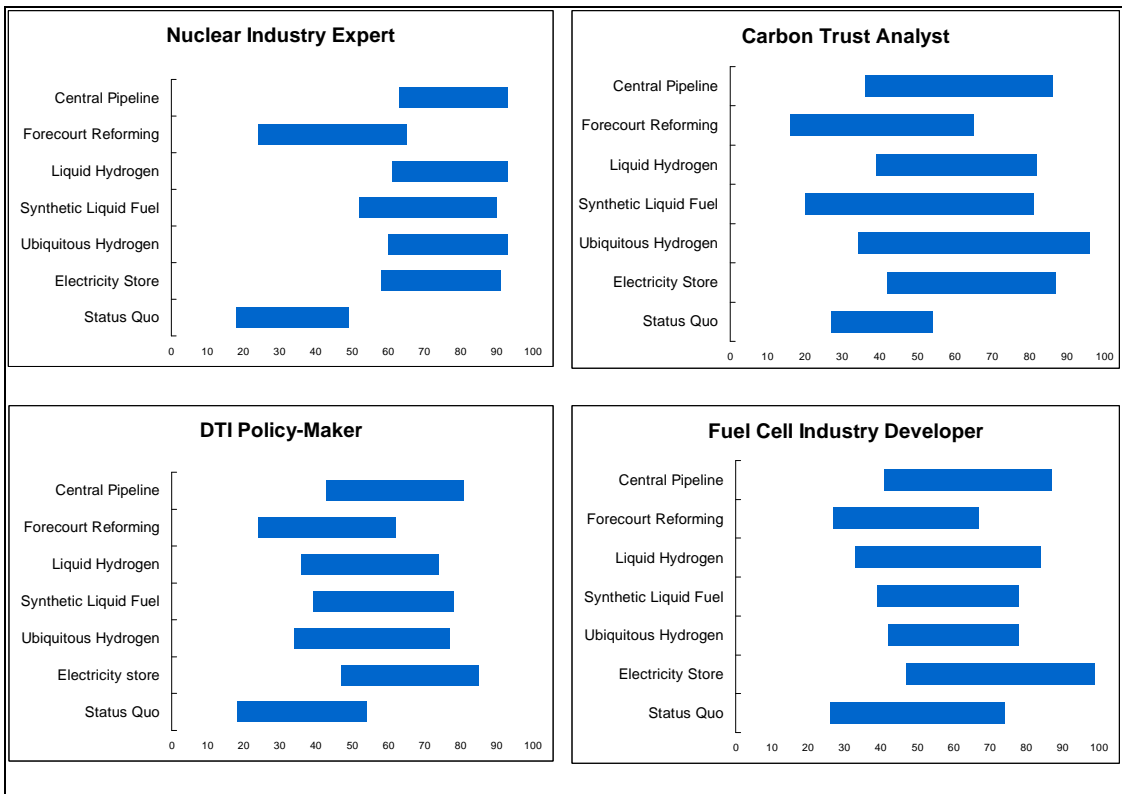
4.2 Ranking the Visions

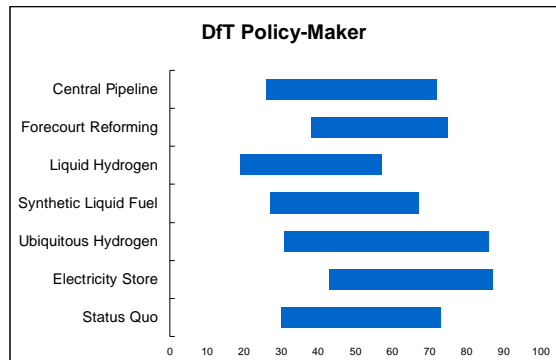
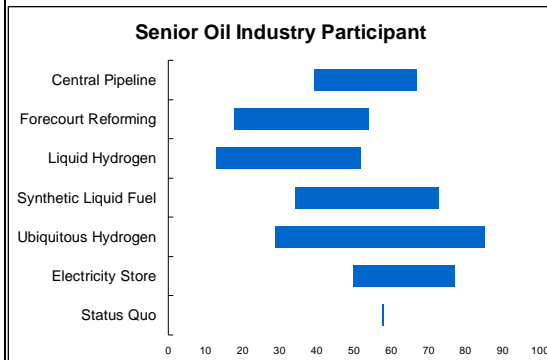
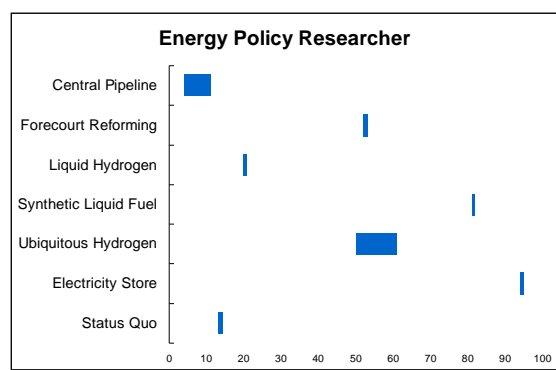
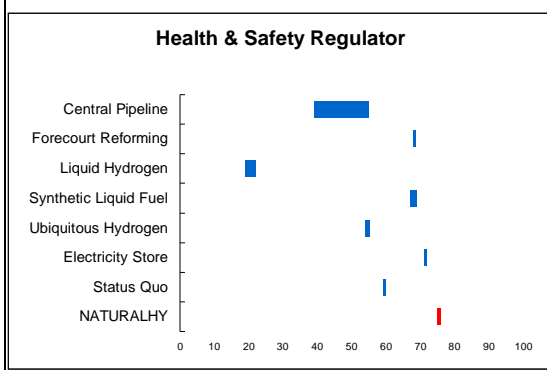
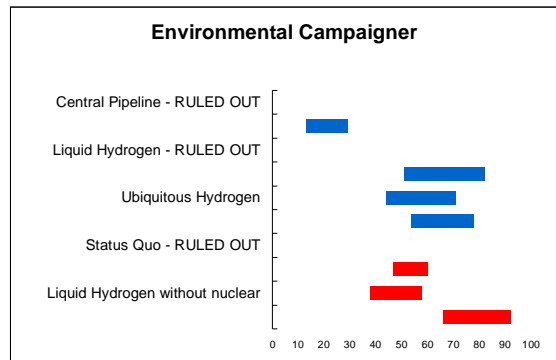
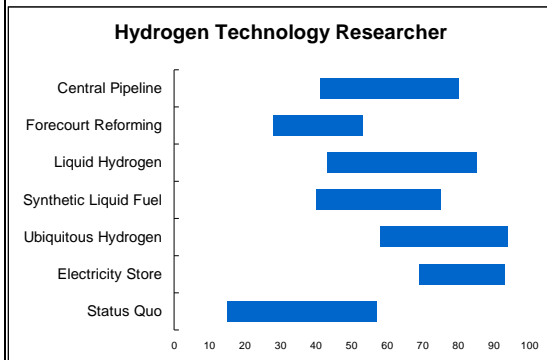
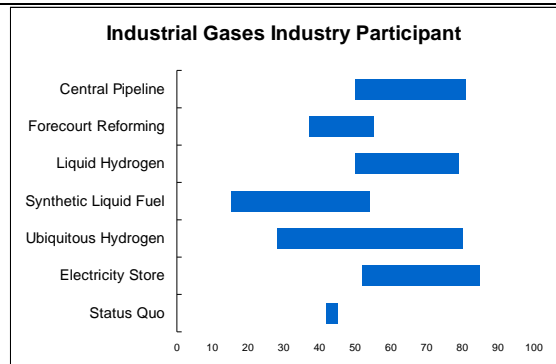
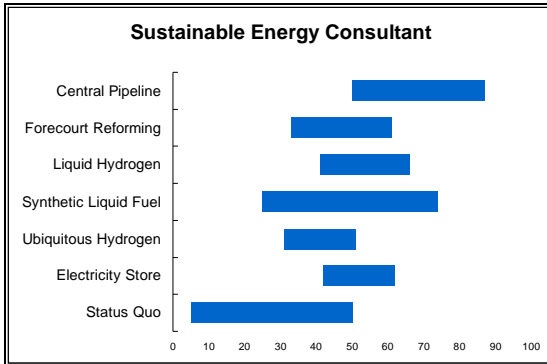
The following diagram shows the final weighted scores for the visions aggregated across all participants. The aggregated results can, at best, produce only a very rough picture of the contours of the appraisal, and can be used as a comparison to examine where individual participants may differ markedly from the panel as a whole.



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

The charts below show the final outputs for each participant, and demonstrate the wide variety of different appraisals.





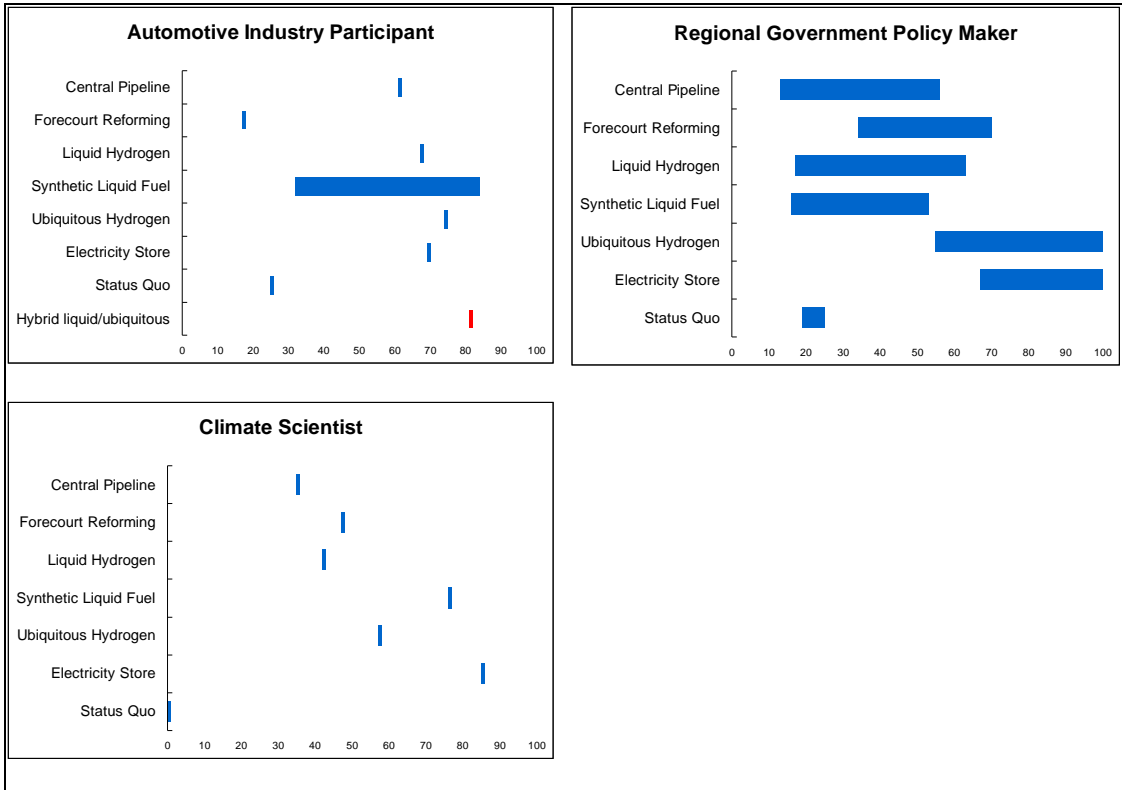


Figure 4.3 Individual weighted score ranges. Blue bars represent the weighted scores for the six core visions plus status quo, while red bars show visions that were introduced by participants during scoring. The x-axis is a relative 1-100 scale showing performance, with better performing visions further to the right. Bar length is a result of the degree of difference between pessimistic and optimistic scores, and is thus a function of the degree of uncertainty.

The picture confirms the highly contested nature of the debate, with no absolute winners or losers, and with a wide range of weighted scores for all visions. This does not mean no patterns are clear, but rather that there are no uncontested winners. Examination of the relative performance of each vision, under both optimistic and pessimistic assumptions, provides some clear messages about the likely sustainability of the different futures. The performance of each vision is discussed below.

Central Pipeline

Central Pipeline was ruled out by the *Environmental Campaigner* because of its inclusion of nuclear, and in the view of the *Energy Policy Researcher* it performed worse than any other vision. In this participants' view, centralised systems with nuclear power and pipelines performed poorly. It also did worst in the view of the *Regional Government Policy Maker*, who also penalised centralised systems, nuclear power and carbon sequestration. In contrast, the *Sustainable Energy Consultant* ranked this vision as the best performing. Costs, and in particular cost effective carbon abatements, were the driving factors in this participants' view, whose appraisal criteria closely resembled UK government policy objectives. Most participants saw this as potentially one of the stronger visions, particularly when greater emphasis is given to the use of renewables rather than nuclear power.

Forecourt Reforming

This vision was seen as the worst performing by six participants. This appears to be largely on the basis of poor performance on carbon criteria, and for some participants, poor performance on energy security criteria. In no case was this seen as the best performing vision (under either most positive or most negative assumptions). Under most optimistic assumptions however, the *Health and Safety Regulator* and *DfT Policy Maker* ranked *Forecourt Reforming* relatively highly, not far behind the best performing visions. These positive rankings reflected these participants' belief in the near term and highly achievable nature of the vision, and in particular recognised the benefits of using an established infrastructure and energy source.

The overall poor performance of this vision is confirmed at the aggregate level, where it performs worst under both optimistic and pessimistic assumptions (see figure 4.2)

Liquid Hydrogen

The *Health and Safety Regulator*, the *Senior Oil Industry Participant*, and the *DfT Policy Maker* ranked *Liquid Hydrogen* worst under both pessimistic and optimistic assumptions. A further participant (the *Environmental Campaigner*) ruled it out entirely, on the basis of its inclusion of nuclear power. In no case was the *Liquid Hydrogen* vision the best performing under most positive assumptions. However, the *Automotive Industry Participant* created an additional vision, a hybrid of liquid hydrogen and ubiquitous hydrogen, which performed very highly in his appraisal. Several participants highlighted the areas in which they felt liquefied hydrogen would have a valuable role. The *Industrial Gases Industry Participant* stressed that it is the most cost effective long-distance transport medium, while others raised purity benefits and bulk storage benefits of liquid hydrogen.

Synthetic Liquid Fuel

The *Sustainable Energy Consultant* and *Industrial Gases Industry Participant* saw scope for this being the worst performing vision, but both of these participants gave this ranking a high degree of uncertainty. Only in the view of the *Industrial Gases Industry Participant* did it remain the worst performing even under most positive assumptions. Both of these participants were sceptical of the carbon balance of this vision, and of its likely feasibility and costs.

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

Ubiquitous Hydrogen

No participant saw this as the worst performing vision under worst possible assumptions, but the *Sustainable Energy Consultant* saw it as performing worst under best possible assumptions. This was largely on the basis of cost and feasibility, and the feeling that hydrogen should not compete with electricity for stationary power. Two participants (the *Carbon Trust Analyst* and *Senior Oil Industry Participant*) saw this as potentially the best performing vision, and a further two participants saw it as joint best with *Electricity Store*. However, no participant ranked it best under least favourable assumptions, suggesting that it would not be seen as a fall-back option.

Electricity Store

No participant saw this as the worst possible vision. Where this vision performed relatively poorly, this was largely on the basis of concerns about feasibility and cost, and scepticism about the availability of sufficient renewables capacity. Several participants saw it as only viable in the very long term. The *Industrial Gases Industry Participant* felt that “if I could simply believe that that was possible then obviously we’d give it fantastic marks.” *Electricity Store* was seen as potentially performing the best under five participants views, and as potentially joint best along with *Ubiquitous Hydrogen* under a further two. In several cases, this was also the best vision under most negative assumptions. This vision did best among participants that strongly supported renewables, rejected nuclear and carbon sequestration, and preferred decentralised systems. In confirmation of this picture, *Electricity Store* performed best overall at the aggregate level (see figure 4.2)

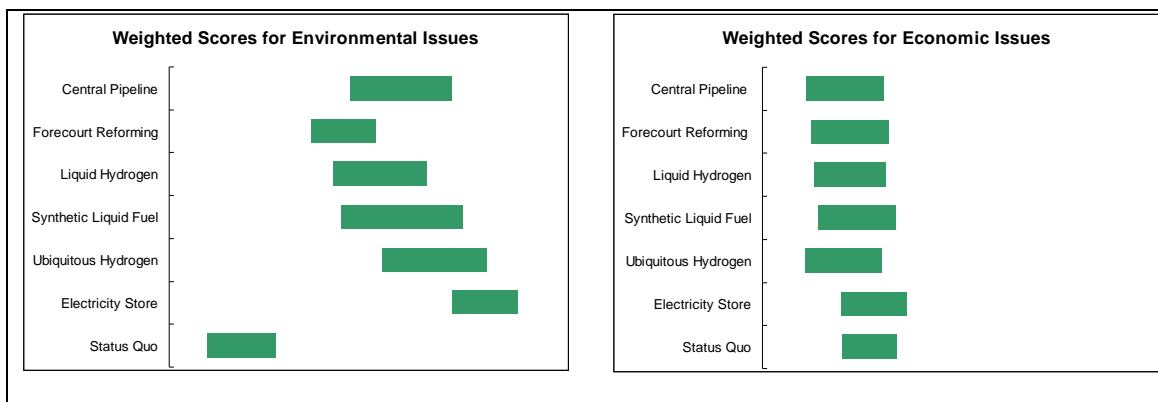
Finally, it is interesting to compare the performance of the *Status Quo* vision with the hydrogen visions.

Status Quo

It was notable that, in the appraisals of many participants, there were conditions under which the status quo was not the worst performing option, implying that some hydrogen futures could be less sustainable than current, or business as usual, activities. However, status quo was frequently the worst performing option under both most positive and most negative assumptions. In no case was status quo seen as the best performing option, either under most positive or most negative assumptions, suggesting broad agreement that many hydrogen systems bring sustainability gains. Not surprisingly, it tended to perform well where cost and feasibility were seen as most important, and worst where carbon was a key concern.

Patterns in the vision rankings under different issues and criteria

The aggregate picture, as outlined above, provides a useful overview of the rankings across all participants, and across all the various criteria groupings. However, we can learn more by looking at the performance of visions under particular criteria grouped into issues (environmental, social, economic and so on).



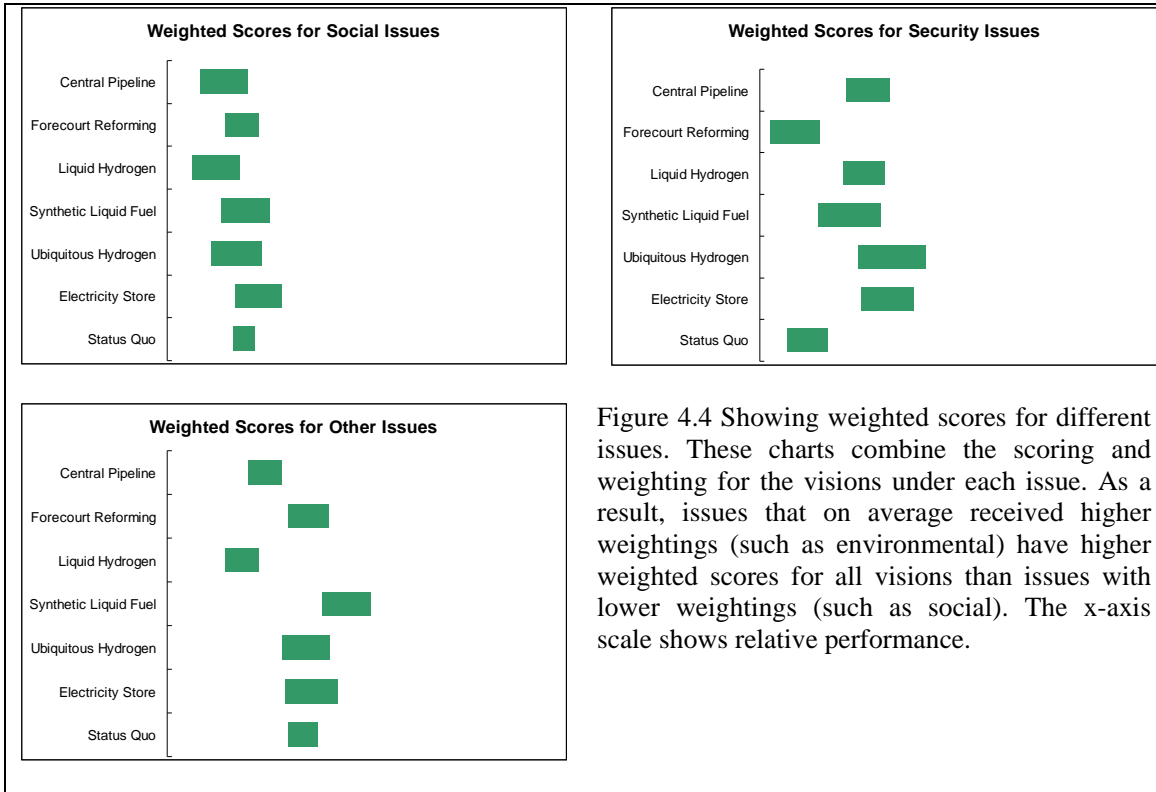


Figure 4.4 Showing weighted scores for different issues. These charts combine the scoring and weighting for the visions under each issue. As a result, issues that on average received higher weightings (such as environmental) have higher weighted scores for all visions than issues with lower weightings (such as social). The x-axis scale shows relative performance.

None of the visions clearly dominates across all issues, although *Electricity Store* performs well under most.

Environmental Issues

As can be seen from figure 4.4, the six visions were relatively clearly differentiated on the basis of their environmental performance. This was dominated by carbon emissions, but included a range of other criteria, including nuclear waste, non-carbon pollution, and local air quality. Uncertainties with respect to these scores occurred despite relatively well characterised ‘wells-to-wheels’ data for different hydrogen infrastructure pathways. Some participants were sceptical of, for example, the performance and viability of sequestration technologies, and gave visions including sequestration a range of scores, with the lower bound representing that risk of technological failure. In terms of weightings across the participants overall carbon emissions were clearly considered to be the most important single determinant of a visions sustainability.

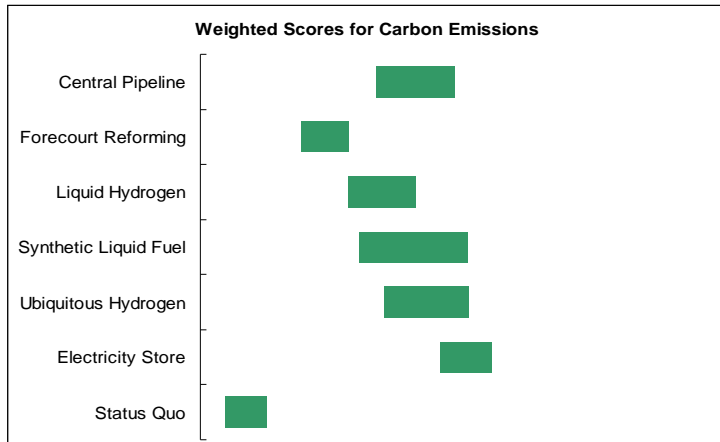


Figure 4.5 Weighted scores under carbon emissions

Five participants scored an ‘air quality’ criterion that focused on emissions from vehicles, although in general these were not weighted highly. There was little difference among most of the visions from a local air quality perspective, although *Synthetic Liquid Fuels* received lower scores.

Environmental issues other than carbon and local air quality favoured *Electricity Store*, and to a lesser extent *Ubiquitous Hydrogen* and *Forecourt Reforming*. Not surprisingly, visions involving nuclear power, and with a predominance of large scale fossil fuels, tended to do less well.

Economic Issues

The economic sub-rankings are interesting, with none of the visions coming out as obviously better or worse when the appraisals of all participants are examined as a whole. This is the aggregate picture, and many participants did see significant variation among the visions in terms of economic performance. All participants scored some form of economic criterion (although for the *Heath and Safety Regulator* this was through a ‘feasibility’ criterion in the ‘other’ category of issues), and these tended to fall into three broad categories.

The most highly weighted economic criteria concerned feasibility, and the economic attractiveness of the vision to investors. Seven participants scored criteria along these lines. Feasibility issues are discussed in more depth in section 5.

Nine participants scored some kind of ‘cost’ criterion. However, these were varied. Some concerned costs to society overall, while others were intended to represent what consumers might pay at the pump. One participant felt that it was impossible to compare the likely future costs of the visions, and instead compared the current costs. Cost was typically given lower weights than the economic feasibility criteria. Variations in the assessments of likely economic performance of the visions were in part dependent on different assumptions about policy frameworks around carbon; fossil fuel prices; the costs of nuclear power; and the relative affordability of more decentralised, modular systems or capital-intensive centralised systems.

Thirdly, the *Carbon Trust Analyst* and the *DTI Policy Maker* attempted to consider the possible impacts of the visions on the UK economy as a whole. This included concerns about the implied energy costs, the degree to which the costs were considered overly dependent on price-volatile sources, and the export opportunities for the UK. However, the uncertainties were felt to be so great that both participants scored all visions with an equally wide range of uncertainty.

Social Issues

As noted above, seven participants scored only a ‘social acceptability’ criterion under this heading, and the way in which it was scored showed that participants felt that this was a potential barrier to feasibility, rather than an ongoing dimension of a desirable or sustainable future. Most participants also gave social acceptability relatively low weightings. The *Status Quo* did best under social acceptability criteria, often on the basis that this was simply by definition (what exists today must be acceptable), and that problems of social acceptability are associated with change and novelty. For example, the *Energy Technology Researcher* argued that the degree of change involved would itself be cause for social resistance, simply because “people don’t like change”. The performance of the other visions varied amongst participants, with some feeling that ‘out of sight’ centralised systems such as *Central Pipeline* would be most acceptable, and others feeling that publics would be most willing to accept the least polluting visions, such as *Electricity Store*.

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

Security Issues

All but three participants (the *Environmental Campaigner*, the *Health and Safety Regulator*, and the *Climate Scientist*) scored a ‘security’ criterion, while three participants (the *Energy Policy Researcher*, *Energy Technology Researcher*, and *Nuclear Industry Expert*) generated more than one criterion under this category, including primary energy security, infrastructural integrity, and diversity of sources. Unsurprisingly, *Forecourt Reforming* did badly under security criteria, given its dependence on natural gas. One participant chose to discuss upstream security under the ‘economic’ category, arguing that “*I think you’d have to categorise that as economic, because when that goes wrong the impact is an economic one.*”

Other Issues

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

Technical feasibility was a component of this category. However, feasibility issues were more commonly addressed under economic criteria, as ‘business case feasibility’ for example. Feasibility issues are discussed more fully in section 5.

As well as feasibility, the ‘other’ category contained several criteria related to aspects of the technological system, such as flexibility, ‘quality’ of supply (related to the robustness of the electricity supply system), and the degree to which the system was seen as complementary or enabling to renewable or decentralised energy systems. This included discussion of whether, for example, particular systems were more likely to lead to a situation of technological ‘lock-in’, and embodied very different assumptions about the nature of technological change and technological systems.

Three participants raised some aspect of ‘usability’ as important, in terms of consumers’ day-to-day experience of dealing with hydrogen technologies.

4.3 Patterns in Uncertainty

A central aim of the multi-criteria mapping approach is to document and explore the uncertainties and dependencies in vision performance. This section explores these issues.

In analysing the patterns of uncertainty and variability in vision performance between optimistic and pessimistic scores, it is hoped that we can identify:

- where uncertainties are so great as to overshadow differences in vision performance
- some of the key contextual uncertainties that influence vision performance, in the face of which policies must be robust against alternative possibilities.
- where some issues, or some visions, are subject to greater or lesser uncertainty than others
- where there may be opportunities for uncertainties to be reduced or resolved with R&D

First of all, ranges within both the individual and aggregate weighted scores demonstrate the very substantial uncertainties involved. There is considerable overlap, with many participants finding no clear winner, and with no one vision clearly dominating across the participants’ appraisals as a whole. As might be expected with long term scenarios, there appears to be rather more uncertainty overall than in previous applications of MCM (Davies et al 2003; Stirling & Mayer 1999).

The degree of uncertainty has a significant impact on the rankings: comparing the optimistic with the pessimistic weighted scores shows that the ranking order does change for both the aggregate picture and for all but one of the individual participants’ appraisals. For most individuals the changes are small, and high ranking visions tend to perform well under both optimistic and pessimistic assumptions. However, for some participants (the *DTI Policy Maker*, the *Carbon Trust Analyst*, and the *Industrial Gases Industry Participant* in particular) the differences are more pronounced, with the uncertainties and variability having an important impact on the rankings. This suggests that in some cases the scale of uncertainties within the visions is as important as the differences between them, a conclusion that should not be surprising given the long time horizons involved. The task of analysis must be to explore the basis of those uncertainties.

The variation between optimistic and pessimistic scores is composed of three components:

1. Uncertainty about future performance and implications of particular technologies or technological systems.
2. Variability in performance depending on assumptions about the exact configuration and implementation of the vision, such as the precise resource mix for hydrogen production.
3. Sensitivity of vision performance to as yet unknowable future context conditions, such as future natural gas prices.

Uncertainty about future performance and implications of technologies

Many of the technologies envisaged in the visions are in the research and development stage, and have little or no history of widespread use in real-world situations. There are substantial uncertainties surrounding some of the technologies, not only in terms of their physical performance, but in terms of what impacts the technologies might have in broader socio-economic terms.

The following uncertainties were each identified by more than three participants, and were reflected in variations between pessimistic and optimistic scores:

- Potential leakages of CO₂ from carbon capture and storage
- Fuel cell performance
- Performance of small scale natural gas reformers – in terms of both cost and pollution
- Likely carbon balance and toxic emissions from synthetic liquid fuel synthesis and use

- ❑ Costs for all technologies were subject to uncertainty, but in particular uncertainties relating to the costs of synthetic liquid fuels, nuclear power, and pipeline infrastructures were raised.
- ❑ Significant uncertainties around public acceptability of technologies in general
- ❑ Performance, integrity and vulnerability of pipelines
- ❑ Very large uncertainties around the possible impacts on the UK economy as a whole

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

Variability in performance depending on the exact configuration of the vision

The visions leave scope for flexibility, and different possible configurations of the technologies within the visions create variation between optimistic and pessimistic scores. This is particularly true of the hydrogen production technologies.

The precise resource mixes of *Central Pipeline*, *Liquid Hydrogen*, and *Synthetic Liquid Fuel* all generated variation between optimistic and pessimistic scores for many participants across a range of criteria. For example, the *Fuel Cell Industry Participant* recorded large uncertainty around the non-carbon environmental impacts of *Central Pipeline*, depending on the relative proportions of coal, nuclear power and renewables in the hydrogen generation mix. Other criteria affected by resource mix assumptions include costs, carbon emissions, and feasibility. The *Energy Technology Researcher* explored the likely impact on biodiversity of different carbon sources in *Synthetic Liquid Fuel* (i.e. biomass sources or from industry flue gases).

Similarly, six participants explored the differences in air quality and pollution from hydrogen vehicles if internal combustion engines rather than fuel cells are used to power vehicles.

Sensitivity of vision performance to different possible future contexts

A final source of variation between optimistic and pessimistic scores concerns assumptions about the broader context in which the visions exist.

Ten participants felt that the future of natural gas, in terms of both price and availability, is a key uncertainty affecting the costs, security, and feasibility of different visions, particularly *Forecourt Reforming*. This uncertainty was reflected in the scoring, with many of these participants giving *Forecourt Reforming* a broad range of scores for cost.

A second major context uncertainty concerned the likely status of national and international policy frameworks with regard to reducing CO₂. The *Fuel Cell Industry Participant* and *Sustainable Energy Consultant* both explored the potential impacts of the presence or absence of strong CO₂ reduction policies on the economic and business attractiveness of the visions. In both cases, the variation was significant, and in both of these participants views, this is clearly a major uncertainty with respect to the likely economic performance of hydrogen systems.

Other contextual uncertainties of this kind included broader social attitudes towards technology and the environment, and the strategic direction taken by the automotive industry, particularly with respect to biofuels and plug-in hybrids.

Are some visions subject to greater uncertainties than others?

While they are all quite uncertain, overall, perhaps unsurprisingly, the most uncertainty was expressed with respect to the *Synthetic Liquid Fuel* vision. This was the vision with which participants were least familiar, and for which only vague indicative indicators about resource requirements were available. Least uncertainty was expressed with respect to *Electricity Store* and *Forecourt Reforming*, partly because these involved the least scope for interpretive flexibility within the vision definitions.

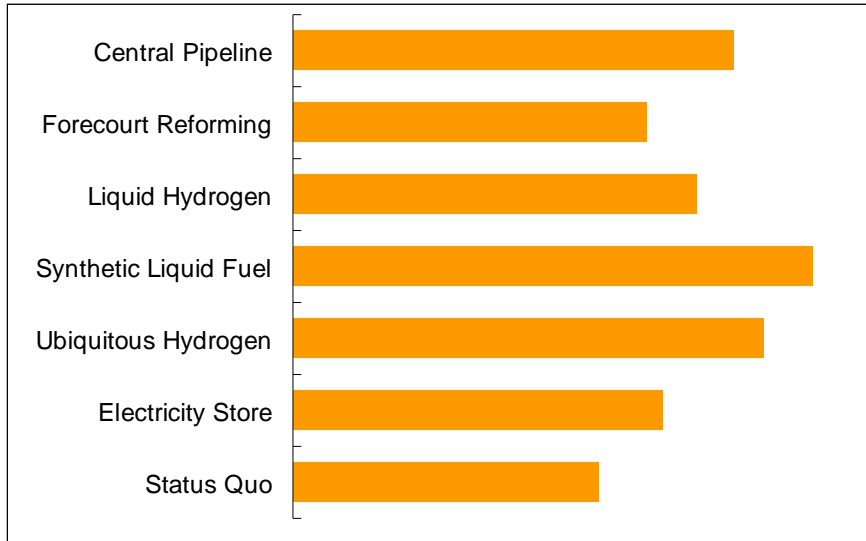


Figure 4.6. Shows relative degrees of uncertainty expressed with respect to the visions

Are some issues more uncertain than others?

There was also a tendency for greater uncertainties to be expressed with respect to particular issues. In general, economic issues were seen as subject to greater uncertainty than environmental, social, security, or 'other' issues. This is partly because costs were felt by many participants to be sensitive to wider context conditions, such as gas prices and policy frameworks. However, this finding also reflects a basic difficulty in attempting to compare the broader social costs, and, for example, 'impacts on the UK economy', which were scored with very high uncertainty.

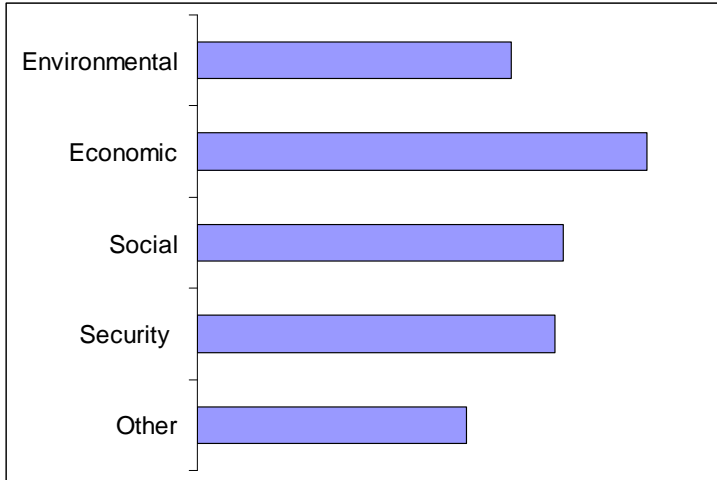


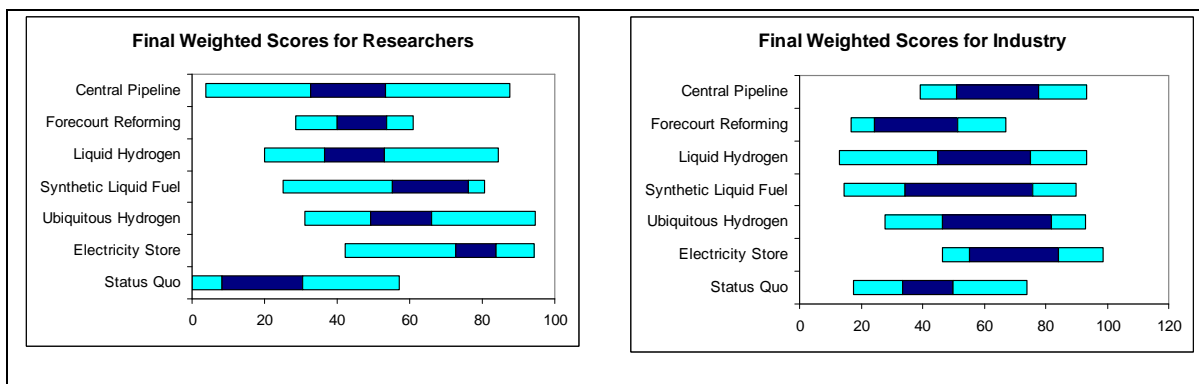
Figure 4.7 Shows relative degrees of uncertainty expressed with respect to different issue groups.

4.4 Patterns of consensus, diversity and disagreement: different perspectives on vision performance

One of the key features of MCM analysis is the exploration of different underlying perspectives that inform participants' appraisals. In the analysis for this report, results have hitherto been presented showing the aggregate picture across all participants, or for participants' individual appraisals. This next section groups participants according to whether they work in government, industry, research, or as campaigners, and shows no clear patterns in participants' appraisals based on such institutional affiliation.

Exploring perspectives from different institutional backgrounds

The following charts show how the picture of appraisal differs when participants are grouped according to their backgrounds, in research, industry, the civil service, or environmental NGOs (note this last group includes only one participant).



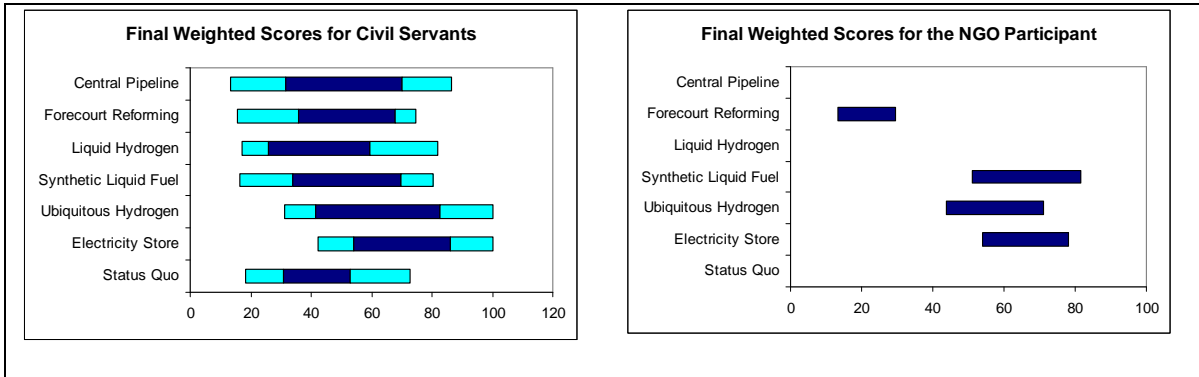


Figure 4.8. Mean (dark blue) and Extreme (light blue) weighted scores by institutional background.

While there are some differences in the mean scores, the extrema show little overall pattern among the different institutional perspectives. This, along with the qualitative material, suggests that participants from different institutional backgrounds have little tendency to share particular views on vision performance.

This is further illustrated with reference to the way in which participants from different institutional backgrounds weighted the criteria, as shown in figure 4.9. The patterns appear to differ little from that of the aggregate picture, shown in figure 4.1.

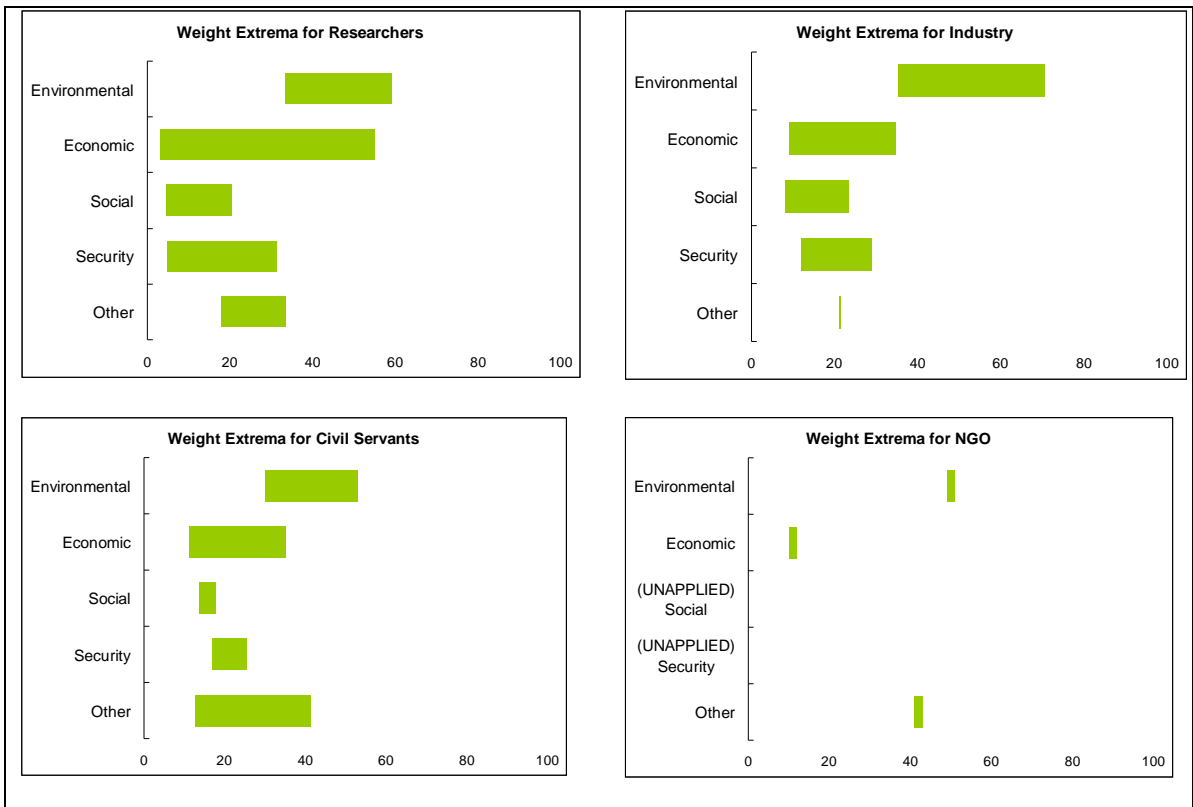


Figure 4.9 Weightings by institutional background. Bars represent the range between the lowest (furthest to the left) and highest weights given by any participant within a particular grouping. Note that there was only one NGO participant.

Exploring alternative perspectives on vision appraisal

On the basis of patterns in the selection and definition of criteria, the broad framing assumptions, and the different rationales participants used to weight criteria, it is possible to group participants who appear to share similar approaches towards the appraisal of the visions.

Three participants (the *Energy Policy Researcher*, *Environmental Campaigner*, and *Regional Government Policy Maker*) held strong beliefs about the social and political implications of different technological systems. All of these participants strongly opposed nuclear power, but they also opposed other centralised systems, partly on the basis of beliefs about the sort of political structures that such systems are associated with, with the *Energy Policy Researcher* describing nuclear as ‘anti-democratic technology’. The *Energy Policy Researcher* and the *Regional Government Policy Maker* also held strong views about the nature of technological change, feeling that the development of large centralised technologies such as nuclear and carbon sequestration would undermine the development of renewables and energy efficiency technologies. None of these participants scored criteria that reflected the relative feasibility of the different visions. The weighted scores and weightings for this group are shown in figure 4.10.

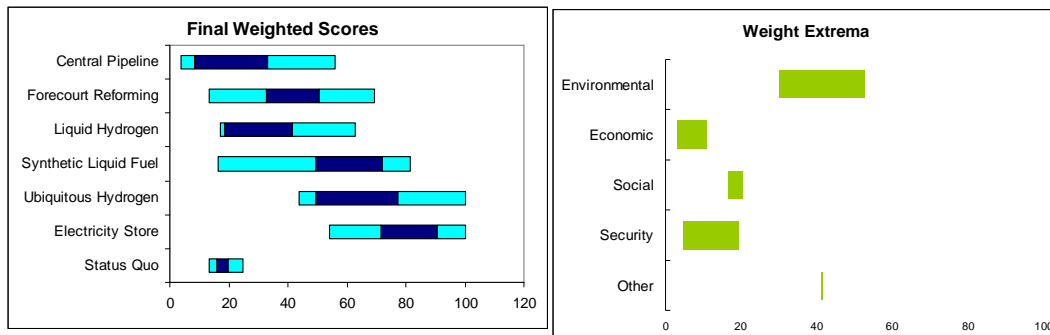


Figure 4.10. Shows weighted scores and weightings for the *Energy Policy Researcher*, *Environmental Campaigner* and *Regional Government Policy Maker*

A second group of participants took a view much more clearly defined by economic feasibility, and by expected carbon emissions. This group comprised the *Sustainable Energy Consultant*, *Industrial Gases Industry Participant*, *DfT Policy Maker*, *Health and Safety Regulator*, *Automotive Industry Participant* and *Nuclear Industry Expert*. These participants tended to see technologies as having relatively well characterised economic and environmental costs and benefits, which can be traded off to provide an overall best solution. In this view, while social issues are recognised to be important, there is little sense that different technological systems have strong implications for social issues or political relations. The *Sustainable Energy Consultant*, for example, argued that ‘this will be decided on the techno-economics’. Participants in this view tend not to be hostile to nuclear power, or at least to see it as a ‘necessary evil’. Some of these participants felt that there would be little difference between the environmental performance of the six visions, with the exception of *Forecourt Reforming*. Instead, the important aspect of appraisal was the relative feasibility and economic attractiveness of the visions. The weighted scores and weightings for this group are shown in figure 4.11. Comparison of the charts shown for this group with those of the preceding group show clear differences. The first group clearly reject visions involving nuclear power, and have very different patterns of weightings. Compare, for example, the relative positions of social and security weightings in the two groups, and the different weights given to economic issues.

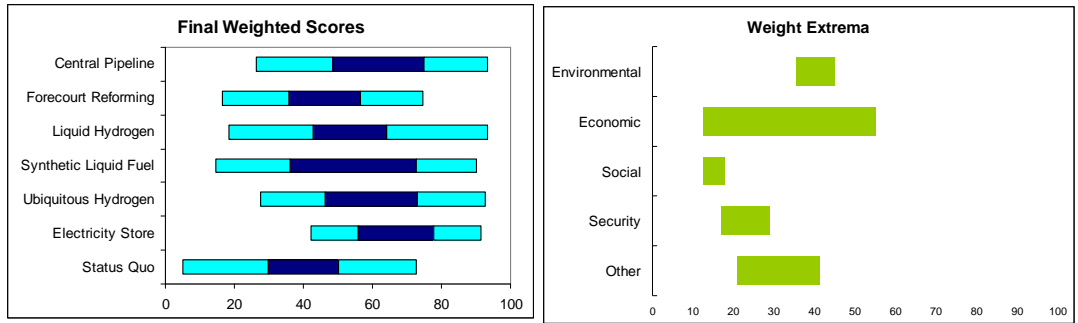


Figure 4.11. Shows the weighted scores and weightings for the *Sustainable Energy Consultant, Industrial Gases Industry Participant, DfT Policy Maker, Health and Safety Regulator, Automotive Industry Participant and Nuclear Industry Expert*

The issues that underlie these differing perspectives are explored in section 5.

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

Box 4.2 Hydrogen as a greenhouse gas?

One participant, the *Climate Scientist*, took a rather different approach to the appraisal. This participant was concerned with the possible implications of hydrogen gas leakages on atmospheric chemistry, and, in short, the potential for hydrogen to act as a greenhouse gas. In this participants’ view, those visions which make hydrogen leakage more likely were scored badly. Although the significance of the effect is small (If a hydrogen economy with a 1% leakage rate completely replaced a fossil-fuel economy, then it would produce 0.6% of the climate impact of the fossil-fuel economy (Derwent 2004)), this participant felt that it is important, and should not be overlooked.

Patterns of disagreement and divergence

While visual inspection of the weighted score charts gives us some idea of the degree to which participants with different perspectives disagreed about vision performance, it is also possible to gauge the degree of disagreement within perspectives. This allows us to identify more contentious visions and issues.

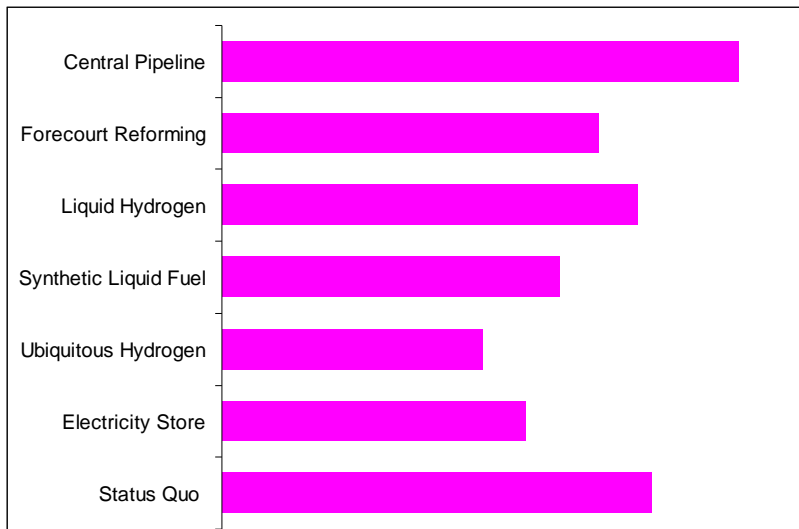


Figure 4.12. Shows relative degree of disagreement between participants' appraisals of the visions.

The chart suggests that participants overall differed most over their appraisals of *Central Pipeline*. This is perhaps not surprising, given the very different perspectives explored in the previous section. Participants with different views about the desirability of large centralised systems and nuclear power scored *Central Pipeline* very differently. Participants also disagreed strongly over their appraisals of *Status Quo*. This is in part an interesting result of different perceptions of where we currently are, and in part because some participants treated the *Status Quo* as a business as usual future scenario, including biofuels, hybrids and other new technologies.

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

Overall, carbon emissions were clearly felt to be the most important factor on which to judge the sustainability of the different visions. However, if this was something that participants could agree on, other issues were important in explaining differences between participants' appraisals. The positions that participants took with respect to three key issues (nuclear power, decentralisation, and feasibility) reflect strongly held beliefs about how to assess energy system sustainability, and about how technology and society inter-relate. This section explores these major issues.

Nuclear Power

The nuclear issue was a major factor dividing participants' appraisals and perspectives. Nuclear was the only component of the future visions that any participant (*the Environmental Campaigner*) felt must be ruled out on principle, as fundamentally unsustainable. It also was a very significant factor in the appraisals of two other participants, the *Energy Policy Researcher* and the *Regional Government Policy Maker*. Typically, their reasons for opposing nuclear power went beyond concerns about the risks of radiation and associated environmental and health impacts, and extended to the political nature of control over nuclear power, and the implications of nuclear on the development of alternative energy systems.

In the *Energy Policy Researcher's* view, nuclear power is "more a kind of political thing as an environmental thing". In detail, this participant saw nuclear as fundamentally 'anti-democratic' technology, that leads to 'militarisation of society', and the erosion of social justice.

"if you've got nuclear power plants you are talking about security guards wandering around with guns And there's a huge, you know, nuclear inspectorate... I mean, it's a frightening world... In that kind of a world... it becomes... a... a world where people are separate.... And I think in a climate change environment, where Europe is likely to become a kind of fortress Europe... a climate change world is an extremely dangerous world with vast numbers of people losing their homes. Huge amount of vulnerability and discontent and general total unhappiness.... And having technologies, which enable a few, just a few of those people to do seriously nasty things to other people, strikes me as stupid, apart from anything else. But then the main problem is with the kind of, democracy side because it seems to me, unless people engage in what they're doing ...then they're not necessary open to making non-parochial... global, socially just decisions."

Both the *Energy Policy Researcher* and *Regional Government Policy Maker* also opposed nuclear on the basis that the development of nuclear would undermine efforts to move towards energy efficiency and renewables. In the words of the *Regional Government Policy Maker*, "I don't believe that a future that's built substantially on nuclear and carbon sequestration will lead to the development of large scale renewables. They work against each other. If you can do nuclear on that scale, you'd probably just do nuclear". This was echoed by the *Energy Policy Researcher*: "I think that you need complementary technologies and not all technologies are complementary. I think that nuclear power is fundamentally undermining technology to the requirement of moving from this current energy system, which is basically fossil fuels and nuclear, through to this new [renewable] energy system, which is looking at things in a completely different way."

Other participants had very different views about nuclear power, with for example, the *Industrial Gases Industry Participant* raising no problems with nuclear at all. Some others raised concerns about radioactive waste and risks of health and environmental impacts of nuclear accidents. The *DTI Policy Maker*, *Energy Technology Researcher*, *Carbon Trust Analyst*, *Fuel Cell Industry*

Participant, and *Health and Safety Regulator* all gave lower scores to visions including nuclear under broader environmental impact criteria. However, for some of those participants, nuclear was only marked down under most pessimistic assumptions, with those assumptions relating to how well the industry might be managed, and how intractable waste problems might prove.

A common view was articulated by the *Sustainable Energy Consultant* and as similar arguments about nuclear being a ‘necessary evil’ were made by others, it is worth quoting at length:

“Nuclear... is fundamentally opposed to the notion of sustainable development. The idea that you have to bury waste in a hole for a hundred years before you can even deal with it, to me flies in the face of the leaving the world in the state that you found it. However, I see it as a lesser of evils debate, because leaving the world closer to the risk of catastrophic climate change is probably a worse thing to do than having a few holes around the UK containing the nasty stuff. And neither of those are desirable. So, the view I’m coming to is that it may be necessary to have a fifty year nuclear program whilst we get ourselves past the risk of catastrophic climate change or we get climate stabilisation.”

Other issues associated with nuclear included socio-political feasibility, with the *DfT Policy Maker* commenting that “I think that my view on nuclear is that it is largely about the public perception of risk”. The *Energy Technology Researcher* raised a long-term prospect of uranium depletion, and the *Sustainable Energy Consultant*, among others, highlighted the high costs of nuclear power: “and by the way, I think it’s completely unbankable, but I’ve heard the chief executive of a large utility say otherwise,as long as the long term liabilities will be underwritten by the government”

Finally, the *Nuclear Industry Expert* felt that it was largely a question of good management, and overcoming social and political resistance. This view is in sharp opposition to the view of the *Energy Policy Researcher*, and illustrates very different beliefs about the nature of the politics of technology.

“I think of that ...you might have some solutions, which might make environmental sense, that is nuclear, and politicians ...are sitting and debating proliferation treaties. So, there are issues there, which... will cause problems. But even then, ... I can foresee things happening in a way that things like nuclear power are managed within a political ground, which allows nuclear to be more widely used. So... some of the fundamental assumptions or some of the, I was going to say fundamentalists prejudiced against nuclear are based on a prior assumptions about the nature of nuclear proliferation and the effect on... global conflict. So, I think sometimes we have to dig down to that level before we say, hang on, there is a solution there! If the need is strong enough, we’ll drive for that solution. And the solution might be, for example, UN managed nuclear power plant around the world ... Sort of protected zones, which are operated by an international operating agency, electricity or what-have-you and hydrogen sold into the host country, but under a UN charter, for example. So, that sort of scenario could emerge if the need is strong enough.”

Centralisation and Decentralisation: Beliefs about the impacts of scale on society

The hydrogen futures literature, and hydrogen debates in the popular press, are full of claims about the manner in which hydrogen could enable decentralisation and enable greater consumer awareness around energy or even, it is argued, greater democratisation and empowerment. The members of the expert panel took a range of views about the likely truth or fiction of such claims, and their approach to decentralisation and community-scale energy was an important factor distinguishing their appraisals. This second broad set of issues is in some ways related to elements

of the nuclear debate, as for some participants, nuclear represented the archetypal large, centralised system.

Several participants (the *Regional Government Policy Maker*, *Senior Oil Industry Participant*, *Automotive Industry Participant*, *DTI Policy Maker*, *Energy Policy Researcher*, and *Environmental Campaigner*) saw value in distributed systems emphasising local energy production. These views were reflected through, for example, criteria examining the economic benefits to local communities (*DTI Policy Maker*) and ‘control over energy’ (*Senior Oil Industry Participant*). The case for distributed systems was put most forcefully by the *Regional Government Policy Maker*:

“I think that hydrogen has the potential to revolutionise, maybe too strong a word, the way we use energy, by enabling us to produce and manage the supply and distribution and use of energy locally, through local networks, through matching heat and power locally, by balancing the needs of different installations in different communities and having local control over that, we can generate better efficiencies, we can emphasise local control of environment so ...to some extent we can empower local people over their control over energy services. We break away from some of the inefficient monopolies that are based on central energy production and international energy.”

However, one of these participants, the *Senior Oil Industry Participant*, felt that, while desirable, decentralised systems may be difficult in practice, since “common facilities never get properly maintained... [so] although the distributed model is good from a point of view of gaining access to energy that you wouldn’t otherwise get, and it’s good because it actually gets people with a sense of ownership, the infrastructure requirement associated with it may be its downfall.”

The *Sustainable Energy Consultant* broadly agreed with the arguments in favour of distributed systems, but felt that the visions could not be differentiated on this basis. The potential benefits of decentralisation were seen as not coming from a particular structure of energy system per se, but instead on the structure of ownership and management. This participant felt that there was nothing inherent in the technologies that implied the social and political worlds that go with them

“I agree, it’s a desirable aspect but I actually don’t see it as differentiating. That’s the problem. You’d be piling assumption upon assumption upon assumption to say hydrogen CAN give you this versus something else, which won’t. To paint a ridiculous scenario... a cooperative gets together and builds an enormous reformer, versus a big oil company owning lots of distributed wind turbines on your roof. I stretch the point for illustration purposes, but in my view there’s a risk from imposing an existing view on something in forty-five years time, which I think is difficult to do.”

Other participants did not talk about putative broader benefits of decentralised systems, although they did see advantages in terms of the feasibility of incremental, relatively low upfront cost approaches based on modular systems (e.g. *Nuclear Industry Expert*, *Health and Safety Regulator*, *Industrial Gases Industry Participant*, *Climate Scientist*).

Feasibility, practicality and speed

For some participants, the most important issue was not to compare the likely sustainability impacts of the various hydrogen systems. With the partial exception of *Forecourt Reforming*, with its relatively poor carbon emissions, all the visions tackle the basic problems of climate change and oil dependency. The question, for these participants, was more to do with the feasibility and practicality of arriving at the visions. As the one participant argued “Yes, but ... in terms of prioritisation, what’s important is how quickly will this particular route get to the end game [of low carbon

emissions]. And ... I would say that's probably THE most important issue. Because we might not have very long."

Because of the framing of the process, which posed the six visions as equally plausible and asked participants to concentrate on their sustainability rather than how they might be achieved, this was also a more difficult area for participants to engage with. The *DfT Policy Maker* struggled with this: "I think, if there is going to be a hydrogen economy, then the transition is probably of key importance. I don't know how you could sum that up as a criteria". At the end of the MCM interview, the *Automotive Industry Participant* felt that the process had not adequately captured feasibility issues, and that as a consequence, the results did not entirely match his sense of which vision, if any, should be pursued. The emphasis for this participant was on the deployment of currently mature technologies, such as hydrogen powered internal combustion engine vehicles, which would allow a more rapid transition to a low carbon energy system, regardless of what that might finally look like.

It was agreed in general that the visions could all be done technically. While some felt that particular technological advances would be necessary (the *Energy Technology Researcher* felt that *Liquid Hydrogen* relied on new "Gen IV" nuclear, the *Regional Government Policy Maker* was sceptical about the feasibility of sequestration), only two participants (the *Nuclear Industry Expert* and *Fuel Cell Industry Participant*) explored a criterion of purely technological feasibility and potential. These technical feasibility criteria also received relatively low weights, when compared with the weights that participants gave to economic aspects of feasibility.

The question of feasibility was more frequently seen as economic and political (e.g. business case feasibility, social/political feasibility). As one participant argued:

"What I mean by practicability/feasibility is a complex mixture of [technical issues], and for most of these the engineering is possible. But more importantly, I suppose, I'm trying to assess why should we do this? Why should the customer want to do this? Rather than do something else or maintain the same status quo? And in a democratic situation the customer is going to have to want to do one of these rather than be told to do one of these."

This raises some fundamental issues of what is possible in a democratic consumer society, and the extent to which governments can force technology choices onto the public. At what point does the need to fight climate change justify riding roughshod over public preferences for a cheap energy lifestyle? In some ways, this goes to the very heart of questions about sustainability.

The *Carbon Trust Analyst* also argued that the visions must be economically attractive to consumers and investors to be plausible. "I always think 'what do you use hydrogen for' is not a bad question. ... at the end of the day, hydrogen won't exist if people don't want to buy hydrogen. If they don't get any benefit from hydrogen they won't buy it". This view was shared by the *Industrial Gases Industry Participant* and the *Sustainable Energy Consultant*, and reflected a belief that the benefits of hydrogen are captured by society at large, rather than by individual consumers, unless incentive structures are developed, or technologies and systems create conditions in which hydrogen will economically out-compete other energy vectors.

Several participants felt that certain context conditions would need to apply for particular visions to be feasible. Both the *Industrial Gases Industry Participant* and *Health and Safety Regulator* felt that *Ubiquitous Hydrogen* would only exist in a post-natural gas era. These assumptions clearly reflect a view that the feasibility of different visions is strongly dependent on future availability and costs of fossil fuels, and that in the near term, *Ubiquitous Hydrogen* has very low feasibility.

Finally, participants differed in their perceptions of which visions might be more or less feasible, particularly from an economic point of view. Some felt that *Electricity Store* was more feasible

because of its modularity and relatively low infrastructure costs; others felt that the high levels of renewables involved in the scenario made it feasible only over very long time horizons, and much less feasible than others.

Participants also differed in their perceptions of the feasibility of *Forecourt Reforming*. The *Industrial Gases Industry Participant* felt that “I think in the short to medium term it’s very viable”, while the *Health and Safety Regulator* argued that *Forecourt Reforming* was a straightforward and pragmatic solution. In contrast, the *Senior Oil Industry Participant* argued that for most refuelling stations, there is no space for reforming technologies. This participant argued that, while it could work for some sites, “as somebody who actually runs, you know, one thousand three hundred petrol stations, I could tell you this is nigh impossible” because of space restrictions at refuelling sites. Similarly, the *Regional Government Policy Maker* also raised the issue of very limited space in urban environments, arguing that it is “potentially a major issue”.

6. Conclusions: Insights on the road to a Sustainable Hydrogen Economy

Sustainability of the UKSHEC Hydrogen Visions

The results from the multi-criteria mapping indicate that, overall, *Electricity Store* was seen as the most sustainable vision, subject to concerns about feasibility. *Forecourt Reforming* was judged to be least sustainable, largely because of carbon emissions, but also concerns about the security and economic implications of natural gas dependence.

Central Pipeline was the most contentious vision, with the widest range of rankings, reflecting divergent opinions on nuclear power, carbon sequestration, and the economic viability of a large, centralised pipeline infrastructure. The relatively strong performance of *Synthetic Liquid Fuels* was somewhat unexpected. This reflected the benefits of a low carbon fuel that is straightforward to store and transport, and that offers fewer technological barriers than the use of pure hydrogen. It was also the vision around which there was greatest uncertainty. *Liquid Hydrogen* did poorly, partly because of some participants' concerns about nuclear power, but more importantly because liquid hydrogen was seen as impractical and inefficient for use as a mainstream transport fuel (although many participants felt that liquefied hydrogen would have a role in some applications). Finally, *Ubiquitous Hydrogen* performed relatively well, but as with *Electricity Store*, there were some concerns about its feasibility.

Since there are many possible configurations of the technologies that compose each vision, the final rankings of the visions tell us only a small part of the story. Alternative configurations of the visions, with technologies such as nuclear included in a different set of visions, might have lead to a rather different pattern of final rankings. The important issues, uncertainties, and participants' perspectives on particular technological components are more useful, and are the more important findings. Analysis of the appraisal outputs leads to the following key conclusions:

Key Conclusions

- ❑ Hydrogen is not automatically a sustainable option. Participants recognised a range of circumstances in which hydrogen energy might be less sustainable than the current system or some non-hydrogen business as usual futures.
- ❑ The panel identified carbon emissions as the most important dimension of sustainability with respect to the hydrogen futures.
- ❑ Even for issues with relatively well characterised data sources (such as wells-to-wheels carbon studies) there were debates about how well technological systems could be expected to perform in real world applications.
- ❑ There is significant uncertainty over the future costs and performance of the technologies, and these uncertainties have important impacts on the likely sustainability of the different futures. In particular, there are uncertainties concerning: the performance and costs of carbon capture and storage, nuclear power, pipelines, small scale reformers, fuel cells and hydrogen storage technologies.
- ❑ There is a wide range of rationales for ranking different futures (e.g. political implications vs. technical appraisals of likely system performance). Some of these issues are amenable to further research, others are based on normative value judgements about the way in which society should operate, and are therefore likely to be a continuing source of disagreement

and dissent. Nuclear power, the degree of decentralisation, and perceived feasibility were key areas dividing participants' appraisals.

- ❑ Nuclear power is a key area of disagreement. For those concerned about nuclear power, opposition was as much to do with social and political aspects as environmental concerns.
- ❑ While there was some disagreement about which of the visions would be most feasible, there was broad support for approaches that made use of existing infrastructures and developed incrementally.
- ❑ Many of the studies examining the potential of hydrogen fail to take into account issues of spatial planning and physical geography – but the space implications of *Forecourt Reforming* were a major concern for some participants. This suggests a need for research into hydrogen to take greater notice of issues of space and place.
- ❑ Assumptions about technological change are important – do some routes mean that we close off others? This is an area that further research might cast some light on.
- ❑ 'Business as usual' or the market alone are thought to be unlikely to deliver any of the visions, at least in the short term. Changes such as shifts in fossil fuel supplies, policy frameworks, or social priorities with respect to climate change are thought necessary to drive a transition.

Recommendations for Policy

- ❑ While carbon emissions were recognised to be the most important single determinant of the sustainability of a hydrogen energy system, there are a wide range of other criteria that are seen as important. Issues other than carbon and cost need to be considered if the introduction of hydrogen is truly to deliver greater sustainability.
- ❑ Hydrogen policy must also be robust in the face of uncertainties about future context conditions, such as future availability and price of natural gas, and public attitudes to technology. The future of political frameworks around carbon and climate change is a key uncertainty affecting the perceived feasibility of the visions.
- ❑ The broad interest coalition promoting hydrogen is fragile. If hydrogen systems develop, there is significant potential for future social conflict over the shape and direction that those systems take.
- ❑ Robust research policy should address 'backstop' technologies – for example, that explore the possibility that storage technologies fail to improve significantly.

Recommendations for Research

- ❑ Public acceptability research needs to take a whole systems approach, including primary energy as well as just the use of hydrogen as a fuel. Studies that only examine the public's attitudes to the safety or end-use of hydrogen in isolation are likely to be of little use in understanding future conflicts over energy technologies overall.
- ❑ Research into social issues must move beyond narrow questions of safety and public acceptance: control, state intervention, access, and consumer choice may all be important.

While public acceptability is important, there appear to be broader concerns about the potential social impacts of hydrogen systems.

- Combining scenario approaches with multi-criteria appraisal provides a valuable tool for exploring and mapping the perspectives, issues and uncertainties involved in long-term strategic technology choice. The approach could be fruitfully explored in other contexts. In particular, many of the issues raised as important for hydrogen would not have been discussed and explored with reliance on a more narrowly framed approach.

Transition Pathways to the UKSHEC Hydrogen Visions

A UKSHEC working paper published in June 2006, *Transitions to a UK Hydrogen Economy*, explores possible transition paths to the visions outlined in this summary report. The transition paths are theoretically-informed qualitative scenarios, drawing on historical patterns of large scale technological change. The working paper will be available from www.psi.org.uk/ukshec

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Annex 1:

Indicators

These have been calculated using data from the GM (2001) and CONCAWE (2004) wells-to-wheels studies, which report, for a number of hydrogen generation pathways, wells-to-wheels energy use (in MJ/100km) and wells-to-wheels carbon emissions (in g/km CO₂). All pathways assume a fuel cell vehicle with hybrid electric powertrain.

Data on typical load factors and capacity sizes for different technologies have been taken from the Tyndall integrated scenario project. Data on current UK energy use and calorific values of fuels were taken from the DTI website. Typical yields of Short Rotation Coppice (SRC) taken from the Forestry Commission website.

The indicators assume are calculated on the basis of road transport demand remaining broadly similar to today, around 600bn passenger kilometres per year, which is also the level assumed in the Global Sustainability scenario of the Energy Review).

The data on synthetic hydrocarbon production routes is highly speculative, and has therefore not been included.

Tables showing calculations used to derive indicators. The letters in brackets indicate the source of the wells-to-wheels estimate, GM or CONCAWE (C).

	Wells-to-Wheels Energy use (MJ/km)	Total Primary Energy Requirement (WTW x 600bn passenger km, in GWh)	Total Capacity Required (Total GWh/ 8760 hours)	Typical load factor	Installation size	Number of installations
Nuclear Electrolysis, pipeline distribution	1.5 (C)	250,000	28.5 GW	0.74	1,200 MW	32
Wind electrolysis, pipeline distribution	1.5 (C) 1.74 (GM)	250,000 (C) 292,000 (GM)	28.5 (C) 33.3 (GM)	0.4	3 MW	24,000 (C) 27,700 (GM)
Wind onsite electrolysis	1.75 (GM)	290,000	33.1	0.4	3 MW	27,600

	Wells-to-Wheels Energy use (MJ/km)	Total Primary Energy Requirement (GWh)	Amount of Feedstock necessary (assuming 26.9 MJ per tonne)	As a percentage of 2003 consumption (53.7 million tonnes)
Coal Gasification, pipeline distribution	1.82 (C)	303,000	40.6m tonnes of coal	76%

	Wells-to-wheels Energy (MJ/km)	Total Energy Requirement (GWh)	As a percentage of 2003 consumption (1,110 TWh)
Steam methane reforming, pipeline distribution	1.5 (C) 1.68 (GM)	250,000 (C) 280,000 (GM)	23% (C) 25% (GM)
Steam methane reforming, onsite	1.6 (C) 2.08 (GM)	267,000 (C) 347,000 (GM)	24% (C) 31% (GM)

	Wells-to-Wheels Energy use (MJ/km)	Total Primary Energy Requirement (GWh)	Amount of Feedstock necessary (assuming 10.6 MJ per tonne)	Acreage (assuming average yield of 10 tonnes per hectare)
Biomass (Short rotation coppice)	1.65 (C) 2.0 (GM)	275,000 (C) 333,000 (GM)	46.7 million tonnes (C) 56.6 million tonnes (GM)	4.7 million hectares (C) 5.7 million hectares (GM)

NB: Both studies (CONCAWE and GM) include only emissions and energy costs in running vehicles, and in fuel production. They are not life-cycle analyses, i.e. no account is taken of the emissions and energy involved in vehicle, power station and infrastructure construction and maintenance.

Annex 2:

This table includes the full list of criteria, along with brief definitions of the criteria as recorded during the MCM interview.

Participant	Issue	Criteria Name	Notes
Nuclear Industry Expert	Environmental	GHG Emissions	Whole basket of greenhouse gas emissions
		Local air quality	Air pollution from transport
		Toxicity	Toxicity from supply chain as a whole, rather than from vehicle emissions.
		Visual impact	Wind turbines particularly, also energy crops.
	Social	Socio-political acceptability	Political and social feasibility: is political feasibility a major barrier to this vision?
	Economic	Affordability of h2 fuel	Is it affordable, not just 'at the pump', but in terms of affordability to the broader UK economy?
	Security	Redundancy/Security of primary supply	Redundancy - ability to access the same energy source from many places, or from secure sources
		Diversity of primary	Diversity of primary sources
	Other	Quality of supply	Issues about supply disruption and system integrity – including downstream security issues
		Technical feasibility	not just feasibility, also technical potential
Carbon Trust Analyst	Environmental	Global Impacts	Greenhouse gas emissions (whole basket), also ozone depleters and other global impacts
		Regional Impacts	Acid emissions (Nox, SOx), water quality & availability
		Local Impacts	Local air quality, noise, waste (solid, liquid, gas), visual impacts
	Social	Access to energy services	Access to energy and transport services. Both fuel poverty and access to transport services.
		Public acceptability	Attitudes to technology in general, and specifically: visual intrusion, issues around waste (nuclear and CCS). How firmly does society apply the precautionary principle?
	Economic	Cost of fuel	Includes running costs, infrastructure, switching costs, stranded assets
		Impact on UK Economy	How do we sustain growth? Does this represent a competitive economy, which supports the desired standard of living?
		Degree of consumer choice	Is choice enabled in this future?
	Security	Security/diversity	Both diversity in primary sources of energy, and diversity in source of energy at local point of use
	DTI Policy Maker	Environmental	Carbon Emissions
Other environmental Issues			Waste (including nuclear), noise and visual amenity, pollution, unknown impacts of hydrogen leakages
Social		Social acceptability	Is this vision socially and politically feasible?
Economic		Impact on UK economy	Jobs in new industries, shedding jobs in old industries, UK opportunities as early adopter.
		Impacts on local economy	Impact on local economy, and Impact on local and community independence
Security		Security	Diversity of sources, and security of primary sources.
Other		Health and safety	Throughout supply chain, but particular implications for use as a transport fuel by 'man in the street'.
		Feasibility	Primarily technical aspects
Fuel Cell Industry Participant	Environmental	Carbon Emissions	Carbon emissions
		Local air quality	Air pollution from transport
		Other environmental impacts	Nuclear waste, coal gasification concerns, disruption from pipelines, wind turbines
	Social	Social acceptability	Vision must meet same standards as today - refuelling time, range, convenience. Also social acceptability problems with carbon capture and storage, nuclear, and renewables - how intrusive is the technology?
	Economic	Fuel Cost	Cost of fuel, including capital costs
		Business case feasibility	Degree to which the future depends on large new capital plant, and losing sunk costs.
	Security	Supply Security	Both primary energy supply AND robustness of the energy distribution system
Sustainable Energy Consultant	Environmental	Cost effective carbon Reductions	Primarily about CO ₂ , but not carbon reductions at any cost.
		Local environmental impact	Noise, air quality, land use disruption, need to carve up landscape and urban environment

	Economic	Upstream Energy Security	Function of abundance of primary energy, and how secure each source is. Categorised as economic, because 'when that goes wrong, the impact is economic'
		Economic Attractiveness	Investment case on both supply and demand side. Must be economically compelling
Industrial Gases Industry Participant	Environmental	Carbon Emissions	Carbon emissions
		Local Air quality	Air pollution from transport
	Economic	Upfront capital costs	This is related to feasibility and economic attractiveness – is there an investment case?
		Ongoing fuel cost	Fuel cost to consumers
Security	Security of supply	Does the vision reduce dependence on limited feedstock?	
Energy Technology Researcher	Environmental	Greenhouse Gas	Greenhouse gas emissions
		Local Air Quality	Pollution from transport
		Other environmental impacts	Carbon sequestration, nuclear waste, pollution
		Biodiversity	Land use impacts, especially implications of bio-energy
	Social	Public Acceptability	Will the vision be subject to social resistance?
	Economic	Cost	Production, distribution and feedstock costs
	Security	Resource Scarcity	Extent of dependence on depleting resources
		Diversity of supply	Diversity of primary energy sources
Environmental Campaigner	Environmental	Greenhouse Gas	Greenhouse gas emissions
		PRINCIPLE: Nuclear	Any vision including nuclear power is unacceptable
	Economic	Cost	Generation cost, infrastructure and capital costs, and ultimately the cost of fuel to the public
		Other	Public Safety
	Flexibility		System robustness and ability to take shocks – and to respond to changing supply conditions
	Upheaval		To what extent does the vision imply major disruption in its realisation? New pipelines, installations in people's homes, digging up of pavements etc.
	Geo-political issues	Does the vision contribute to geo-political sustainability? Explored in terms of energy interdependence of Europe and developing countries	
Health and Safety Regulator	Environmental	Greenhouse gases	Greenhouse gas emissions
		Non-carbon pollution	Including nuclear, and life-cycle impacts of primary energy routes
	Social	Public acceptability	Public perception of risks, and ultimately political feasibility.
	Other	Practicability/feasibility	Feasibility, including potential costs and economic attractiveness. 'Why would people want this?'
		Flexibility	Can the vision cope with changes, or does the system limit the sorts of technologies that can be used?
Energy Policy Researcher	Environmental	Carbon Emissions trajectory	Carbon emissions trajectory over time.
		Natural Environment/wilderness	Impacts on wildlife, landscape, and the natural environment
		Catastrophic risk	Does the vision include technologies that may lead to catastrophic health risks, such as nuclear and carbon storage?
	Social	Social Justice	What are the political worlds implied by different technological systems? Includes access to political power, access to democracy, access to education and housing.
	Economic	Least cost portfolio	Least cost technology portfolio over time.
	Security	Primary supply	Upstream security issues
		Infrastructure	Downstream reliability issues
	Other	Radioactive waste	Political, environmental and social aspects.
		Complementarity	Must be complementary to an energy system that emphasises efficiency, reduced demand, and renewables.
Oil Industry Participant	Environmental	Energy Efficiency	Both an environmental and economic criterion. It is assumed that environmentally friendly energy is going to be in short supply, and as a result will be expensive, so efficient use will be important.
		Physical integrity	Leaks, safety issues, spills & toxicity, and potential environmental damage as a result.
	Social	Physical intrusion	How much disruption does this cause in day to day life - noise, upheaval, digging up the lawn.
		Control of energy	Is the energy system is "the servant or master of society" – i.e. is there choice, or are you dominated by few large players/single system?
		Usability	How easy is it for consumers, and does the system enable access? How do people experience their interaction with the technology?

	Economic	Affordability	Affordability of energy supply to the consumer, from a societal perspective, i.e. including subsidies and wider costs to the economy
	Security	Diversity of sources	Substitutability and flexibility, and diversity of sources – can you change sources when one is constrained?
DfT Policy Maker	Environmental	Carbon	Carbon reductions
		Other environmental issues	Pollution, air quality, nuclear waste, landscape, noise
	Social	Public acceptability	What's in my backyard? Political feasibility and potential for social opposition
	Economic	Business case feasibility	Is there a reasonable payback period for investors? Cost is a major factor, but also broader economic attractiveness
	Security	Security of supply	Primary source of energy, as well as integrity of infrastructure and its ability to withstand shocks.
Automotive Industry Participant	Environmental	WTW Carbon	Wells-to-wheels carbon emissions
		Utilisation of available resources	Efficiency, and best use of available renewables, biomass, waste streams.
	Social	Degree of state intervention required	How much state interference is necessary to achieve the vision, and political freedom
	Economic	Economic feasibility	Upfront and ongoing costs
Security	Security/diversity	Diversity of primary sources in fuel supply	
Regional Government Policy Maker	Environmental	Carbon	Carbon emissions
		Air quality	Air pollution from transport
		Complementarity with renewables	Fit with renewables – does the vision support the development of low carbon and renewable energy technologies?
	Social	Acceptability/risk	Perceptions of risk, and actual physical risks
	Economic	Cost	Direct economic cost of infrastructure, running costs, management.
Security	Compatibility with decentralised	Degree to which the vision facilitates local control, downstream energy security, and micro/local generation.	
Climate Scientist	Environmental	Global environmental improvement	Probability that implementation will lead to global environmental improvement. This is about leakage of h2, replacement of co2 etc.
	Economic	Cost competitiveness	Likelihood of it being competitive - competing with alternatives in energy & transport.
	Other	Scale of tech deployment	If a tech is only going to be implemented on a small scale, must be exceptionally good. The bigger the better, in this sense.