H-delivery WP 3 – Task 3.2: Characterisation of prospective technologies

Analysis of Delphi surveys relating to the development of a hydrogen economy and complementing or competing technologies.

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Contents

Background

SUPERGEN XIV - Delivery of Sustainable Hydrogen brings together 12 of the UK's leading universities to jointly work on a range of research topics aiming to radically improve the way in which Hydrogen and hydrogen-based fuels are produced and delivered. Work Package (WP) 3 Socio-technical Analysis and Appraisal of Hydrogen Production brings together the engineering and socio-economic dimensions of the consortium's research. We aim to undertake rigorous interdisciplinary assessment and modelling of the potential for novel and emerging technologies to contribute to the large-scale delivery of sustainable hydrogen, and identify specific recommendations for future research, policy and industrial development.

Introduction

This paper contributes to H-Delivery Task W3.2: Technology Characterisation. It provides a detailed review of existing Delphi literature dealing with low carbon technologies which either complement or compete with the future of hydrogen energy.

The review aims to identify predicted timescales of the technologies discussed as well as the likely drivers and barriers to progress. Where it is possible, the forecasts made in the past will be considered in light of actual progress. However, it is usually better to consider the results of a Delphi survey as the condensed opinion of experts about the future rather than as an actual forecast.

Overview of Low Carbon Energy Delphi Studies

Table 1 shows a summary of the Delphi surveys on energy which have been undertaken. The surveys have been divided into main topics (i.e. Hydrogen, Renewables, Fossil fuels and carbon capture & storage and General reviews). The table shows:

- the time period considered
- the number of participants
- the location considered
- the survey method

Table 1 Summary of Delphi Surveys including energy

Author and Year of Survey	Time Period	No of participants	Location	Survey Description
Hydrogen - *Production, Storage and Distribution*				
Valette [1] 1978	1985 / 2000	86	Global	3 round Delphi survey
Tzeng [2] 2005	2005	Unspecified	Taiwan	2 round Delphi survey with Multi criteria analysis using VIKOR and TOPSIS
Yuzugullu [3] 2007	2007	12	Unspecified	Phase 1: Multiple iterations of Delphi survey Phase 2: Multi Criteria Decision Making Analysis

Hart [4] 2009	2019 / 2024	49	US / Global	Quasi –Delphi: 1 round of semi-structured interviews
Bristow [5] 2008	2050	Unspecified	UK	Unspecified
Renewables				
Terrados et al [6, 7] 2000	2000-2010	9	Spain	Phase 1: SWOT analysis Phase 2: 2 round Delphi Phase 3: Multi Criteria Decision Making Analysis
Brent [8] 2009	2015	7	Africa	2 round Delphi survey
Iniyan et al [9-11] 1998	2020	151 (round 1)	India	2 round Delphi survey
Rikkonen [12] 2009	2004 / 2025	20	Finland	Phase 1: semi-structured interviews Phase 2: postal survey Phase 3: 1 day seminar
Al Saleh [13] 2009	2050	33	Saudi Arabia	3 round Delphi survey
Fossil Fuels and Carbon Capture & Storage				
Gough [14] 2008	2010-2050	88	UK	phase 1: online survey phase 2: workshop
General Ene rgy Reviews				
Utgikar [15] assessment (2006) of Smil [16] 1974	1985 / 2000	40	Global	unspecified
Rohatgi [17] 1979	3000	Unspecified	India	2 round Delphi survey
Georghiou [18] 1996	1995-2015	2585	UK	2 round Delphi survey Parallel regional workshops
Wehnert [19] 2007	2010-2040	669	Europe	Phase 1: Vision Workshop Phase 2: 2 round Delphi survey Phase 3: Scenario Development workshops
Wilenius [20] 1997	2050	142	Finland	Phase 1: survey Phase 2: group discussions (separate policy makers and researchers) Phase 3: group discussion (mix of policy makers and researchers)
Glenn [21] 1999	2000-2050	270	Global	Phase 1: interviews Phase 2: e-mail survey Phase 3: interviews
De Oliveira Matias [22] 2007	2010-2060	180	US	Not specified

A chronological and geographical discussion of the Delphi surveys for each topic is given below.

Hydrogen production, storage and distribution

2000 – production level and method

A three round Delphi survey of eighty six technical experts representing thirteen countries in 1978 [1] predicted that hydrogen would provide 5% of global energy consumption by 2000. This prediction was based on an expected increase in the use of fission reactors for electricity generation and spare capacity used for hydrogen production. It was expected that most of the remaining hydrogen would be produced from steam methane reforming. These predictions have been severely impacted by the increasing resistance to fission use.

2007 – Societal Welfare

Yuzugullu and Deason's Delphi survey [3] developed a hierarchy to be used when considering the impact of hydrogen production on societal welfare. The variety of methods which can be used to produce hydrogen presents a challenge to identify the methods with least impact. The criteria to be considered are shown in Figure 1 Hierarchy of hydrogen impacts on societal welfareFigure 1.

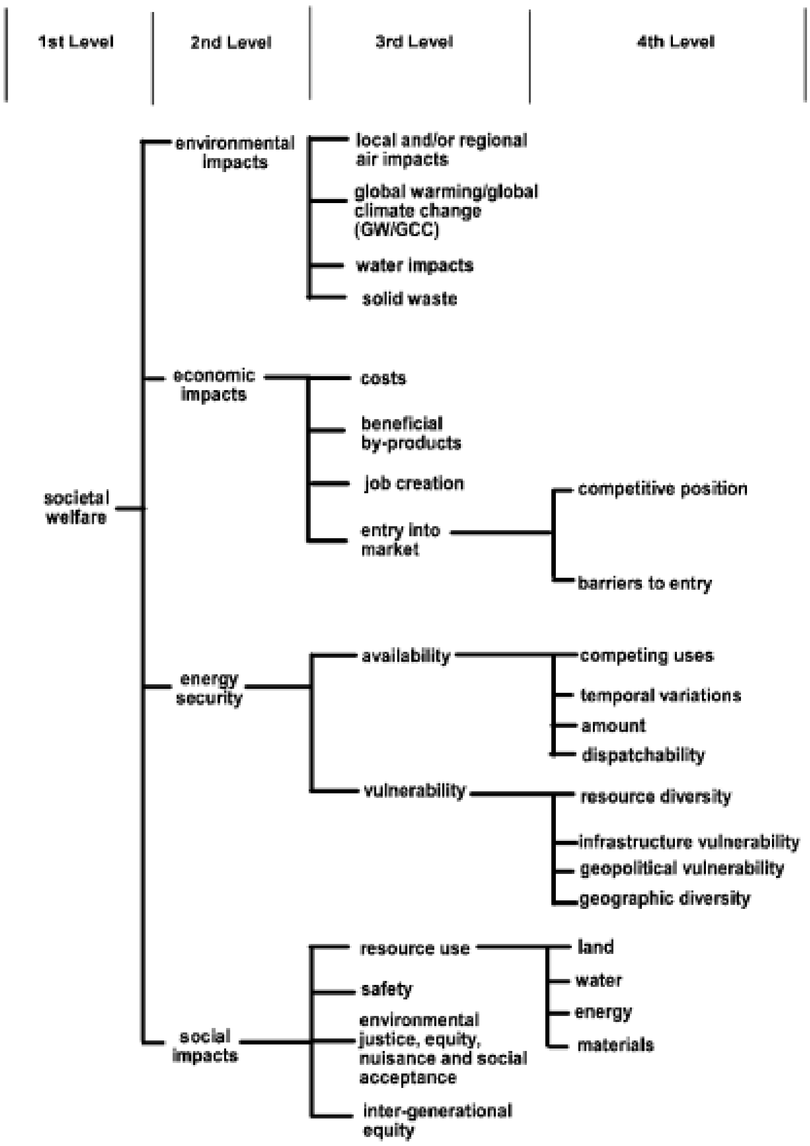

Figure 1 Hierarchy of hydrogen impacts on societal welfare

2009 - barriers

Hart's 2009 investigation [4] of global barriers to hydrogen use in transport included issues relating to hydrogen production and storage. Findings include:

- China is carrying out very little research in the field of small-scale hydrogen production or on-board (automotive) storage.
- Japan is concerned about the dependability and cost of small scale hydrogen production plant. This is aggravated by the requirement for Japan to import liquefied natural gas as a raw fuel to convert to hydrogen. High pressure hydrogen storage is considered the most likely form for the near to mid term.
- North American experts believed that cost, energy density and public acceptance issues relating to hydrogen storage would be solved within ten years.
- European experts not working directly on vehicles were concerned about hydrogen storage density. However, this concern was not shared by original equipment manufacturers and fuel cell drivetrain experts.

2040 – practical use

The European Energy Futures Study [19] considered technical drivers for future energy sources by asking participants to state the Time of Occurrence for a variety of statements. The findings related to hydrogen are shown in Table 2. The mean result is an indicator of how long it may take for certain technologies to develop. However, the spread between the interquartile results indicates the confidence of the participants in their prediction (i.e. a large interquartile range indicates lower confidence in the mean result). The actions required to promote early occurrence of the statement were also considered.

Table 2 European Hydrogen Development (results interpolated from Fig 11.25 [19])

	Mean	Interquartile
Biological or bio-chemical production of hydrogen in practical use (basic then applied R&D*)	2029	2021-2038
Hydrogen produced from diverse sources and used as an energy carrier constitutes a significant part of the energy system (basic & applied R&D then fiscal measures*)	2033	2024-2041
Hydrogen produced solely from renewables and used as an energy carrier constitutes a significant part of the energy system (basic & applied R&D then fiscal measures*)	2034	2026-2043

* action needed to promote early occurrence

Hydrogen Applications

The share of total hydrogen demand predicted by a 1978 Delphi survey [1] is shown in Table 3.

Table 3 **Share of total Hydrogen Demand for 1990 and 2000**

	1990		2000	
	%	Mtons	%	Mtons
Chemical Industry	77	44-65	41	63-109
Iron and Steel	13	7.4-11	17	26-45
Other industry	8	4.5-6.8	12	18-32
Residential and commercial	0	0	12	18-32
Transport	2	1.1-1.7	12	18-32
Electricity generation	0	0	6	9-16
Total		84.5		266

The combination of increasing hydrogen requirement by traditional hydrogen users and new applications was considered to require a threefold increase in the amount of hydrogen produced between 1990 and 2000.

Transport
2000
The Delphi study conducted by Valette et al [1] considered that liquid hydrogen would be a likely fuel for air and sea transport by 2000 with methanol more likely for individual cars and a split of methanol and liquid hydrogen for land based public transport. It also predicted that hydrogen would power 10% of private and 20% of public land transport, 10% of air transport and 2% of sea transport.

2005
Twelve fuels including hydrogen were assessed against eleven criteria for powering the public bus system in Taiwan [2]. The fuels under consideration were:

- Hybrid electric with gasoline engine
- Hybrid electric with diesel engine
- Hybrid electric with compressed natural gas engine
- Hybrid electric with liquid propane gas engine
- Electric bus – exchangeable battery
- Electric bus – opportunity charging
- Electric bus – direct charging
- Liquid propane gas
- Compressed natural gas
- Diesel
- Hydrogen
- Methanol

The ranking of hydrogen (where 1st is most desirable) for each of the criteria was:

- Availability of energy supply – 11th
- Energy efficiency (used in fuel cell) – 10th
- Air pollution – 4th
- Noise pollution – 4th
- Industrial relations – 11th
- Employment cost – 5th
- Maintenance cost – 12th

- Capability of continuous travel– 8th
- Road facility – 8th
- Speed of traffic – 12th
- Sense of comfort – 9th

In the short to medium term the hybrid electric bus was considered the most suitable, although if the cruising distance of the electric bus could be extended to an acceptable range it would be the best option.

This Delphi survey included service users who were considered to have an expert view on the situation and therefore included in the Delphi survey along with bus manufacturers, bus operators, research organisations, environmental groups, city and national transport departments, vehicle associations and energy experts.

2024

Potential barriers to the implementation of hydrogen fuel supplies in transport by 2024 were explored on a global scale by Hart [4]. In general it was thought that individual technical problems (e.g. catalyst loss, membrane degradation and contaminant resistance) were solvable by known techniques although it was acknowledged that interaction between these issues created a more complex challenge. A more significant challenge was considered to be the development of a suitable supply chain for automotive fuel cell parts since existing automotive suppliers do not understand fuel cells and fuel cell suppliers are not equipped for low cost mass production at near zero defect rates.

Regional findings were:

- China – the national government is supporting fuel cell R&D; however, China is potentially behind other regions in solving key technical problems. So far the government is only providing limited funds towards deployment. Although issues with infrastructure are expected, issues with public acceptance are not. Although experts from other regions felt that China had opportunities to leapfrog other regions and deploy fuel cells early, the Chinese experts were concerned that there were many policy issues to be dealt with and relatively weak corporate support.
- Japan – the government is supporting deployment; however, there is concern that the codes and standards for high pressure gases developed for industry may result in over-engineering of hydrogen fuelling solutions. There are also issues for small companies specialising in specific technologies to achieve lower costs before receiving the large orders that would enable cost reductions. Experts from other regions identified Japan as the prime location for commercial deployment of fuel cell vehicles.
- North America - The larger size of North American vehicles gives more opportunity for integrating bulky components but also requires more power. Particular barriers are anticipated to be:
    - local variation of codes and standards
    - public acceptance of high pressure gas tanks
    - high stack costs
    - insufficient and unfocused public and government support – particularly relating to infrastructure

- Europe – although most technological problems were considered likely to be solved within five years, the issues of public acceptance and competing with incumbent technologies were viewed as requiring fifteen years to solve.

North American and European experts shared the view that technology was less of an issue than the overarching deployment strategy. It was felt that more coherent government support was required to co-ordinate vehicle roll out with infrastructure and support supply chain development.

2040

The European Energy Futures Study [19] considered the future of hydrogen as a transport fuel. It was considered that fuel cell driven cars would reach a 20% share of the European market by 2027 (interquartile range 2022-2030). Initially this would be based on gases other than hydrogen, until a suitable supply of hydrogen could be made.

2050

A Delphi study was used to explore the impact of a range of transport strategies that might achieve emission targets by 2050 [5]. The options explored were:

1. Develop technology but allow demand to continue unrestrained – this scenario included the use of carbon neutral hydrogen as a transport fuel, along with increasing use of biofuels and decarbonised electricity
2. Develop technology but restrain demand through pricing (3.5% annual increase)
3. Develop technology and improve public transport service
4. Develop technology and implement telecommunications and soft measures

Option 1 suffers from concerns about availability of carbon neutral hydrogen as well as the potential that hydrogen use in other areas could result in more substantial carbon displacement. However, it was felt that a combination of all four options would be required to make a significant impact in future transport carbon emissions.

Renewables

2010: Spain

Terrados et al [6, 7] made use of the Delphi survey in conjunction with Multicriteria Decision-making analysis (MCDA) and analysis for Strengths, Weaknesses, Opportunities and Threats (SWOT) to consider a major socioeconomic development for the Spanish province of Jaén. The energy aspects of the region and initial strategy selections were considered using the SWOT analysis. The Delphi survey was used to validate and assess twenty eight selected strategies, then the alternatives were ranked using MCDA. The MCDA considered such aspects as:

- Total primary energy saved
- Continuity and predictability of resource
- Sustainability according to CO_2 and other emissions
- Sustainability according to other impacts
- Job creation
- Financial requirements
- Compatibility with local, regional and national policies

This allowed prioritisation of the potential actions which included:

- Combustion and gasification of olive and wood industry residues and other wastes
- Biomass heating systems
- Installation of new small hydro plants and refurbishment of existing facilities
- Photovoltaics
- Solar thermal heating
- Wind turbines
- Energy crop exploitation

Although hydrogen has not been included in this assessment, the technologies considered could be utilised to produce hydrogen.

2015: Africa

Brent and Kruger [8] investigated the high failure rate of renewable energy projects in Africa. Issues which have tarnished the reputation of renewables include project based provision which leave communities without maintenance or assistance at the end of the project. The rural poverty which hinders access to finance for technological developments is probably also a factor in the prevailing level of technological ignorance. The barriers faced by renewable energy may also apply to the introduction of hydrogen based technologies in this region.

2015: UK

The UK Technology Foresight [18] exercise considered the benefit to the UK of fifteen areas (including Energy) by 2015. The topics were rated in relation to their benefit to quality of life and wealth creation. Environmental improvements and renewable energy were considered most beneficial to quality of life. Apart from energy efficiency developments, the main topic which rated well in wealth creation and benefit to quality of life was "development of chemical components for solar cells with energy conversion greater than 30%". Hydrogen was not mentioned in this report.

2020: India

Iniyan et al [9-11] have investigated the social acceptability of renewable energy contributions to cooking, heating, pumping, transport, lighting and cooling in India looking forward to 2020. The renewable technologies being considered are biomass, wind, small hydro, ocean thermal energy conversion (OTEC), solar direct thermal, solar thermal electric conversion and photovoltaics.

A two round Delphi survey was carried out. The majority of the participants were academics, industrialists, scientists and policy makers. Users of renewable energy systems were included in the group. Each technology was assessed on Technology, Equipment efficiency, Price, Availability and Environmental quality. The first round was assessed on the mean response. The second round was assessed on skewness (shift between rounds) and rank.

The preferred options for each application were found to be (in descending order of preference):

- Cooking - solar cookers and biofuel options (techniques that involved conversion to electricity were considered uneconomical).
- Pumping – wind, biomas gasifier, photovoltaic, small hydro and biogas. Ethanol, solar thermal electric conversion, solar thermal and OTEC were considered uneconomical.
- Heating – solar thermal, biomass combustion, solar thermal electric conversion, biomass gasifier and biogas (other techniques were considered uneconomical).
- Cooling – solar thermal electric conversion, photovoltaic, solar thermal, wind and biomass gasifier. Other techniques were considered to have low potential or high unit cost.
- Transport – ethanol, photovoltaic and solar thermal electric conversion were all viewed favourably.

It was found that factors adversely affecting the utilisation of renewables included price, equipment efficiency, technology, availability and environmental factors.

Although hydrogen was not included in this assessment, some of the technologies considered have potential to produce hydrogen.

2025: Finland

The probable and desirable potential of agriculturally produced bioenergy in Finland was investigated by Rikkonen and Tapio [12]. This would result in farms becoming energy self-sufficient and providing biomass to the energy industry. On a national level this would provide rural job opportunities and reduce dependence on imported energy. Different agricultural products and wastes can be used for different applications:

- Wood and agrobiomass (e.g. canary grass, crop residues and willow) are likely to be used for heating
- Biogas (related to livestock) has potential use in heating and transport
- Biodiesel also has potential use for transport and can be cultivated from a variety of plants

These sources could all be utilised to produce hydrogen.

Five potential visions were developed from the responses.
Incremental change – EU climate policy has little effect on Finnish energy and agricultural policies, but there is some progress on a local level since biomass burning systems have been implemented.
Renewable Prosperity – all renewable energy forms utilised strongly. In addition to energy self-sufficiency, farms produce energy for the local community and take on board technical solutions such as district heating, biogas production and biomass for power plants as well as wind turbines and solar for on-farm electricity.
Sun, Wind and Wood – is similar to renewable prosperity, with the exception that biomass could displace food production.
Let's burn it all – takes the existing use of biomass combustion to the logical next step of field biomass burning. It will also utilise water power, but solar energy and wind power will be marginalised.

Flood of waterpower – the waterpower system will be modernised and a new artificial lake will be built in Northern Finland as well as smaller rivers harnessed for agricultural use integrating irrigation and electricity production. Biomass, solar and wind power will be marginalised.

The national integration of the EU Energy and Climate Change Package is seen as key in influencing future developments.

2040: Europe

The Time of Occurrence and actions required to promote early occurrence for statements relating to renewable energy in Europe are shown in Table 4.

Table 4 Potential Renewable Energy Developments (results interpolated from Fig 11.25 [19])

	Mean	Interquartile Range
Biomass for central heating and district heating systems is widely used (Applied R&D, Fiscal Measures, Regulation & Public Acceptance*)	2017	2013-2020
Renewable energy sources cover 25% of Europe's total energy supply - 6% in 2007 (Applied R&D, Fiscal Measures, Regulation & Public Acceptance*)	2027	2022-2035
Biofuels will have an European market share of >25% in the road transport sector (Basic & Applied R&D & Fiscal Measures*)	2027	2020-2032
Large international grids allow an energy production based on regional renewables - solar thermal power from North Africa, biomass from Central Europe etc (Applied R&D, Fiscal Measures & Regulation*)	2033	2024-2042
Photovoltaic cells contribute with >5% of European electricity generation - 0.15% in 2007 (Basic & Applied R&D & Fiscal Measures*)	2034	2025-2042
Ocean technologies (e.g. tidal, currents and wave) are in practical use (Applied R&D & Fiscal Measures*)	2036	2018-2044

* action needed to promote early occurrence

There is potential to integrate hydrogen production as a method of storing energy from intermittent renewable technologies. The predicted increase in renewable technologies may provide opportunities for hydrogen storage; however, cheaper options for energy storage are being explored.

2050: Saudi Arabia

Al Saleh [13] investigated the potential use of renewable energy in Saudi Arabia depending on the future availability of fossil fuels and requirement for environmental protection. There was little concern regarding the land density of energy generation due to the large area available for the population. Many of the challenges to transforming the energy system from fossil fuels to renewables revolve around the political situation of a monarchy with considerable power and financial resource.

Fossil Fuels and Carbon Capture & Storage (CCS)

Carbon capture and storage will be an essential process to prevent carbon emissions if fossil fuel resources are used for the manufacture of hydrogen.

2040: Europe

The future use of fossil fuels along with carbon capture and storage was considered in the European Energy Futures Study [19], see Table 5.

Table 5 Fossil Fuels and Carbon Capture & Storage Developments (results interpolated from Fig 11.25 [19])

	Mean	Interquartile range
CO_2 capture and sequestration from fossil fuel power plants is in practical use (basic & Applied R&D, Fiscal Measures and Regulation*)	2022	2014-2027
Liquefied Natural Gas terminals and advanced high-pressure pipeline systems permit to multiply Europe's gas imports by 10	2023	2014-2028

* action needed to promote early occurrence

Although it is accepted that fossil fuels will be required to facilitate the transition, the future of a hydrogen economy depends on its being produced from other sources.

2050: UK

Gough reports on a Delphi study which explored various aspects of carbon capture and storage from now until 2050 in the UK [14]. The survey included a Delphi survey of eighty eight people representing industry, academics public sector research, environmental NGOs, government departments and policy development bodies. This was followed by a workshop involving some of the original survey participants along with selected additional stakeholders.

The Delphi study was split into sections which are discussed below.

Electricity Generation
The 38 qualified respondents were asked their opinion on the fuel mix for electricity generation which they expect in 2050, and what they would like it to be. Tent diagrams plotting the response of the 10^{th}, 50^{th} (median) and 90^{th} percentile were plotted to allow comparison (Figure 2. Graphs showing expectation and preference for the electricity supply fuel mix to 2050Figure 2).

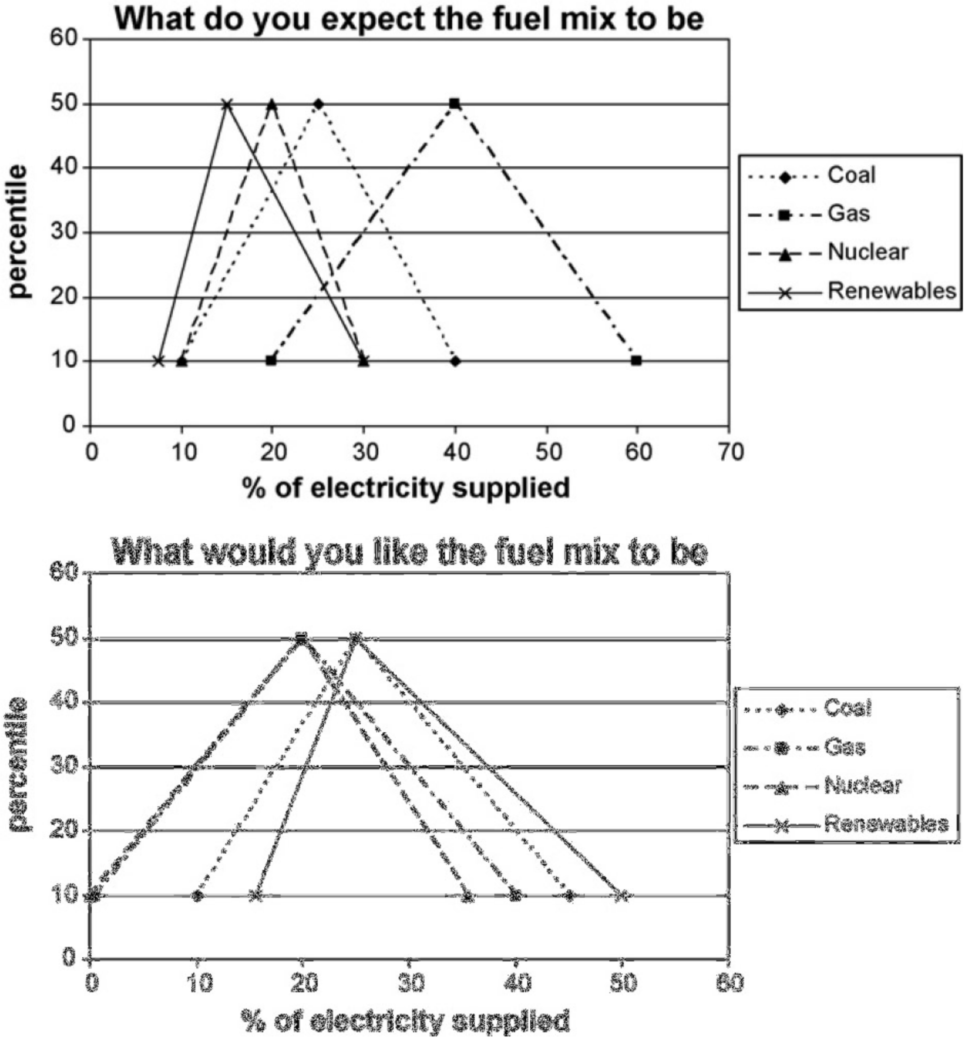

Figure 2. Graphs showing expectation and preference for the electricity supply fuel mix to 2050

It is noted that although half of the respondents would like renewables to supply approximately 25% or more of the electricity, 15% was considered to be a more realistic figure. Coal is expected to play a more significant role than the respondents hoped, perhaps indicating a stronger case for CCS.

Carbon Capture and Storage

Respondents were asked to identify the most important challenges that could prevent the implementation of CCS in the UK. Their response is illustrated in Figure 3.

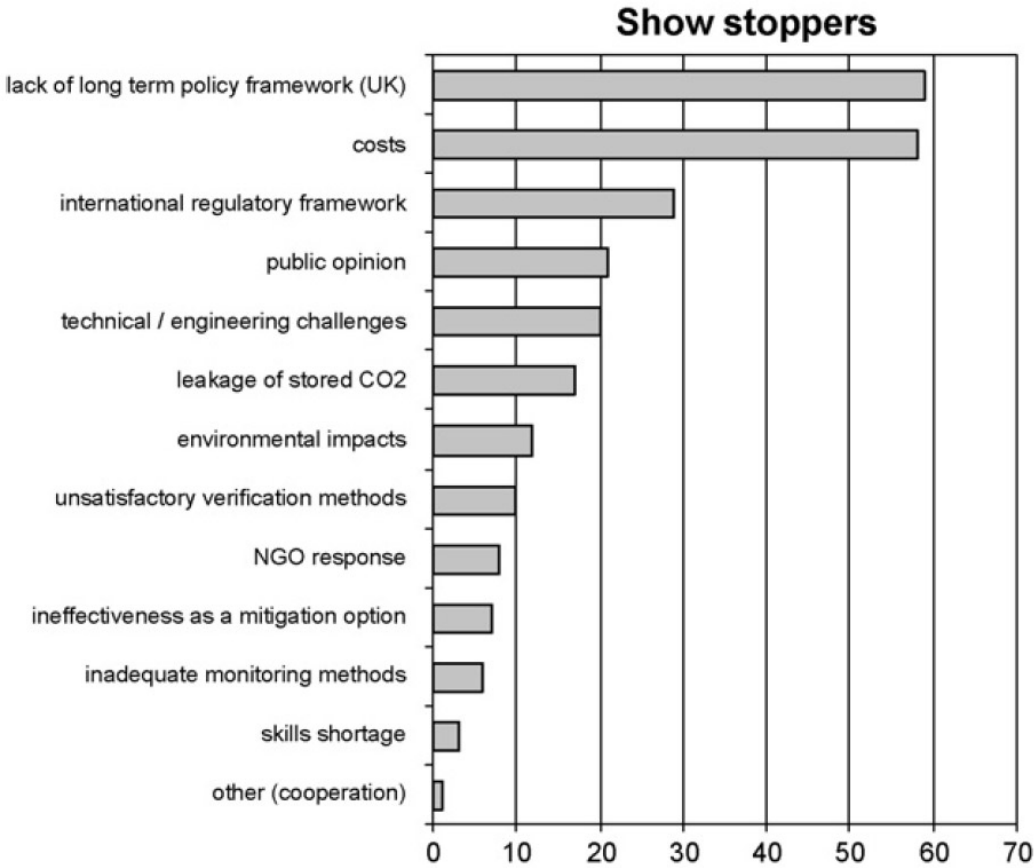

Figure 3. The most important challenges that could prevent the implementation of CCS in the UK

It should be noted that technical / engineering challenges only rate as the fifth most frequently cited barrier to the implementation of CCS in the UK. Several of the non-technical challenges could equally be applied to the development of hydrogen technologies, although possibly with different priorities.

CO_2 infrastructure
On the topic of "Who should pay for new pipeline construction to transport CO_2?" 48% thought the cost should be shared between the storage site operators and the CO_2 providers, while 42% thought the government should also share the burden.

Environmental and safety risks which were associated with CO_2 transport by onshore pipelines included: CO_2 emissions, landscape effects, drinking water contamination, soil contamination, ecosystem impacts and health and safety impacts (including potential suffocation or jet of solid particles in event of a rupture). Similar questions about costs and environmental / safety risks could equally apply to hydrogen infrastructure.

Risks and leakage
The environmental risks associated with CCS were compared to those of an equivalent (in terms of CO_2 reduction) use of nuclear power. Of the 46 respondents,

74% thought that CCS would be slightly less or much less risky than nuclear power. Many respondents qualified their statement by commenting that CCS had a much higher probability of a leak but that the repercussions would be far less than for a nuclear leak. This method of comparing risks with other relevant technologies may be useful when investigating in considering hydrogen.

Costs and economics
Only 10 qualified responses to this section were received – this was the lowest expertise response to a section.

Costs were considered in terms of the likely impact on electricity prices. The utilisation of hydrogen in conjunction with renewables as an energy storage mechanism may also impact on electricity prices, although it is likely that hydrogen itself will be traded independently for chemical and energy uses. The likely increase in the cost of fuel should be compared with the premium that the majority of people are willing to pay for energy which does not cause carbon emissions. The 2005 Eurobarometer survey found that a 5-10% premium was generally accepted in terms of renewable energy. The question "What would lead to the greatest reduction in costs?" would be equally applicable to the hydrogen sector.

Incentives
92% of respondents believed that the CCS industry should receive incentives – most particularly in the form of support for R&D.

Regulation
Changes to national and international regulations are required to facilitate the transport and storage of CO_2 offshore. Similar issues may apply to removing barriers for hydrogen production, transport, storage and application.

International context
Although the majority of respondents agreed that UK should aim for a leadership position in the CCS market, the majority also felt that UK currently only had an average capability for carbon capture, transport and storage.

General Energy Reviews

The information from the general energy reviews have been considered under the following headings:

- Nuclear
- Energy Storage Supply and Transmission
- Energy Policy

Nuclear

The European Energy Futures Study [19] considers technical drivers for future energy developments including nuclear power. The mean and interquartile range for the considered developments are shown in **Error! Reference source not found.**.

Table 6 Mean Year and Interquartile range for potential nuclear power developments (results interpolated from Fig 11.25 [19])

	Mean	Interquartile range
Nuclear power plants based on passive safe reactor types are in practical use (Basic & Applied R&D, Public Acceptance*)	2026	2018-2029
Plasma confinement technologies for nuclear fusion are in practical use (Basic & Applied R&D, Public Acceptance*)	2038	2033-2045

* action needed to promote early occurrence

Nuclear energy elicited a divided response from the participants. The apparent contradiction between the high level of funding for fusion energy research versus the anticipated benefits within the next thirty five years was noted several times. As regards fission, the established potential for low carbon energy and improved energy security was acknowledged at the same time as the issues of waste management, political instability and terrorism were highlighted.

Energy Storage, Supply and Transmission

Energy storage and supply was considered as part of the European Energy Futures Study [19]. The Time of Occurrence for three key factors in this area are shown in **Error! Reference source not found.**.

Table 7 Potential energy developments relating to Energy Storage, Supply and Transmission (results interpolated from Fig 11.25 [19])

	Mean	Interquartile
Distributed energy systems supply 30% of Europe's electricity (applied R&D, fiscal measures, regulations then public acceptance*)	2021	2014-2025
Advanced energy storage technologies are widely used in renewable energy supply systems (basic & applied R&D*)	2023	2016-2027
Widespread use of superconductive materials in transformers and generators (basic R&D*)	2028	2022-2035

* action needed to promote early occurrence

The increase of distributed energy systems will increase the requirement for energy storage. Although hydrogen can have a role to play in energy storage, the participants of this study considered that cheaper options would be required for the majority of storage. It was considered that the development of hydrogen as an energy carrier would be likely to diminish the importance of using superconductive materials to improve the efficiency of electricity transmission.

Energy Policy

The information relating to energy policy has been presented in order of increasing scale (i.e. individual countries, then Europe followed by global).

2050: Finland

A review of Finland's greenhouse gas emissions revealed that they are increasing faster than any other country belonging to the Organisation for Economic Co-operation and Development. With this information in mind, a Delphi survey on Finnish carbon emissions was carried out [20]. The participant population was made up of Policy makers (civil servants, economists and representatives of industry, the economy and interest groups) and Researchers (mainly climatologists and natural scientists with some social scientists, economists and technology experts).

The survey considered the different policies which could drive Finnish society to very different shapes by 2050. These policies could favour technical development, qualitative change, ecological restructuring or stay with 'business as usual'. The view for future energy policy in Finland relies heavily on technological developments to improve energy efficiency and reduce the carbon emissions of energy generation.

2040: Europe

The societal 'pull' for potential technologies was analysed as well as the technical 'push'. The societal pull was analysed through its potential impact, its importance to future society models and finally in its position within considered scenarios.

Potential Impact

The substitute technologies considered in the European Energy Futures Review [19] and listed in Tables 2 and 4-7 were considered in terms of their impact on:

- Wealth creation
- Environment
- Quality of life
- Security of supply

The technology considered to be the most beneficial in all four categories was renewable energy sources, closely followed by energy efficiency in buildings and industry.

Hydrogen related technologies were perceived as providing medium benefits, although hydrogen from renewable sources was considered more favourably than hydrogen from other sources.

Nuclear technologies had low ratings over all, although they had an average impact for security of supply. Similarly CO_2 capture and sequestration received very low ratings although it was considered as beneficial for environmental reasons.

In general the technologies scored higher on environment and security of supply than they did on wealth creation and quality of life.

Future Society Models / Societal Visions

Since it is practically impossible to predict the type of society which will exist in the future, three boundary points for future society were envisioned within which it is expected future society will exist. The three boundary points are:

- Individual Choice – emphasis on individual needs, liberalised markets and consumer sovereignty in the choice of products and services
- Ecological Balance – valued protection of the ecosystem, ecological awareness and sustainable production and consumption

- Social Equity – reduction of income disparities and social exclusion accompanied by community balance and cohesion at European level (allowing for regional solutions)

The importance of substitute technologies was assessed for each vision. The ranking for each type of technology is shown in Table 8.

Table 8 Ranking of technology for Societal Visions

Ranking	Individual Choice	Ecological Balance	Social Equity	Mean
High	Energy conservation	Energy conservation	Energy conservation	Energy conservation
	Fuel cells	Wind	Biomass	Demand Side Management
	Demand Side Management	Biomass	Demand Side Management	*Biomass*
	Alternative transport fuels	Photovoltaics	Wind	Fuel cells
	Energy storage for electricity	Fuel cells	Alternative transport fuels	*Wind*
	Pan European electricity and gas grid	Demand Side Management	*Energy storage for electricity*	Alternative transport fuels
	Natural gas import by pipeline	Alternative transport fuels	*Photovoltaics*	Energy storage for electricity
	Hydrogen production and storage	**Hydrogen production and storage**	Fuel cells	Photovoltaics
	Biomass	Energy storage for electricity	**Hydrogen production and storage**	**Hydrogen production and storage**
	Wind	CO_2 sequestration	*Pan European electricity and gas grid*	Pan European electricity and gas grid
	Photovoltaics	Geothermal	Natural gas import by pipeline	CO_2 sequestration
	Liquefied natural gas imports	Ocean Power	Geothermal	Natural gas import by pipeline
	Nuclear fission	Pan European electricity and gas grid	Liquefied natural gas imports	Geothermal
	CO_2 sequestration	Natural gas import by pipeline	CO_2 sequestration	Ocean Power
	Geothermal	Liquefied natural gas imports	Ocean Power	Liquefied natural gas imports
Low	Ocean Power	Nuclear fission	Nuclear fission	Nuclear fission

(NB italics denote that the technology has the same ranking as the technology above it, the position of hydrogen production and storage in each ranking has been highlighted)

For "Individual Choice" the flexibility of the energy technology matters more than the energy source (i.e. whether or not the energy is renewable). Renewable technologies are rated higher for "Ecological Balance" than for "Social Equity" which has similar ratings to the mean of all three visions. In general, energy conservation and demand side management technologies topped all three visions, followed by biomass then fuel cells.

The difference in analysis between technology push (summarised in Tables 2 and 4-7) and social pull (summarised above in Table 8) can lead to a ‘feasibility gap’ which indicates that although the technology is well appreciated by the energy community it may face troubles in implementation due to less of an appreciation at social level and thereby suffer from underinvestment. Technologies facing a feasibility gap include:

- Energy conservation technologies (all three societal visions)
- Pan European electricity and gas grid (Individual Choice)
- Natural gas imports by pipelines (Individual Choice)
- Biomass (Social Equity)

Scenarios

When constructing scenarios for 2030, it was impossible to predict a ‘*business as usual*’ situation since major structural changes are already taking place and serious upheavals are likely in the future. A *desirable* scenario would be the combination of demand reduction with sustainable exploitation of renewable energy sources; however, there is no clear pathway to this point. Potential scenarios are described below.

“Muddling through across a gas bridge” - use of natural gas as an intermediary solution for transport and power generation while a slow transition towards sustainable energy takes place. This late response would result in depleting reserves and evident effects of climate change in some European areas before 2030. In this scenario it is unlikely that enough hydrogen would be produced by 2030 to allow its substitution of electricity or transport fuel.

“Fossil fuel wars” - a general lack of willingness among citizens and companies to bear the increasing costs of environmental protection. There is a strong likelihood that this would lead to armed conflict over the control of oil and gas reserves with increased international trade barriers. The signals of depleting reserves may not be obvious until 2020, then the tightening supply will cause a sudden increase of tensions. During the period to 2030 the slow development of hydrogen infrastructure will have held back the market penetration of fuel cell cars. The main hydrogen sources will be renewable with some contribution from fossil fuels; however, there will not be sufficient amounts for transport or power generation except as backup for remote areas and crucial sectors (e.g. hospitals). The hydrogen is likely to be distributed in pressurized bottles by road or rail or in some areas by local pipeline networks. Some countries will have invested in enough R&D for wind, biomass and solar thermal to have reduced investment costs. However, photovoltaics are still likely to have problems penetrating markets where there aren’t enough public subsidies. The energy squeeze will lead to a reluctant public acceptance of nuclear power.

“Change of Paradigm” – a strong policy shift towards sustainable development combines political will, technological progress and structural changes in the economy to answer urgent environmental pressures. Alternative energy sources will be developed resulting in only a minimal requirement for oil by 2050.Vehicle fleets will use regional substitute fuels (e.g. biofuels, natural gas, hydrogen). Major efficiency improvements will allow biofuels to reach a 25% market share of road transport and fuel cells will also play a major role. Industry will half the energy input per unit requirement and solar thermal will produce the majority of heating, hot water and air conditioning. Liquefied natural gas (LNG) infrastructure development will be halted due to rising costs and decreasing reserves. Fission will be rejected due to lack of public acceptance and fusion for cost reasons. On-shore wind will be fully developed and off-shore wind will be developed to avoid conflict with other marine uses. Biomass will mainly be used for heating, while photovoltaic will approach a 5% market share in electricity production. By 2030 hydrogen will be a potential competitor to electricity – particularly in small, remote communities; however, it will not be price competitive on a large scale. Hydrogen will mainly be produced from CO_2 free sources and will act as an important storage medium for intermittent renewables. Although security aspects related to hydrogen use will have been taken care of, other environmental threats will become visible – mainly due to small but continuous leakages.

Summary
The technologies considered were assessed for their coherence with the societal visions and the scenarios. Those technologies which were found to be coherent with both of these were designated as 'safe bet' technologies. All others were considered to be 'conditional' technologies.

Safe Bets
Energy efficiency in industry and housing takes the highest priority from every view and related technologies are considered to be safe bets. However, applied R&D, fiscal measures and improved regulations are likely to be required for both sectors, along with increased public acceptance for energy efficiency in the housing sector. Although low energy housing technology is available and is likely to be implemented in 50% of European houses by 2030, there is a need to focus on existing homes. There are also issues relating to the increase of energy intensive appliances and the increasing use of domestic air conditioning. The potential to decrease industrial energy use by 50% is greatly facilitated by the enlargement of the EU to include member states with greater energy saving potentials. In both sectors mature energy saving technologies are most likely to benefit from fiscal measures.

Fuel cells are expected to play a major role in future transport systems even before the hydrogen economy is established – flexibility in design allowing the use of natural gas as a transition fuel will be important. Although substantial research support is still required, fuel cell related technologies could also benefit from the application of market measures (fiscal incentives) since strong cost reductions would arise from economies of scale.

Distributed electricity generation and energy storage are required in combination with the development of renewable technologies. Although hydrogen use as energy storage for renewables has potential on the longer time horizon it is not necessarily seen as a safe bet and other options need to be pursued. Redox flow batteries, flywheels and super capacitors are currently too expensive for widespread use but may be important in specific applications in the medium term.

The next highest priority is the development of renewables. However, achieving 25% of EU energy from renewables by 2030 is only realistic if the appropriate support is received in combination with strong energy efficiency improvements. Biomass has great potential especially for job and wealth creation, but issues need to be dealt with including competition for land. Wind is expected to be a major contributor to the total renewable energy produced. Public acceptance in relation to land change issues, landscape, pollution, reduced comfort and distrust of unknown technologies are key factors hindering development of renewables.

Conditional
The future of the hydrogen economy depends on its being produced from renewable sources, although natural gas, coal and nuclear may be required during the transition.

Photovoltaics could contribute significant energy if it becomes competitive; however, this will require a major technical breakthrough (R&D) and market expansion through economic incentives.

Superconductive materials fulfil major policy and technology goals (i.e. strengthen the EU electricity transmission grid, reduce transmission/ distribution losses and increasing storage efficiency). However, it was considered that the development of hydrogen as an energy carrier would reduce the importance of superconductivity in energy transport.

Although no specific comment was given, geothermal and ocean technologies were also considered to be conditional technologies.

Both fusion and fission nuclear technologies were considered to be conditional.

The long term viability of carbon capture and storage is held in doubt due to the high cost of the infrastructure necessary to sequestrate CO_2 in relation to other emission reduction options (e.g. energy conservation, fuel switching, renewable energy development and reforestation). There is also major uncertainty regarding the long-term storage of CO_2 in relation to the risks of leakage, industrial accidents and earthquakes.

2000-2050: Global
The Millennium Project considered "Developing alternative sources of energy" [21] as one of its fifteen global opportunities to be considered in its study. Alternative energy sources were considered as a group rather than as discrete technologies.

Although the survey participants were mainly from Europe, North America and Asia, there were also representatives from Latin America and Africa.

The results of this study were more focussed on changing policy to encourage alternative sources of energy than focussed on the technical potentials of different energy sources. The suggested actions to develop alternative sources of energy were:

- Offer large monetary incentives for breakthroughs
- Implement full-cost accounting for external and environmental impacts in energy pricing

- Carry out R&D to provide alternative sources of energy and energy storage and extend duration of non-renewable sources
- Initiate eco/energy taxes
- Implement relevant sections of Agenda 21
- Eliminate trade tariffs/taxes on alternative energy related goods
- Encourage international co-operation in peaceful space projects, particularly related to solar power satellites
- Consider policies to permit oil production to rise while prices remain low

2010 – 2060: Global

De Oliveira Matias and Devezas [22] included hydrogen in their consideration of the dynamics of primary energy sources. They analysed four technological transformations which have already occurred. This analysis indicates that economic, geopolitical, environmental and social issues are far more important motivators for change than simple resource depletion. The information was used in combination with logistic substitution and Delphi to predict a future perspective of energy sources:

- 2010: 'dusk' of wood as a traditional energy falling to a market share of $\leq 1\%$
- 2040-2050:
    - 'dusk' of coal as a traditional energy
    - Natural gas becomes a transition fuel between oil and alternative energies
- 2050-2060: leading fuels are non solid fuels (including gas)
- 2060 onwards: alternative energies (including hydrogen) assume leading role

Throughout this period nuclear fission is anticipated to remain as a source of energy production and has the potential to increase its market share significantly. Fusion is not expected to be available in significant quantities before 2060.

Assessable foresight

A few energy foresight exercises took place early enough that their results can be compared with actual progress.

India: 2000

Delphi was used to identify future appropriate technologies for India in 1979 [17]. Energy was one of the three key areas identified for analysis. Appropriate technology was defined as being:

- Available
- Suitable
- With employment potential
- Appropriate to literacy level
- Beneficial to the maximum number of people as possible below the poverty line

The appropriate energy technologies suggested (with likely year of occurrence) were:

- 300,000 biogas plants in operation by 1999 – Nearly 2.5 million family-size biogas plants for cooking had been constructed by the end of 1996 [23] as referenced in [24].

- Power transmissions losses reduced to 5% by 2000 – By 2008 aggregate technical and commercial losses have a national average of 35% with some states rising above 60%; however, almost 50% of these losses are due to non-technical issues like energy theft [25]
- Ganges Cauvery canal start functioning by 2000 – this project is still subject to discussion and has not been started

Two other suggestions were high technology / low employment:

- Breeder reactors using thorium cycle for commercial power generation by 1997 – currently all operational nuclear reactors in India are boiling water reactors or pressurised heavy water reactors [26]
- Indigenous production of India's first 2000MW power generating plant by 1997 – it is possible that this statement meant 2000MW power generated from a single unit, which has not yet been achieved. However, at least four super thermal power stations with a combined installed capacity of 2000MW or higher were commissioned before 1997. These are Singrauli, Vindyachal, Korba and Ramagundam.

Europe: 2040

As part of the European Energy review [19] the Delphi results summarised in Tables 2 and 4-7 were compared against quantitative economic models. It was found that the Delphi results anticipate more rapid development and higher market shares of substitute technologies than the economic models. However, it should be realised that the Delphi results should be interpreted as identifying achievable future developments given the right framework conditions and incentives.

Global: 1985 / 2000

The 1974 Delphi survey by Smil [16] on energy and environment has been reviewed by Utgikar and Scott [15]. A very well qualified group was assembled to conduct the energy forecast. Half the group were professionals associated with the energy industries with approximately 21 years experience. Although only 15% of the group were academics, 85% held an advanced degree and nearly half of the participants held a doctorate. The group represented the views of private industry, academia and government agencies. They also represented Europe, Japan and the Americas.

The review found that the forecasts were highly optimistic. By 2000 fission was predicted to generate 50-75% of electricity for most nations through increased capacity of traditional plants and maturation of new fission plant technologies. Similarly full scale demonstration of fusion and significant commercialisation of fuel cells, shale oil recovery and coal conversion was forecast. In reality by 2006, the majority of countries (except France) obtain 15-30% of their electricity from fission. Fast breeder fission reactors are not yet commercialised and fusion is still in early development stages.

By 1985 fuel cells were expected to provide peaking power, while coal gasification and liquefaction was expected to be commercialised. Large scale shale oil recovery was predicted to be well developed by 1985. 10,000MW coal plants for electricity were expected by 2000. These developments in energy generation were to be matched by developments in energy transmission including extra high voltage (1100-

1400kV) lines, cryogenic superconducting cables underground and progress in laser / microwave power transmission. By 2006, the general maximum capacity of an electricity plant was actually 1,000MW, oil shale was still an insignificant energy source and coal gasification and liquefaction was still in development. Energy transmission was still generally 69-765kV and the other technologies had not materialised.

Environmental considerations such as water thermal pollution and waste flue gases were expected to be under control by 1985 although oil spills were expected to continue until 2000. The only type of renewable energy considered in any volume was hydroelectric which was expected to have been developed to the limits of practical feasibility by 2000.

Utgikar and Scott's review of the reasons why the study did not forecast progress which correlated to reality found the following:

- Technique – the process required to develop a consensus in a Delphi survey often means eliminating outlying opinions. However, there is no other forecasting method which has a better reputation than Delphi survey, so this may only have had a marginal role in the failure of the study.
- Socio-political considerations are likely to have played a major part in the variation. In particular the Three Mile Island and Chernobyl incidents have had a major effect on the public support available for fission development.
- Economic factors are likely to be the single most important reason for technology development to stall. Taking fission as an example: uranium resources are generally considered to be cheap and plentiful, whereas the capital investment in a new type of reactor is significant. This gives little incentive to develop more efficient fission reactors. Similarly developing technologies that don't require traditional fossil fuels tend to be based on the premise that world oil production will dwindle in the future. *This makes the accuracy of global oil-supply predictions the most important factor in all future energy related forecasts.*

The 1978 Delphi study [1] assumed a significant increase in hydrogen production and application over the two decades to 2000. This development was considered to have a significant dependence on the expected growth and development of fission electricity production which could be used to generate hydrogen. Since fission has not developed to this extent, the related forecasts appear to have been invalidated.

Insights

From the studies reviewed, a number of key insights can be considered. These include the drivers for development and deployment of energy technologies as well as the inter relationship between the energy technologies.

Drivers for energy technology deployment

Gough [14] investigated the key drivers for energy technology deployment in the UK. In order of decreasing frequency, the following issues were highlighted:

- CO_2 emissions / other environmental

- Energy security
- Cost / economics
- Government
- Politics
- NGO / public opinion
- Incentives
- Private industry / profit
- Technical
- Reliability
- Energy efficiency
- Meeting energy demand
- Ageing infrastructure
- Diversity of supply
- International commitments

This fits in part with Utgikar's [15] assertion that the level of oil supply is a major factor in future change and high quality data on oil supply is essential for modelling. However, De Oliveira Matias [22] believes that economic, geopolitical, environmental and social issues have more of an impact on change than resource depletion does.

Inter relation between energy technologies

There are many potential relationships between hydrogen and other energy technologies.

The development of fission was expected to lead to high hydrogen production [1]. Since the development of fission reactors has stalled in many countries, the expected increase in hydrogen production has not occurred.

Since emphasis has been placed on the necessity of low-carbon sources for hydrogen production [19] initial development of hydrogen from fossil fuels could involve a requirement for carbon capture and storage systems.

As the availability of fossil fuel sources are expected to reduce, renewable sources are hoped to take their place. This could be a symbiotic relationship where hydrogen provides a storage mechanism for intermittent renewable technologies. However, the costs of using hydrogen are considered to be high for this type of application and other technologies may be developed instead [19].

Some technologies can be viewed as being directly in competition with hydrogen. In particular the development of hydrogen as an energy carrier could reduce the importance of superconductivity in energy transport [19].

Chronology

Pre 1970 forecasts for hydrogen production in 2000 [1] expected an increase hand in hand with the use of fission reactors for electricity generation. This centralised hydrogen production model would have required large scale hydrogen transportation and storage. This level of hydrogen production was expected to power 10% of private and 20% of public land transport as well as 10% of air transport and 2% of sea transport. However, this level of hydrogen production and use has not been achieved by 2009.

A current review of global barriers [4] to hydrogen transport found that different issues were of concern in different parts of the world. Although the complexities of technical problems were acknowledged, the development of a suitable supply chain was considered to be a more significant problem.

A technical forecast considering Europe's energy future [19] considered the practical use of hydrogen from biological, biochemical and renewable sources to be likely between the 2021 and 2043. This is likely to be preceded by the development of non-hydrogen fuel cell driven cars between 2022 and 2030.

Although hydrogen is often considered as a symbiotic technology for intermittent renewable technologies, the development of energy storage technologies in conjunction with renewable energy supplies is expected to take place between 2016 and 2027, so non-hydrogen technologies are expected to make a significant impact in this sector [19].

The surveys which can be compared with real life [1, 16, 17, 19] at least in part, have been found to be optimistic. This is considered to relate to the difference between technological possibilities and the society's wish to support these possibilities, for this reason it is important to incorporate non technological viewpoints into future studies.

Conclusions

Several aspects of hydrogen have been explored using Delphi techniques in a timescale which is still valid. These include:

- identifying barriers to the use of hydrogen in transport [4]
- exploring the future usefulness of hydrogen related technologies on a European scale [19]
- exploring energy technologies which could be synergistic / competitive with hydrogen including renewables [6-8, 12, 13] in Spain, Africa, Finland and Saudi Arabia as well as fossil fuels [14].
- energy reviews applying to Europe and US [19, 22]

These analyses still leave some gaps worth exploring. There has not been a Delphi survey analysing hydrogen production since 1978 [1]. The past survey was compromised by the failure of fission based electricity generation with spare capacity for hydrogen production to materialise. In addition, a hierarchy of hydrogen societal welfare impacts has been identified [3] but their potential has not been explored.

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