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Technology Characterisation of the Hydrogen Economy

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Introduction

The purpose of this paper is in offering an overview and literature review of 10 ‘emblematic’ technology characterisation (TC) documents of a variety of hydrogen technologies. These documents are seen as emblematic in that they are authored by recognised names in the field, address a broad span of hydrogen technologies (in that they deal with issues of production, storage, distribution, fuel cells, etc), and through preliminary analysis were found to exhibit many of the features of TCs which early trawls of TC literature identified. The TCs were reviewed on the basis of a pro-forma (see Annex A) which addressed bibliographic information, methodological issues, the technological, geographical and temporal scope of documents, a brief abstract, a listing of technological and economic data sources, and any references to environmental or health and safety issues.

This paper is drafted as a collected literature resource and source of pertinent information for those researchers addressing issues of hydrogen technologies and the development of a hydrogen economy(-ies). Where possible electronic links have been provided to documents. It may be read as a standalone paper, outlining many key characteristics of hydrogen technologies in line with technological characterisation approaches (OAO Corp, 1979; Taylor, 1978; Chandra, 1995), or in tandem with a more critical appreciation of the approach known as technology characterisation (Hodson and Marvin, 2004).

The report proceeds through an outline of contents offering an ‘at a glance’ overview of the bibliographic details of papers addressed. Following this it moves to the main body of the paper which proceeds through the 10 emblematic documents in line with the pro-forma outlined in Annex A.

Contents of Papers

1. Geoff Dutton, 'Hydrogen Energy Technology', April 2002, Tyndall Centre for Climate Change Research.

2. Joan Ogden, 'Prospects for Building a Hydrogen Energy Infrastructure', 1999, Annual Review of Energy and the Environment, vol.24.

3. George Marsh, Peter Taylor, Heather Haydock, Dennis Anderson, Matthew Leach, 'Options for a Low Carbon Future', February 2002, AEA Technology PLC.

4. Duane B. Myers, Gregory D. Ariff, Brian D. James, John S. Lettow, C.E. (Sandy) Thomas, and Reed C. Kuhn, 'Cost and Performance Comparison of Stationary Hydrogen Fueling Appliances', April 2002, Directed Technologies Inc. paper prepared for the Hydrogen Program Office, Office of Power Technologies, US Department of Energy, Washington DC.

5. J.B. Lakeman and D.J. Browning, 'Global Status of Hydrogen Research', 2001, Contractor, Defence Evaluation and Research Agency as part of the DTI Sustainable Energy Programmes.

6. C.E. Grégoire Padró and V. Putsche, 'Survey of the Economics of Hydrogen Technologies', September 1999, National Renewable Energy Laboratory, a US Department of Energy Laboratory, operated by Midwest Research Institute.

7. Paul Watkiss and Nikolas Hill, 'The Feasibility, Costs and Markets for Hydrogen Production', September 2002, AEA Technology Environment for British Energy.

8. Nigel Brandon and David Hart, 'An introduction to fuel cell technology and economics', July 1999, Imperial College Centre for Energy Policy and Technology, Occasional Paper 1.

9. Timothy E. Lipman, Jennifer L. Edwards and Daniel M. Kammen, 'EconomicAnalysis of Hydrogen Energy Station Concepts: Are 'H2E-Stations' a Key Link to a Hydrogen Fuel Cell Vehicle Infrastructure'?, November, 2002, Renewable and Appropriate Energy Laboratory, Energy and Resources Group, University of California, Berkeley, CA 94720.

10. J. Maddy, S. Cherryman, F. Hawkes, D Hawkes, R. Dinsdale, A. Guwy, G. Premier, and S. Cole, 'Economics' (Chapter 11 of 'Hydrogen 2003'), 2003, Hydrogen 2003 Report Number 1 ERDF part-funded project entitled: 'A Sustainable Energy Supply for Wales: Towards the Hydrogen Economy', University of Glamorgan, Hydrogen Research Unit.

Hydrogen Technologies Technology Characterisation by Template

One.

1. Bibliographic information:

Title: 'Hydrogen Energy Technology'.

Author(s): Geoff Dutton.

Date: April 2002.

Source/Publisher: Tyndall Centre for Climate Change Research.

2. Summary Information:

Type of study: Tyndall Centre Working Paper. One of three documents from phase one of the Tyndall Centre project: 'The Hydrogen Energy Economy: Its Long Term Role in Greenhouse Gas Reduction'.
www.tyndall.ac.uk/publications/working_papers/wp17.pdf

Methodology (if specified): Largely unspecified, but draws on secondary literature and on three sources in particular:

Lakeman and Browning (2001): *Global Status of Hydrogen Research* carried out by DERA for the DTI 'and which includes a state of the art overview of hydrogen energy technologies'.
www.dti.gov.uk/energy/renewables/publications/pdfs/F0300239.pdf

Padró and Putsche (1999): *Survey of the economics of hydrogen technologies* carried out by NREL for the US Department of Energy 'and which includes an attempt to produced levelised cost comparisons for the major production and distribution technologies'.

www.eere.energy.gov/hydrogenandfuelcells/pdfs/27079.pdf

Ogden (1999): *Prospects for building a hydrogen energy infrastructure* 'which considers a wide range of possible architectures for hydrogen energy systems'.

In particular there is a strong reliance on the work of Padró and Putsch in offering reference costs for various methods of production, storage systems, transmission and transportation, economics of fuel cells, and for overall hydrogen production. Many of these costs that Dutton draws on are themselves from secondary sources in Padró and Putsch (see Table 2). This table offers the example of hydrogen production. A similar picture can be illustrated for the other areas listed above.

Table 2 : (Taken from Dutton (2002)).Reference costs for hydrogen production from more conventional technologies (derived from Padró and Putsche, 1999 [2])

Facility size (10^6 Nm^3/day)	**References**	**Specific TCI ($/GJ)**	**Hydrogen price ($/GJ)**
Steam methane reforming -48% of world hydrogen production (1998)			
0.27 (small)	Leiby 1994 in Padro and Putsche (1999)[2]	27.46	11.22
1.34 (large)	Leiby 1994 in Padro and Putsche (1999)[2]	14.74	7.46
2.14	Leiby 1994 in Padro and Putsche (1999)[2]	12.61	6.90
2.80	Kirk-Othmer 1991 in Padro and Putsche (1999)[2]	9.01	6.26
6.75	Foster-Wheeler 1996 in Padro and Putsche (1999)[2]	10.00	5.44
25.4	Blok et al 1997 in Padro and Putsche (1999)[2]	10.82	5.97
Coal gasification – economic where oil and/or natural gas is expensive			
2.80	Kirk-Othmer 1991 in Padro and Putsche (1999)[2]	34.2	11.57
6.78	Foster-Wheeler 1996 in Padro and Putsche (1999)[2]	33.1	9.87
Partial oxidation of hydrocarbons			
0.27 (small)	Feedstock - coker off-gas (Leiby 1994 in Padro and Putsche (1999)[2])	21.96	10.73
1.34 (large)	Feedstock - coker off-gas (Leiby 1994 in Padro and Putsche (1999)[2])	11.24	7.39
2.14	Feedstock - coker off-gas (Leiby 1994 in Padro and Putsche (1999)[2])	9.63	6.94
2.80	Feedstock - residual oil (Kirk-Othmer 1991 in Padro and Putsche (1999)[2])	22.2[8]	9.83

Biomass gasification - costs vary depending on gasifier technology			
0.720	Mann 1995 in Padro and Putsche (1999)[2]	38.19	13.09 [9]
2.16	Larson 1992 in Padro and Putsche (1999)[2]	20.60	8.69
2.26	Larson 1992 in Padro and Putsche (1999)[2]	26.91	10.03
Biomass pyrolysis			
0.024	Mann 1995a in Padro and Putsche (1999)[2]	30.66	12.73
0.243	Mann 1995a in Padro and Putsche (1999)[2]	19.31	10.11
0.811	Mann 1995a in Padro and Putsche (1999)[2]	16.74	8.86
Methane pyrolysis – Gaudernack and Lynum (1998)[4]			
SMR	Without CO_2 sequestration		6.0
SMR	With CO_2 sequestration		7.5
CB&H process	Without carbon black revenue		10.6
CB&H process	With carbon black revenue		5.8

[8] More expensive than coker off-gas due to increased equipment for feed handling and impurity removal

[9] Delivered hydrogen price depends on biomass feedstock costs which can vary widely from expected price for dedicated biomass production ($46.30/dry tonne) to the price for waste product ($16.50/dry tonne).

Technological scope and focus of the document/study: Offers an overview of hydrogen energy technologies with focus on production, storage, distribution, transport and end use systems.

Geographical scope and focus of the document/study: Not explicitly specified but draws predominantly on UK and US literature, and funded by UK-based Tyndall Centre.

Temporal scope and focus of document: Time-scales of 10, 20 and 50 years.

Institutional affiliations: Energy Research Unit (ERU), Rutherford Appleton Laboratory, Chilton, Didcot, Oxon. OX11 0QX.

3. Abstract or brief summary:

A 'report on hydrogen energy conversion technologies [which] aims to identify the current state of the art in terms of typical plant sizes, readiness for large scale application, estimated capital and running costs, and the need and potential for significant innovation against time scales of 10, 20 and 50 years'. Suggests that whilst much current emphasis is on the production of hydrogen from renewables 'current cost projections clearly favour the production of hydrogen from fossil fuel sources, most notably from methane by the SMR process'. Furthermore, if SMR is the chosen technology, and significant costs are added to production through the mandating or desirability of sequestration, 'then this can be achieved more cheaply in larger, centralised plants'. For carbon sequestration pyrolysis holds out the possibility of a 'still more promising route'. 'Hydrogen production by electrolysis depends on the price of electricity and the capital cost of the electrolysis plant'. Suggests that further technological developments are needed in areas of hydrogen storage and distribution.

4. Does the document include technological performance data?
(If yes give a brief description and list any primary sources)

Draws on predominantly secondary sources to outline technological performance data for: production - steam methane reforming, partial oxidation, integrated gasification combined cycle, pyrolysis, water electrolysis, reversible fuel cell, hydrogen bromide electrolysis, hydrogen production during manufacture of chlorine, photoelectrolysis, biological hydrogen production; storage and distribution – compressed gas, liquefaction, solid state hydrogen storage, metal hydride storage systems, hydride hydrolysis, glass microspheres; distribution and transport; end-use systems – hydrogen-fuelled internal combustion engines; hydrogen-fuelled turbines, fuel cells.

5. Does the document include cost estimates/economic performance data?
(If yes give a brief description and list any primary sources)

The document includes: 'reference costs for hydrogen production from more conventional technologies'; from electrolysis and 'less conventional technologies'; the 'relative merits of hydrogen storage systems and comparison of costs'; 'hydrogen transmission and transportation costs'; the 'economics of fuel cells'; and the overall economics of hydrogen systems'. These draw upon secondary sources and largely on one source in particular – Padró and Putsche (1999). This study itself draws on a number of secondary sources (outlined above).

6. Does the document include information on environmental, health or safety risks of H2 technologies?
(If yes give a brief description and list any primary sources)

The explicit claim of the project of which the document was a constituent was in informing ways in which hydrogen energy technologies relate to a ‘long-term role in greenhouse gas reduction’. This said a focus on environmental, health or safety risks of H2 technologies is largely limited to a table of ‘hydrogen characteristics and safety’, presented as an appendix.

<u>Two.</u>

1. Bibliographic information:

Title: ‘Prospects for Building a Hydrogen Energy Infrastructure’.

Author(s): Joan M. Ogden.

Date: 1999.

Source/Publisher: Annual Review of Energy and the Environment, Vol.24.

2. Summary Information:

Type of study: Academic study.
http://www.princeton.edu/~cmi/research/papers/prospects.pdf [draft]

Methodology (if specified): Draws on a range of secondary literature and also the following assumptions in addressing the technological issues outlined below:

Table 1. Conversion Factors And Economic Assumptions

1 GJ (Gigajoule) = 10 9 Joules = 0.95 Million BTU

1 EJ (Exajoule) = 10 18 Joules = 0.95 Quadrillion (10 15) BTUs

1 million standard cubic feet (scf)
= 26,850 Normal cubic meters (m_N^3)
= 343 GJ (HHV)

1 million scf/day = 2.66 tons/day
= 3.97 MW H_2 (based on the HHV of hydrogen)

1 scf H_2 = 343 kJ (HHV) = 325 BTU (HHV); 1 lb H_2 = 64.4 MJ (HHV) = 61.4 kBTU (HHV) = 187.8 scf
1 m_N^3 = 12.8 MJ (HHV); 1 kg H_2 =141.9 MJ (HHV) = 414 scf

1 gallon gasoline = 130.8 MJ (HHV) = 115,400 BTU/gallon (LHV)
Gasoline Heating value = 45.9 MJ/kg (HHV) = 43.0 MJ/kg (LHV)
$1/gallon gasoline = $7.67/GJ (HHV)

1 gallon methanol = 64,600 BTU/gallon (HHV)
= 56,560 BTU/gallon (LHV)

Methanol Heating value = 22.7 MJ/kg (HHV) = 19.9 MJ/kg (LHV)
$1/gallon methanol = $15.4/GJ (HHV)

All costs are given in constant $1995.

Capital recovery factor for hydrogen production systems, distribution systems and refueling stations = 15%

Technological scope and focus of the document/study: Examines: hydrogen production (thermochemical methods – SMR, partial oxidation of hydrocarbons, gasification of biomass, coal or wastes; technologies for sequestering carbon during thermochemical hydrogen production; electrolysis of water; experimental production methods); hydrogen storage (large scale stationary storage of hydrogen – underground gas storage in aquifers, caverns; intermediate scale storage of hydrogen - liquid hydrogen storage, above ground compressed gas storage); storing hydrogen on board vehicles – compressed gas storage in pressure cylinders, liquid hydrogen storage, metal hydrides; novel approaches to hydrogen storage); hydrogen transmission, distribution and delivery (the current industrial hydrogen transmission and distribution system, long distance pipeline transmission of hydrogen, local distribution of hydrogen, gaseous hydrogen refuelling stations); possible scenarios for development of hydrogen infrastructure.

Geographical scope and focus of the document/study: Not entirely clear although there are numerous reference to the US and to the Los Angeles Basin. The author was based at Princeton University when she wrote this paper.

Temporal scope and focus of document: 'Near term' and 'long term'.

Institutional affiliations: Center for Energy and Environmental Studies, Princeton University, Princeton, NJ 08544 USA

3. Abstract or brief summary:

In this paper Ogden reviews 'the current status of technologies for hydrogen production, storage, transmission and distribution; describe likely areas for technological progress; and discuss the implications for developing hydrogen as an energy carrier'. The paper offers a range of technical and economic possibilities for the development of hydrogen energy infrastructures. For example, 'near term gaseous H2 supply options'.

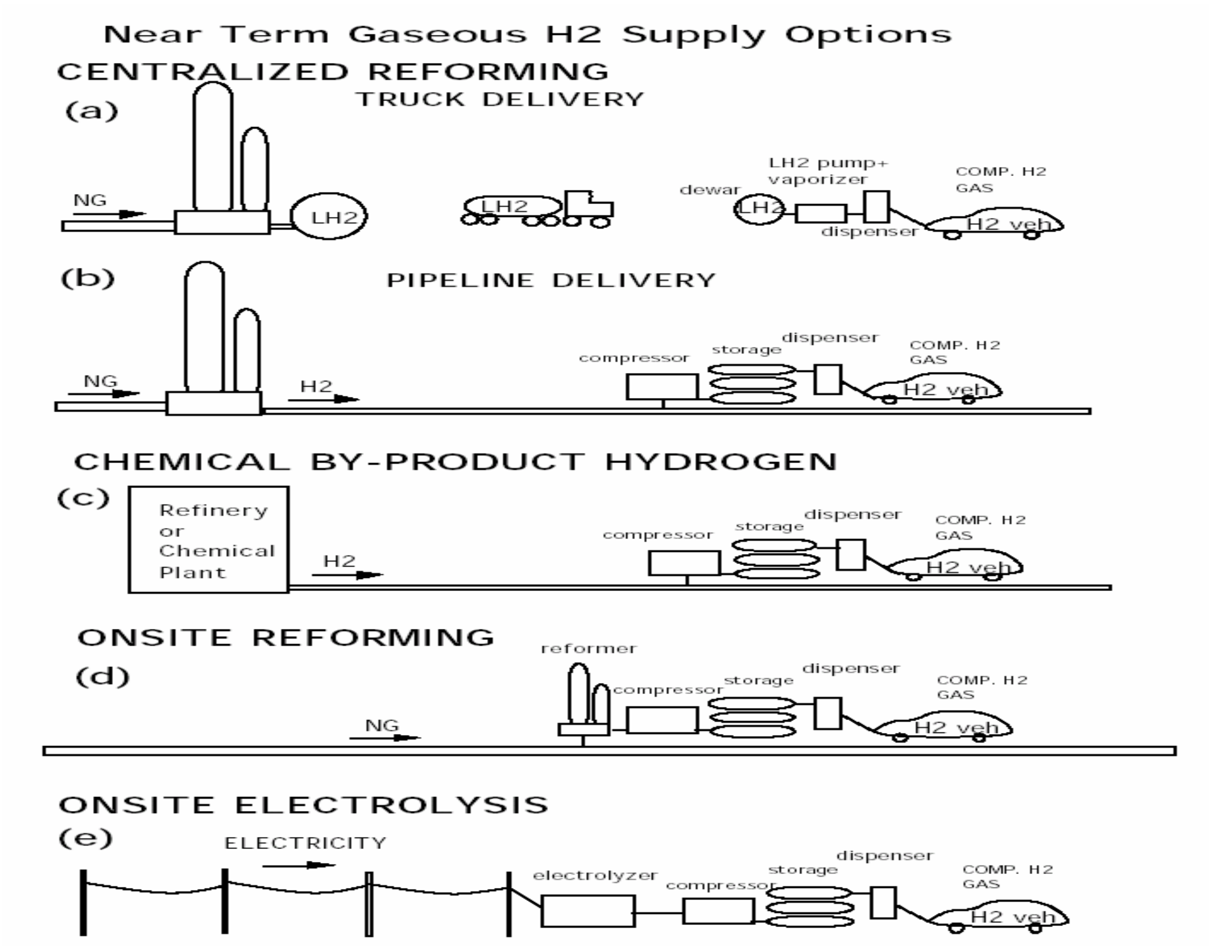

Figure 8

4. Does the document include technological performance data?
(If yes give a brief description and list any primary sources)

Yes with reference to the issues outlined above. Draws on a range of assumptions and secondary sources.

5. Does the document include cost estimates/economic performance data?
(If yes give a brief description and list any primary sources)

There is a focus on the design and economics of hydrogen energy systems (estimating the hydrogen demand, choosing the best supply alternative: general considerations, delivered cost of hydrogen transportation fuel, capital cost of hydrogen infrastructure, hydrogen infrastructure capital costs compared to those for methanol, gasoline and synthetic middle distillates, lifecycle cost of automotive transport). This is addressed using the assumptions outlined above in relation to a series of secondary sources, some of which have been ‘adapted’, and which are detailed in the bibliography. A series of graphical representations of comparative costs are displayed.

6. Does the document include information on environmental, health or safety risks of H2 technologies?
(If yes give a brief description and list any primary sources)

The report includes environmental and safety considerations for hydrogen energy systems (emissions of greenhouse gases and other pollutants, resource issues for hydrogen production, safety issues). This draws largely on secondary sources, and includes the table below.

Table 5.
Safety Related Properties of
Hydrogen, Methane and Gasoline

	Hydrogen	Methane	Gasoline
Flammability Limits (% volume)	4.0-75.0	5.3-15.0	1.0-7.6
Detonability Limits (% volume)	18.3-59.0	6.3-13.5	1.1-3.3
Diffusion velocity in air (meter/sec)	2.0	0.51	0.17
Buoyant velocity in air (meter/sec)	1.2-9.0	0.8-6.0	non-buoyant
Ignition energy at stoichiometric mixture (milliJoules)	0.02	0.29	0.24
Ignition energy at lower flammability limit (milliJoules)	10	20	n.a.
Toxicity	non-toxic	non-toxic	toxic in concentrations> 500 ppm

adapted from J. Hord, 1978.

Three.

1. Bibliographic information:

Title: ‘Options for a Low Carbon Future’.

Author(s): George Marsh, Peter Taylor, Heather Haydock, Dennis Anderson, Matthew Leach.

Date: February 2002.

Source/Publisher: AEA Technology PLC.

2. Summary Information:

Type of study: Report produced for DTI, DEFRA and PIU by Future Energy Solutions from AEA Technology in collaboration with ICCEPT.
www.etsu.com/en_env/rep_ED_50099_1.pdf

Methodology (if specified): MARKAL energy systems model. This ‘was used as a framework…to calculate the cost optimum mix of energy technologies needed under different scenario assumptions regarding the demand for energy service and primary energy prices’, underpinned by a technology characterisation ‘to cover a broad range of current and prospective technologies relevant to the 2050 time horizon and the potential for major constraints on CO2 emissions’. A ‘schematic representation of the key features’ of the MARKAL model can be seen below.

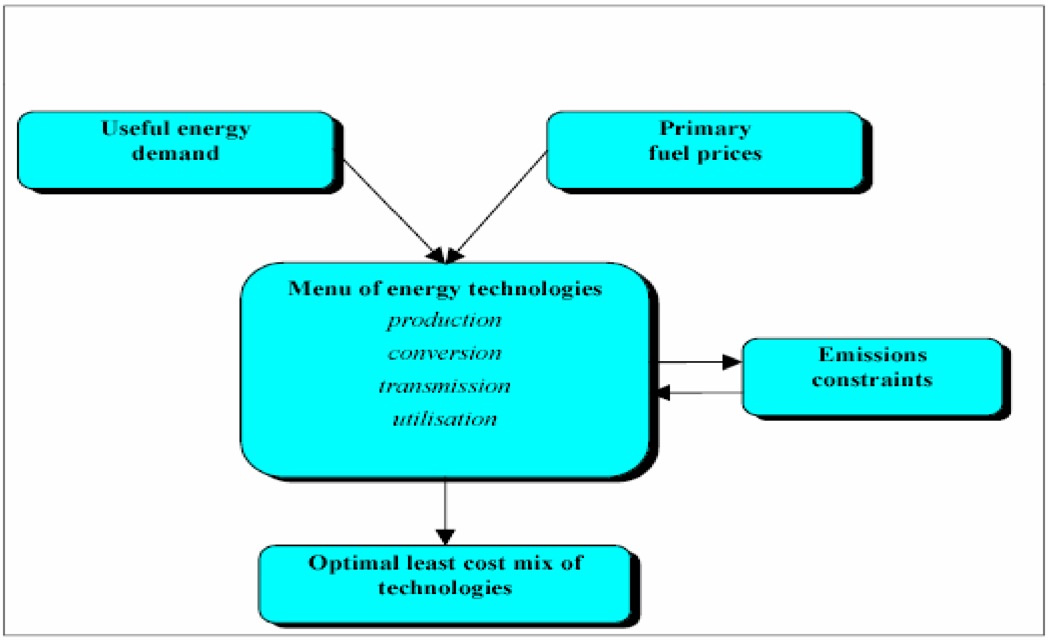

Figure 1 Schematic representation of the key features of the Markal Model

The authors' own justification for the use of this methodology is as follows:

- Permits coverage of all technologies in the energy system within a single framework, and thereby takes account of feedback between energy supply and demand sides.
- Provides a framework to evaluate technologies on a level playing field, check the consistency of results and explore sensitivities to key data and assumptions.
- Enables the assessment to examine a timeframe, thus providing information on the phasing of technology deployment and carbon emissions abatement.
- Enables emissions constraints to be applied, with the energy system adjusting to meet these at least cost.
- Supports a comprehensive analysis of the costs associated with changes to the energy system including discounted net present value, annualised and marginal costs. (pp.1-2).

The results, according to the authors, ‘are not forecasts [but] an analysis of what technology can in principle deliver, and of what the costs and effects on emissions might be’. Future developments and costs, it is acknowledged, ‘will turn on many factors including the policies implemented, the social acceptability of the technologies, the readiness of householders and business to invest in energy efficiency and the rate of innovation’.

‘In addition to the scenario assumptions on energy demand and primary fuel prices, the results depend crucially on the range of technology options included in the system model, and the assumptions made in characterising their long term performance and costs. These factors are just as uncertain as the scenario parameters discussed above, therefore the study has sought to investigate these uncertainties by covering a comprehensive range of present and prospective technologies for both the supply and demand sides’.

Technological scope and focus of the document/study: Current and prospective technologies ‘relevant to the 2050 time horizon and the potential for major constraints on CO2 emissions’. Includes: electricity generation (centralised and decentralised); production of alternative fuels for transport; hydrogen production and distribution; passenger car transport; freight transport (road and rail); public transport (road, rail and air); domestic sector; commercial and services sector; and industry sector. ‘The choice of technologies to be included in a system analysis study is crucial because this effectively sets limits on the range of options available’.

Geographical scope and focus of the document/study: UK.

Temporal scope and focus of document: Up to 2050.

Institutional affiliations: AEA Technology PLC, Harwell, Didcot, Oxfordshire, OX11 0QJ, UK.

3. Abstract or brief summary:

'The study examined three scenarios for the possible future development of the UK economy and the associated demands for energy related services'. To develop a range of bottom-up estimates of carbon dioxide emissions from the UK energy sector up to 2050, 'and to identify the technical possibilities for the abatement of these emissions'. To identify 'technical possibilities and costs' for the abatement of CO2 emissions. Includes estimates of future energy consumption and CO2 emissions for three scenarios using the IEA's MARKAL model to provide 'cost optimised solutions for the UK energy system to 2050, taking account of the costs, performance and emissions of alternative supply and demand technologies'.

These technologies included: electricity generation (centralised and decentralised); production of alternative fuels for transport; hydrogen production and distribution; passenger car transport; freight transport (road and rail); public transport (road, rail and air); domestic sector; commercial and services sector; and industry sector. The choosing of these technologies 'sets limits on the range of options available'.

This paper is included here not only as offering TC and 'costs and performance' data for a range technologies but also as showing the ways in which this characterisation informs a 'systems analysis study'. Or in other words it moves from TC to the use and options of TC in informing scenarios. Three scenarios were examined: Baseline ('in which the current values of society remain unchanged and policy intervention in support of environmental objectives is pursued in a similar way to now' – GDP growth 2.25% per year); World Markets ('based on individual consumerist values, a high degree of globalisation and scant regard for the global environment' – GDP growth 3% per year); and Global Sustainability ('based on the predominance of social and ecological values, strong collective environmental action and globalisation of governance systems' – GDP growth 2.25% per year). Assessment of each scenario involved four runs of the model. First run there was no constraint on carbon emissions in the period of study (2000-2050), then subsequently emissions targets of 45%, 60% and 70% respectively were set for 2050.

4. Does the document include technological performance data?
(If yes give a brief description and list any primary sources)

Technology data and comparisons are found in Annex D of the report. 'A broad range of data sources was used [see Bibliography of the report] to establish a reference database on all technologies'. 'These data were assessed and adjusted to produce an internally consistent database by comparison of both the individual performance parameters and their overall production/end-use costs. Gaps in data time series were filled by interpolation and extrapolation'. Annex E contains Revised Technology and Data Comparisons.

5. Does the document include cost estimates/economic performance data?
(If yes give a brief description and list any primary sources)

As Point 4. 'The costs and performance data were set to be representative of commercially deployed technologies enjoying the benefits of volume production (i.e. not first of a kind costs)'. 'Technologies with low deployment prospects in the UK were still assumed to gain the benefits of volume of production if they had significant global potential (e.g. PV)'. The 'electricity generation costs' and 'total transport costs' listed in the data tables 'are provided only to facilitate comparisons between technologies'. 'The costs have been calculated using a 15% discount rate and the Baseline Scenario fuel costs'. 'Calculations of total transport costs assumed the following annual vehicle usage:

Cars: 16,682 km/yr.
LGV: 20,782 km/yr.
HGV: 103,000 km/yr.
Bus: 76,643 km/yr.
Train: 186,000 km/yr.
Plane: 800,000 km/yr.

6. Does the document include information on environmental, health or safety risks of H2 technologies?
(If yes give a brief description and list any primary sources)

The report takes as its focus developing ‘a range of ‘bottom-up’ estimates of carbon dioxide emissions from the UK energy sector up to 2050, and to identify the technical possibilities and costs for the abatement of these emissions’.

<u>Four.</u>

1. Bibliographic information:

Title: ‘Cost and Performance Comparison of Stationary Hydrogen Fueling Appliances’.

Author(s): Duane B. Myers, Gregory D. Ariff, Brian D. James, John S. Lettow, C.E. (Sandy) Thomas, and Reed C. Kuhn.

Date: April 2002.

Source/Publisher: Directed Technologies Inc. paper prepared for the Hydrogen Program Office, Office of Power Technologies, US Department of Energy, Washington DC.

2. Summary Information:

Type of study: Report as part of contract for The Hydrogen Program Office at the US Department of Energy.
www.eere.energy.gov/hydrogenandfuelcells/pdfs/32405b2.pdf

Methodology (if specified): DFMA Methodology (DFMA Methodology developed by Boothroyd and Dewhurst, 2002, in *Product Design for Manufacture and Assembly*) - Design for Manufacturing and Assembly was used for cost estimates. ‘The methodology is used extensively by industry for product cost estimation and to compare the relative cost of competing manufacturing and assembly approaches. The DFMA methodology is both a rigorous cost estimation technique and a method of product redesign to achieve lowest cost. The DFMA approach used for this analysis provides a solid framework for the cost study and is the only fair way to compare the cost of potential HFA [hydrogen fuelling appliances] configurations'.

DFMA was used to 'estimate costs for equipment for which high-volume manufacturing methods may not currently exist. Detailed manufacturing and assembly methods were designed to 'construct' the equipment from ground up as much as possible rather than using factored estimates that are common at this level of capital cost estimation'. 'The cost of any component includes direct material cost, manufacturing cost, and assembly cost. Direct material costs are determined from the exact type and mass of material employed in the component. This cost is usually based on either historical volume prices for the material or vendor price quotations. In the case of materials not widely used at present, the manufacturing process must be analyzed to determine the probable high-volume price for the material. Also addresses manufacturing costs and assembly costs. Assumptions for 'production volume considerations' included that for 'each reforming system detailed…a production volume of 25 identical units per year was assumed'. Additional to this a 'production life' of two years was 'generally assumed, where applicable' for equipment and tooling after which it was deemed to need replacing. 'Markup rate assumptions' were also made for general and administrative expenses, material scrap, R&D spending, and profit. Two levels of markup are used: a lower one from the vendor to the 'final assembler' and a higher one from the final assembler to the fuel station owner. A series of assumptions inform calculations of markup. 'Design considerations' were also considered in cost projections.

Technological scope and focus of the document/study: From two previous studies undertaken by Directed Technologies the 'most promising hydrogen supply pathway…consists of small scale natural gas reformation units producing pure hydrogen gas which is then compressed to >5,000 psi for dispensing to FCV's [fuel cell vehicles]. These Hydrogen Fuelling Appliances (HFA's) consist of: a natural gas reformer unit; a gas cleanup unit to purify the reformer outlet to a pure 99.99+% hydrogen stream; hydrogen compressor (to allow onsite storage); onsite storage of the hydrogen (for reformer unit load levelling); and hydrogen dispenser to allow dispensing of the hydrogen into vehicular high pressure storage tanks at 5,000psi. These units are designed for low hydrogen production rate (approx. 2,000 scfh (115 kg/day of hydrogen). Therefore, the focus of this report is in examining the projected cost of HFA's if produced in 'moderate' quantities (250 units) 'quantities consistent with annual FCV production rates of 50,000/year'. The report, thus, 'examines multiple natural gas reformation chemical pathways' (SMR, ATR) 'and multiple gas cleanup methods' (PSA, membrane separation, PrOx).

Geographical scope and focus of the document/study: Report is sponsored and undertaken by US interests, although geographical focus is not particularly explicitly stated. This said the report implicitly refers to US context, for example in discussing 'federal and state highway taxes'.

Temporal scope and focus of document: Not particularly clear.

Institutional affiliations: Directed Technologies Inc., 1 Virginia Square, 3601 Wilson Boulevard, Suite 650, Arlington, Virginia 222o1, USA.

3. Abstract or brief summary:

'This work was funded by the Hydrogen Program Office of the U.S. Department of Energy. The objective of the report was to provide detailed analysis of the cost of providing small-scale stationary hydrogen fuelling appliances (HFAs) for the on-site production and storage of hydrogen from natural gas to fuel hydrogen Fuel Cell Vehicles. Four potential reforming systems were studied: 10-atm steam methane reforming (SMR) with pressure-swing adsorption (PSA) as gas clean up, 20-atm SMR with metal membrane gas cleanup, 10-atm autothermal reforming (ATR) with PSA gas cleanup, and 20-atm ATR with metal membrane gas cleanup' (Myers *et al*, their abstract). They suggest from their study that 'the most cost effective option as determined by the cost of hydrogen is steam methane reforming (SMR) with pressure swing adsorption (PSA) hydrogen purification'.

4. Does the document include technological performance data?
(If yes give a brief description and list any primary sources)

Includes technological performance data for a number of technologies in line with those detailed above. The data and characterisation of various technologies appears to be on the basis of a series of formulae and assumptions presumably underpinned by the technical and tacit knowledge of the authors and also from a variety of secondary sources which are outlined at the bottom of relevant pages as footnotes.

5. Does the document include cost estimates/economic performance data?
(If yes give a brief description and list any primary sources)

The aim of the document is to offer cost comparisons of stationary HFAs. This it does on the basis of the technologies mentioned previously and also in terms of the methodology and the assumptions associated with it outlined above. For example, in the 'cost of hydrogen produced from the 2,000 scfh HFA options' an HFA 'assumed to run an average of 69% of capacity with 98% availability'. Similarly, in the table: 'cost of hydrogen from 16,000 scfh (8x) SMR/PSA HFA with Optimistic assumptions', the suggestion is that '[e]stimates are based on a scaled-up version of a 2,000 scfh HFA. Scale-up may not retain accuracy of original analysis'. The Appendix offers 'cost estimate for scale-up of small-scale HFA'.

6. Does the document include information on environmental, health or safety risks of H2 technologies?
(If yes give a brief description and list any primary sources)

There is little reference to these issues.

Five.

1. Bibliographic information:

Title: 'Global Status of Hydrogen Research'.

Author(s): J.B. Lakeman and D.J. Browning.

Date: 2001.

Source/Publisher: Contractor, Defence Evaluation and Research Agency as part of the DTI Sustainable Energy Programmes.

2. Summary Information:

Type of study: Report for DERA as part of DTI Sustainable Energy Programmes.
www.dti.gov.uk/energy/renewables/publications/pdfs/F0300239.pdf

Methodology (if specified): Not explicitly stated. The Appendices to this report contains tables and data pertaining to: 'properties of hydrogen'; 'energy densities of fuels'; 'efficiency of fuel cells'; and 'cost conversion rates'.

Technological scope and focus of the document/study: Focuses on a number of 'current R&D issues' including options for: hydrogen production (including: water electrolysis; photo-electrolysis; hydrogen bromide electrolysis; pyrolysis; reformation; large-scale hydrogen production; automotive reformation; micro-channel technology; plasma reformation; fuel and reformate clean-up; and biological production); hydrogen storage (conventional metal hydrides; novel metal hydrides; carbon nano-adsorbents; active carbons; nano-tubes; alkali metal doped nano-tubes; fullerenes; carbon nano-fibres; composite cylinders; liquid hydrogen; hydride hydrolysis; and glass microspheres); hydrogen transport and distribution; hydrogen utilisation technologies (ICE; turbines; fuel cells).

Also focuses on 'future R&D needs' in terms of: production and 'related issues'; storage; transport and distribution; and utilisation.

Geographical scope and focus of the document/study: Many of the characterisations of 'current' and 'future' R&D activities are offered at a level of abstraction. This said the report is authored by two UK-based scientists, drawing on much, though not exclusively, US and UK literature. Furthermore, there is a brief discussion of hydrogen activities internationally, including national programmes in: Japan, USA, Germany, Canada, Iceland, UAE, Norway, and Italy, and also reference to programmes of the International Energy Agency, EU, Euro-Quebec Hydro-Hydrogen Pilto Project (EQHHPP), and the United Nations Agency.

Temporal scope and focus of document: 'Current' and 'future'. Report concludes that 'there will be a 30 year transition phase to the full implementation of the hydrogen economy'.

Institutional affiliations: Not stated on the report but a WWW search suggests that Lakeman is employed by DSTL (a branch of the UK Ministry of Defence, and which was previously part of DERA) and Browning by QinetiQ, a public-private partnership including much of what was previously DERA.

3. Abstract or brief summary:

The 'report surveys the global status of hydrogen research and identifies technological barriers to the implementation of a global hydrogen economy'. Though there is a brief discussion of national programmes of development towards hydrogen economies, the report largely functions at a level of abstraction. Hence the possibility of making the 'universalistic' statement 'there will be a 30 year transition phase to the full implementation of the hydrogen economy', whilst not specifying issues of place, space or context and the reference to time being reduced to 'current' and 'future'. In the interim period the suggestion is that 'hydrogen will be largely produced by the reformation of hydrocarbons, particularly methane'. From a review of the 'status of hydrogen research in the UK' the conclusion is made that there is little strategy for the adoption of the hydrogen economy in the UK and there is little co-ordinated or coherent R&D ‘addressing barriers to the hydrogen economy’. The report makes a number of suggestions which will make it ‘still possible for the UK to formulate a coherent strategy and make a significant contribution to the global implementation of the hydrogen economy, as there are still unresolved technology issues’.

4. Does the document include technological performance data?
(If yes give a brief description and list any primary sources)

Technological performance data is included from a variety of secondary sources (see the report’s bibliography) for the areas of technological focus outlined above. Much, though certainly not all, of this data is from reports produced in the US and UK contexts.

The report also acknowledges data received from Julie Foley at IPPR.

5. Does the document include cost estimates/economic performance data?
(If yes give a brief description and list any primary sources)

The document addresses cost estimates in respect of the technological scope of the document outlined above. Highlights some US Department of Energy (DOE) cost targets for different production routes. Offers a table of ‘costs of hydrogen by different production methods’ (see below), taken from A. Bauen’s presentation to the IPPR’s seminar (29th March 2001), ‘Hydrogen – driving the future?’, and entitled ‘Prospects for H2 Production Using Renewable Energy Sources’.

Method	*Cost Pence per kWh*	*Cost ($/GJ)*
Reformation of Natural Gas	1.23-2.00	5-8
Other fossil (Oil pox, cal gas)	2.50-3.00	10-12
Biomass Gasification	2.25-3.25	9-13
Hydroelectric Electrolysis	2.50-5.00	10-20
Wind Electrolysis	5.00-10.00	20-40
Solar Thermal Electrolysis	10.00-15.00	40-60
Solar Photovoltaic Electrolysis	12.50-25.00	50-100

Table 3: Costs of hydrogen by different production

Has tables for 'present and target hydrogen production costs' and 'target costs for fuel cells and electrolysers'. Both of these tables are summaries derived from the US DOE: 'A Multi year Plan for the Hydrogen R&D Programme Rationale, Structure, and Technology Roadmaps', Office of Power Delivery Office, Office of Power Technologies Energy, Efficiency and Renewable Energy, August 1999.

The report also draws on a variety of secondary literature listed in the bibliography.

6. Does the document include information on environmental, health or safety risks of H2 technologies?
(If yes give a brief description and list any primary sources)

Explicit mention of 'safety' is limited to two short paragraphs of comment. Similarly there is little explicit mention of environmental issues. This said weaved into the narrative of the report are characterisations of various renewable energy sources.

<u>Six.</u>

1. Bibliographic information:

Title: 'Survey of the Economics of Hydrogen Technologies'.

Author(s): C.E. Grégoire Padró and V. Putsche.

Date: September 1999.

Source/Publisher: National Renewable Energy Laboratory, a US Department of Energy Laboratory, operated by Midwest Research Institute.

2. Summary Information:

Type of study: 'Technical Report' surveying the economics of hydrogen technologies sponsored by an agency of the US government.
www.eere.energy.gov/hydrogenandfuelcells/pdfs/27079.pdf

Methodology (if specified): Draws on more than 100 publications ‘concerning the economics of current and near-term hydrogen technologies’. The report ‘briefly describes each technology, summarizes the status, and presents the results of the survey and standardization analysis’. Standardisation was undertaken to ‘ensure level comparisons among the technologies, they were converted to a standard basis because each report used its own assumptions and methods’. Capital costs are shown as the total capital investment (TCI) in $/GJ. ‘Specific TCI is a measure of the capital cost of a facility for each unit of hydrogen produced, processed or stored. For hydrogen production technologies, this value is the TCI divided by the annual hydrogen production capacity. For hydrogen storage technologies, the specific TCI is the TCI divided by the annual throughput. Another important convention of the report is the energy convention. Unless otherwise specified, all energy units (e.g., GJ) are reported on a lower heating value (LHV) basis’. Importantly in terms of the sources drawn upon: ‘The sources also differed in the level of detail provided. For example, some reports outlined all the technical and economic assumptions and provided a mass balance while others simply presented an overall cost (e.g., $10.23/GJ)’. This being the case ‘two methodologies, detailed and nondetailed, were used for standardization, depending on the information available in the report. ‘For the nondetailed cases, the costs provided in the source were scaled to the study basis (i.e., mid-1998$) using the appropriate Chemical Engineering Cost index’ (see below) ‘and all costs were converted to an LHV basis. If the energy basis was not provided in the source, to ensure conservative projections, it was assumed to be on an HHV [higher heating value] basis. Although rough, this method provides estimates that can be used for order-of-magnitude checks against the detailed estimates’.

Table A-2: Annual Cost Index

Year	C&E Index
1982	314.0
1983	316.9
1984	322.7
1985	325.3
1986	318.4
1987	323.8
1988	342.5
1989	355.4
1990	357.6
1991	361.3
1992	358.2
1993	359.2
1994	368.1
1995	381.1
1996	381.7
1997	386.5
Mid-1998	387

'Sources that contained detailed design and economic information were standardized using the following assumptions. The source of each assumption is also provided' (see below).

Table A-1: Economic Analysis Parameters

Parameter	Value	Source
General Parameters		
Heating values		
Hydrogen		
LHV	10,795 kJ/Nm^3	Foster-Wheeler 1996
HHV	12,761 kJ/Nm^3	Himmelblau 1982
Natural gas	40,398 kJ/Nm^3	EIA 1998
Coal	25,507 kJ/kg	EIA 1998
Biomass	19,705 kJ/kg	EIA 1998
Residual oil	41,680 kJ/L	EIA 1998
Energy/Feedstock Costs		
Natural gas	\$2.96/GJ	EIA 1998 – Industrial
Coal	\$1.46/GJ	EIA 1998 – Industrial
Biomass	\$46.30/dry tonne	Mann 1995a
Residual oil	\$1.8/GJ	EIA 1998 – Industrial
Electricity	\$0.049/kWh	EIA 1998 – Industrial
Other Operating Costs		
Labor	\$30,000/yr	Engineering judgement
Solid waste disposal	\$20.31/tonne	Foster-Wheeler 1996
Basic Economic Parameters		
Discount rate	10%	Foster-Wheeler 1996, 1998
Economic lifetime	20 years	
Depreciation schedule	None	Will depend on location
Income tax rate	None	Will depend on location
Construction period	3 years	Foster-Wheeler 1996, 1998
Construction expenditures	Year 1 – 10% Year 2 – 35% Year 3 – 55%	Foster-Wheeler 1996, 1998
Production Capacities		
Base case	Variable	Based on reference size
On-line factor		
Natural gas plants		
Year 1	60%	Foster-Wheeler 1996, 1998
Year 2+	90%	
Coal plants		
Year 1	45%	Foster-Wheeler 1996, 1998

Parameter	Value	Source
Year 2	73.3%	
Year 3	83.3%	
Year 4+	85%	
Biomass[1]		
Year 1	45%	Mann 1995a
Year 2+	90%	
Electrolysis		Foster-Wheeler 1996, 1998
Year 1	60%	
Year 2+	90%	
Storage		
Year 1	61%	Engineering judgement
Year 2+	98.6%	
Transport		
Year 1+	98.6%	Engineering judgement
Refueling		
Fleet and larger (Year 1+)	76%	Berry 1996
Home (Year 1+)	52%	Berry 1996
Storage Parameters		
Storage period	1 day and 30 days	Engineering judgement

[1] To be consistent with other analyses, the initial year of 50% production was scaled to be 50% of maximum annual production, 90% or 45%. This differs from Mann (1995a)

'Only the capital and major operating costs for each technology were standardized. Unit operating costs (e.g., fuel price) were modified to match the standard value and capital costs were scaled to mid-1998 US dollars using the Chemical Engineering C&E index of 387. If a source did not provide the dollar-year estimate, then it was assumed the same as the publication year'.

'The original methodology used to develop the costs in the source document was not changed'. 'Another major change for each analysis was the basis for the economic viability. Each source used its own methodology and determined its own level of acceptability (e.g., hurdle rate)…the standard economic methodology is based on a discounted-cash-flow-rate-of-return (DCFROR) analysis with an internal rate of 10%. Although most of the detailed analyses included the effect of depreciation and income tax, these factors were not evaluated because the laws governing them are country-specific. The effect of inflation (or deflation) was also ignored because it may also depend on the location and it may introduce more *uncertainty* in the analysis' (emphasis added).

As many of the sources used currencies other than $US conversion to $US often took place based on the conversion table below. 'No attempt was made to match the dollar-year used in the publication with the currency conversion for that year. After converting costs to US dollars, the values were escalated to 1998 dollars as described earlier'.

Table A-3: Currency Conversions

Currency	U.S. Dollar Equivalent
German Deutsche Mark (DM)	$0.61
Norwegian Kroner (NOK)	$0.134
Canadian Dollar (CAN$)	$0.83
European Currency (ECU)	$1.20
Dutch Florin (*f*)	$0.55
French Franc (FF)	$0.18

Technological scope and focus of the document/study: Hydrogen production (including: SMR, noncatalytic partial oxidation, coal gasification, biomass gasification, biomass pyrolysis, electrolysis); hydrogen storage (compressed gas, liquefied gas, metal hydride, carbon-based, chemical hydrides); hydrogen transport (pipelines, truck transport, rail transport, ship transport); stationary power (PEM fuel cells, PA fuel cells, SO fuel cells, MC fuel cells, alkaline fuel cells, gas turbine, stationary internal combustion engine); transportation applications (hydrogen fuel cell vehicles, hydrogen internal combustion engines, hybrid vehicles, onboard storage, onboard reforming, refuelling options).

Geographical scope and focus of the document/study: The authors are from the US-based National Renewable Energy Laboratory. The attempts to standardise the assumptions and costs pertaining to a variety of different reports from a number of different countries suggests, at least implicitly, that the authors tried to disembed the assumptions, costings and findings from various contexts and standardise them in terms of their own abstract criteria.

Temporal scope and focus of document: The 'study basis' was mid-1998. Any technologies 'more than 20 years from commercialization were not considered'.

Institutional affiliations: National Renewable Energy Laboratory, 1617 Cole Boulevard, Golden, Colorado 80401-3393.

3. Abstract or brief summary:

Drawing on more than 100 publications a survey of the economics of hydrogen production, storage, transport, and end-use technologies has been completed. The study analyses the comparative costs of different hydrogen technologies no more than 20 years from commercialisation.

4. Does the document include technological performance data?
(If yes give a brief description and list any primary sources)

Some technological performance data were included in the report in line with the technological focus outlined above. However this report was primarily an economic survey.

5. Does the document include cost estimates/economic performance data?
(If yes give a brief description and list any primary sources)

Cost estimates and economic performance data were included in line with the technologies outlined above following the methodology highlighted previously. Data sources were from numerous sources outlined in the report's bibliography.

6. Does the document include information on environmental, health or safety risks of H2 technologies?
(If yes give a brief description and list any primary sources)

Little focus explicitly although these issues cut across a number of the report's sections.

Seven.

1. Bibliographic information:

Title: 'The Feasibility, Costs and Markets for Hydrogen Production'.

Author(s): Paul Watkiss and Nikolas Hill.

Date: September 2002.

Source/Publisher: AEA Technology Environment for British Energy.

2. Summary Information:

Type of study: Final report by AEA Technology Environment for British Energy. www.theenergyreview.com/docs/hydrogen_energy_review.pdf

Methodology (if specified): Not explicitly stated but draws on a variety of assumptions (see example below for calculation of costs of hydrogen production by low pressure electrolysis) and secondary sources and thus 'evaluates current and longer-term technologies for hydrogen production and looks at their technical status, economics, constraints and carbon emissions'.

Table 4. Production Costs for Low Pressure Electrolysis.

Facility	Reference	Total Capital Costs (S/GJ)	Fuel price	Hydrogen Price (S/GJ)
6.75 Million Nm^3/d	Forster-Wheeler, 1996	31.0		24.5
	FCW, 2002			20.1
~2 million Nm^3/day ($125MW_{elec.}$)	NREL, 1999		\$0.02/kWh	12
	NREL, 1999		\$0.04/kWh	24.5
	Andreassen 1998	31.9		28.7
PV based				
0.195 (2000)	Mann 1995	486		41.8
0.209 (2010)	Mann 1995	242		24.8
Wind based				
0.247 (2000)	Mann 1995	159		20.2
0.279 (2010)	Mann 1995	93		11.0

Costs for a number of production options are collated in tables and graphs. For example, a review of the literature on production costs are summarised for SMR with or without sequestration (see below), and the 'economic costs of hydrogen production from SMR' are represented in a graph reproduced from Padro and Putsche (1999) (see below).

Table 2. Production Costs for SMR with and without sequestration.

Facility (Million Nm^3/d)	Reference	Total Capital Costs ($/GJ)	Hydrogen Price ($/GJ)
6.75	Forster-Wheeler 1996	10.00	5.44
Plus sequestration	Forster-Wheeler 1996 Assuming capture efficiency 85% (amine scrubbing and ocean disposal)		6.83 (@$23/t$CO_2$)
25.4	Blok et al 1997	10.82	5.97
Plus sequestration	Blok et al 1997 Assuming capture efficiency 70% (no scrubbing and reservoir diposal)		6.50 (@$13/t$CO_2$)

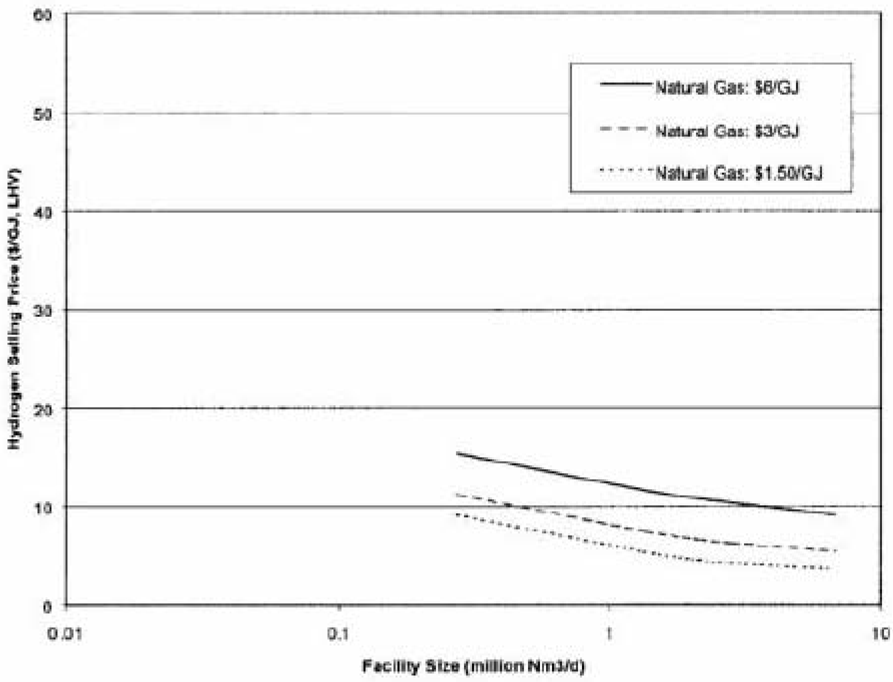

Figure 1. Economic costs of Hydrogen Production from SMR.

Reproduced from Padro and Putsche (1999).

A comparison is then made, drawing from existing literature, examining 'cost and efficiency estimates for hydrogen production' represented in a table (see below) and a bar chart (see below).

Table 6. Cost and Efficiency Estimates for Hydrogen Production from the Literature.

Production Method	CO_2 Capture	H_2 Production Efficiency (%)		Capital Cost £/GJ/a		H_2 Cost £/GJ		Carbon Emissions
		Low	*High*	*Low*	*High*	*Low*	*High*	
Steam reforming of Natural Gas	No	65%	90%	9.06		3.27	7.31	Significant
With CO_2 sequestration	Yes	65%	90%			4.41	9.14	Low
Partial oxidation of heavy hydrocarbons (gasification)	No	75%	86%	13.59	15.85	4.57	9.06	Significant
With CO_2 sequestration	Yes	75%	86%	Not known				Low
Partial oxidation of coal (gasification)	No	45%	50%	20.38	22.65	6.46	10.87	Significant
With CO_2 sequestration	Yes	45%	50%	Not known				Low
Partial oxidation of biomass (gasification)	No	65%	65%			5.67	11.17	Low**
Biomass pyrolysis	-					5.79	10.13	Zero
Methane pyrolysis	-					3.79	6.92	Low
Electrolysis - conventional*	-	63%	80%	7.88	15.76	6.53	16.00	Significant-Zero

*Does not take into account efficiency in electricity generation;
** Essentially low/zero net emission, as carbon of biomass origin.

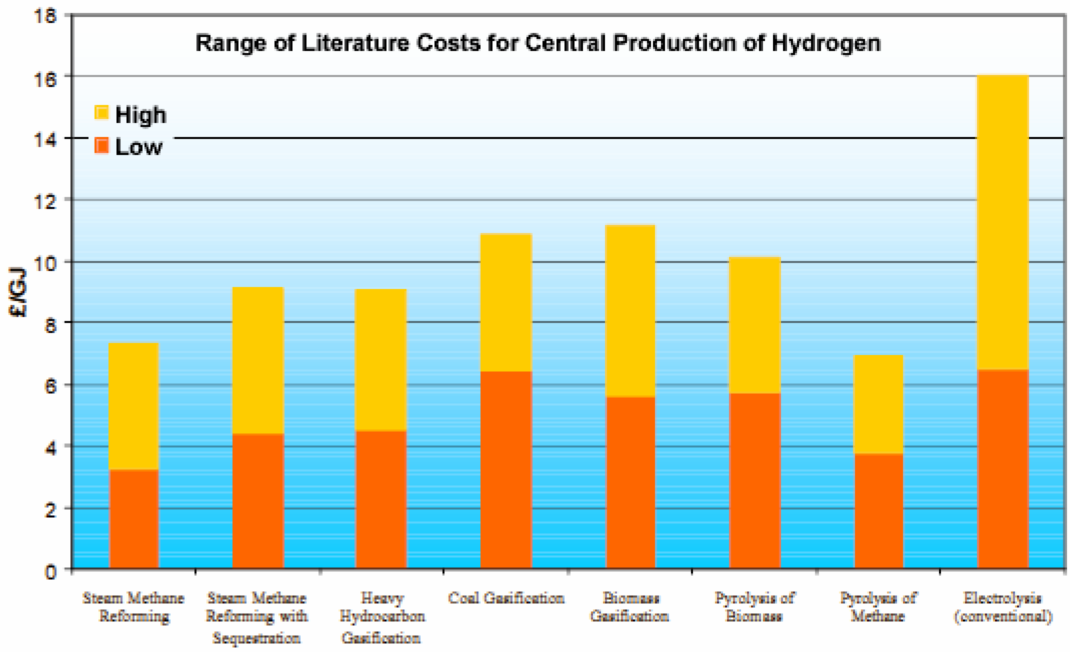

Figure 3 Costs of Hydrogen Production.

Distribution and storage issues are addressed, again drawing on secondary literature. Furthermore ‘key assumptions for modelling’ for a number of vehicle options are presented (see below).

Table 10. Vehicle key assumptions for modelling (ETSU/IC, 2000).

Vehicle	Daily distance (km)	Annual distance (km)	H2 consumption (kg/day)	H2 consumption (t/yr)	H2 consumption (kWh/yr)
Urban Bus	200	70,000	16.80	5.88	196,000
LGV	150	52,500	2.82	0.987	32,900
Taxi	300	105,000	2.67	0.935	31,167

NB: vehicle operates 350 days/yr

Technological scope and focus of the document/study: The focus of the document is on a variety of hydrogen production options in terms of the 'current' and the 'future'. Current options addressed include: steam reforming of natural gas, partial oxidation of heavy hydrocarbons and coal, carbon emissions, electrolysis of water (low pressure), and carbon emissions. Future options include: pyrolysis, small reformers, production from biomass, carbon emissions, advanced electrolysis, hydrogen from nuclear heat.

Also addresses distribution and storage issues with particular emphasis on hydrogen transport and delivery.

Geographical scope and focus of the document/study: The study 'assesses the possible rate of future demand for hydrogen in the UK'. This said, there is little explicit reference to place. There is also a significant use of secondary material drafted in both the UK and the US context.

Temporal scope and focus of document: A variety of timescales are interweaved into the document in different ways. Thus the focus of the document at different times is on the 'short-term', the 'medium-term', '2010', '2020', '2050', '5 years', and '10 years'. The report's self-stated scope is on 'current and longer-term technologies'.

Institutional affiliations: AEA Technology Environment.

3. Abstract or brief summary:

The 'paper evaluates current and longer-term technologies for hydrogen production and looks at their technical status, economics, constraints and carbon emissions'. The report offers a series of findings in terms of a variety of hydrogen production technologies. It also focuses on the ‘potential demand for hydrogen in the UK including the industrial sector, transport, domestic energy supply and electricity storage (e.g. for intermittent renewables)’. The report suggests that in ‘the short-term, gas reforming is likely to offer the least cost option for producing a hydrogen product. However, with increasing concerns over climate change, and the growth in demand towards 2020, other options are likely to emerge. The choice of infrastructure for hydrogen transportation will also influence the choice of technology as demand increases, especially in the transport sector. A number of other factors will also influence distribution systems, including: ‘CO2 concerns and reduction targets’, ‘costs of a hydrogen infrastructure network’, ‘costs of small-scale electrolysis units for distributed production’, the ‘availability of low cost, low carbon electricity, for hydrogen, especially given the challenging targets for renewables in power production’, the ‘longer term availability and costs of natural gas’. ‘An analysis of these issues leads us to conclude that nuclear generation has a major role to play in a zero carbon hydrogen economy’.

4. Does the document include technological performance data?
(If yes give a brief description and list any primary sources)

Technological performance data is included in the report in line with the technological focus of the document. The data is largely from secondary sources outlined in the text and referenced in the bibliography.

5. Does the document include cost estimates/economic performance data?
(If yes give a brief description and list any primary sources)

Economic performance data is included on the basis of individual technologies and also in terms of comparison between technologies. Again data is largely from secondary sources and is derived from sources and presented in a way which has already been highlighted previously in the Methodology section of this report.

6. Does the document include information on environmental, health or safety risks of H2 technologies?
(If yes give a brief description and list any primary sources)

Issues of addressing carbon emissions are largely in terms of the 'costs of production'. Again this analysis is largely in terms of secondary data. An important conclusion that is reached from the analysis is that whilst electrolysis is very expensive 'the technology offers carbon-free hydrogen when produced by nuclear or renewable energy'. 'Interestingly, whilst most of the literature on a carbon free hydrogen economy has focused on electrolysis powered by renewables, the analysis here has shown that a more favourable low cost option would be to use nuclear power'.

<u>Eight.</u>

1. Bibliographic information:

Title: 'An introduction to fuel cell technology and economics'.

Author(s): Nigel Brandon and David Hart.

Date: July 1999.

Source/Publisher: Imperial College Centre for Energy Policy and Technology, Occasional Paper 1.

2. Summary Information:

Type of study: Occasional Paper from an academic research centre.
www.iccept.ic.ac.uk/pdfs/fuelcell.pdf

Methodology (if specified): Not explicit, but mentions, and provides formulae for, 'Carnot efficiency', 'fuel cell efficiency', and looks at 'fuel cell system costs – now and predicted' (see below). The paper also examines the 'relative theoretical efficiency change with temperature of a fuel cell and heat engine'.

Costs ($/kW)	Technology: AFC	SPFC - stationary	SPFC - transport	PAFC	MCFC	SOFC
Cost in 1999	2000	8000	550	3000	5000	10,000
Predicted cost	50-100	300	30	1000	600	600

Table 4: Fuel cell system costs - now and predicted

Technological scope and focus of the document/study: The paper addresses a number of technological issues. These include: 'what is a fuel cell'? 'What are the different types of fuel cell'? 'What fuel do they run on'? 'Applications' ('stationary power generation', 'transport', 'battery "replacement"'), 'specific fuel cells for specific markets'. The paper also contains a table of 'fuel cell types' (see below) and a diagram of a 'possible vehicle fuel cell system in schematic' (see below).

Fuel cell type	Alkaline	Solid Polymer	Phosphoric Acid	Molten Carbonate	Solid Oxide
Acronym	AFC	SPFC	PAFC	MCFC	SOFC
Operating temp.	60-90°C	80-100°C	200°C	650°C	800-1000°C

Table 1: Fuel cell types

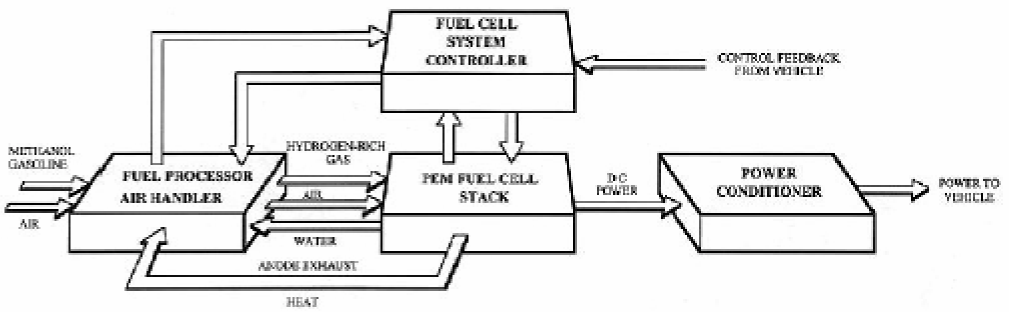

Figure 5: Possible vehicle fuel cell system in schematic

Geographical scope and focus of the document/study: Not specified but the paper is written by two UK-based academics. However, in looking at 'national funding' the paper outlines 'approximate public fuel cell funding in three key countries' (USA, Japan and Germany).

Temporal scope and focus of document: Not particularly explicit although timescales for specific technologies are mentioned at various points of the paper (see the Abstract below, for example).

Institutional affiliations: Imperial College Centre for Energy Policy and Technology (ICCEPT).

3. Abstract or brief summary:

The 'paper seeks to act as a first introduction to fuel cell technology, and to discuss in an objective manner the pros and cons of different fuel cell types, and their suitability for different applications. Further, the paper looks to introduce both the technical and economic issues facing the introduction of this technology'. Suggests that although fuel cells are already commercially available, 'albeit at high cost, for applications such as portable power sources and small-scale power generation' the expectation is that 'commercial devices for battery replacement will be commercially available around 2001', whilst 'manufacturers are evenly divided between 2003 and 2004 for the first commercial car release'. Furthermore, 'the larger-scale stationary fuel cell systems are inevitably the furthest from commercialisation'. The paper suggests that not only 'does more investment have to be put into the development and systems integration, but long-term tests are required and, like automotive fuel cell production, large manufacturing facilities. It is likely to be 2005-2010 before these systems are available on the market'. The paper also suggests 'suitable applications' for different types of fuel cells (see below).

			Suitable applications				
Fuel cell type	*Module size range (kW)*	*Waste heat output (°C)*	*Domestic power*	*Small-scale power*	*Large-scale cogeneration*	*Transport*	*Battery replacement*
AFC	<1-200	<60	✔	✔	✘	✔	✘
SPFC	<1-500	<80	✔	✔	✘	✔	✔
PAFC	5-500	<200	✘	✔	✘	-	✘
MCFC	250-5000	~600	✘	✔	✔	✘	✘
SOFC	5-5000	~850	✔	✔	✔	✘	-

Table 2: Applications for different fuel cell types

4. Does the document include technological performance data?
(If yes give a brief description and list any primary sources)

Technological performance data is provided for a variety of fuel cell types in relation to issues outlined above in the Methodology and Abstract sections. It isn't particularly explicit as to the sources of this data although there is a short bibliography and further reading section at the end of the paper.

5. Does the document include cost estimates/economic performance data?
(If yes give a brief description and list any primary sources)

The paper contains a table outlining ‘fuel cell system costs – now and predicted’. It is unclear from reading the paper how these figures are arrived at. Again there is a short bibliography and further reading section at the end of the paper.

6. Does the document include information on environmental, health or safety risks of H2 technologies?
(If yes give a brief description and list any primary sources)

The paper contains a half page section which is entitled ‘Environment’. It is unclear from reading the paper as to how the small number of estimates in this section are arrived at. For example, the suggestion is that: ‘Estimates suggest that a fuel cell power plant could produce 20-30% less CO_2 than traditional power plants, and that vehicles powered by fuel cells could provide similar benefits’.

Nine.

1. Bibliographic information:

Title: ‘Economic Analysis of Hydrogen Energy Station Concepts: Are ‘H2E-Stations’ a Key Link to a Hydrogen Fuel Cell Vehicle Infrastructure’?

Author(s): Timothy E. Lipman, Jennifer L. Edwards, Daniel M. Kammen.

Date: November 2002.

Source/Publisher: Renewable and Appropriate Energy Laboratory, Energy and Resources Group, University of California, Berkeley, CA 94720.

2. Summary Information:

Type of study: Final Report by the Renewable and Appropriate Energy Laboratory for BP and DaimlerChrysler.
http://ist-socrates.berkeley.edu/~rael/EStation_Final_Report.pdf

Methodology (if specified): This report conducts an analysis of H2E stations ('hydrogen energy stations'). The paper follows up earlier preliminary analysis using 'an integrated Excel/MATLAB/Simulink fuel cell system cost and performance model called CETEEM'. The report offers an overview of the CETEEM approach. This approach, according to the report's authors, permits analysis to adopt the following focus:

- 'Inclusion of several energy station designs based on different sizes of fuel cell systems and hydrogen storage and delivery systems for service station and office building settings';

- 'Characterization of a typical year of operation based on seasonally varying electrical load profiles for office building H2E-Station cases, rather than a single daily load profile';

- 'More careful specification of input variables, including 'high' and 'low' cost future cases and hydrogen sale prices of \$10/GJ, \$15/GJ, and \$20/GJ';

- 'Sensitivity analysis of key variables including natural gas prices, fuel cell costs, reformer system costs, and other capital and operating costs'; and

- 'Examination of greater numbers of FCVs per day supported, up to 75 per day, and examination of additional cases with station design and operational variations. This expanded analysis allows for a more complete feasibility analysis of the H2E-Station concept'.

‘There are, however, many more energy station design concepts that are possible, and additional facets of this concept that will be explored in future analysis’.

The analysis rests on numerous assumptions. It also includes and excludes a number of issues (see table below).

Table 1: Costs and Revenues Included and Not Included in the Analysis

Costs and Revenues Included in the Analysis	**Costs and Revenues Not Included in the Analysis**
• Fuel cell system capital costs	• Equipment installation costs
• Natural gas reformer capital costs	• Safety equipment costs
• Capital costs for FCV refueling equipment, including H2 compressor, H2 storage, and H2 dispensing pump	• Costs of any required construction permits or regulatory permits
• Natural gas fuel costs for electricity and hydrogen production	• Costs associated with any property that is devoted to FCV refueling
• Fuel cell system annual maintenance and periodic stack refurbishment	• Utility ‘standby charges’ for providing backup for electricity self-generation
• Reformer maintenance	• Costs of any labor associated with energy station operation or administration
• Purchased electricity, including fixed monthly charges, energy charges, and demand charges	• Federal, state, and local taxes on corporate income, including tax credits for equipment depreciation, etc.
• Revenues from hydrogen sales to FCVs	• Revenues from government incentives for fuel cell installation/operation or hydrogen dispensing
• Avoided electricity costs due to self-generation	
• Avoided natural gas costs due to co-generation of hot water with fuel cell system waste heat	

Technological scope and focus of the document/study: Fuel cell vehicles and hydrogen refuelling infrastructures.

Geographical scope and focus of the document/study: Focuses on a 'southern California location'.

Temporal scope and focus of document: Addresses 'medium term' cases (5-7 years) and 'future' high and low cost cases.

Institutional affiliations: Renewable and Appropriate Energy Laboratory, Energy and Resources Group, University of California, Berkeley, CA 94720.

3. Abstract or brief summary:

This paper suggests that in 'principle, many different H2E-Station concepts and designs are possible'. These include: 'service station' 'type designs that are primarily intended to produce H2 for FCV refueling'; 'office building' 'based designs that primarily provide electricity and waste heat to the building but also include a small off-shoot for FCV refueling'; and 'distributed generation' facilities that are primarily intended to supply excess electricity to the power grid, but that also include some provision for FCV refueling'. It concludes that in 'general, and particularly in the low-cost future cases, the H2E-Station design that appears to be the most economically attractive is the office building setting where relatively large fuel cells in the 100-250 kW size displace significant electricity purchases in the form of electricity energy and demand charges. These avoided electricity costs help to cover the costs of producing hydrogen for FCVs, and the economics of these stations tend to look better than those of H2E-Stations based at gasoline service stations. However, even these H2E-Stations at gasoline stations are more attractive than simply adding hydrogen dispensing infrastructure to a gasoline station without co-producing electricity, and this generally reinforces the potential attractiveness of the hydrogen energy station scheme in both office building and service station locations'.

4. Does the document include technological performance data?
(If yes give a brief description and list any primary sources)

This is largely an economic analysis, however the paper draws on technological performance data in line with the focus of the report outlined above. Focuses on different sizes of fuel cell systems in relation to refuelling infrastructures.

5. Does the document include cost estimates/economic performance data?
(If yes give a brief description and list any primary sources)

Draws on economic performance data in line with the focus of the report outlined above. In doing so use is made of various assumptions and estimates. The report's bibliography contains three sources and it is one of these by researchers at Directed Technologies Inc. (DTI) to which most reference is made:

Thomas, C. E., J. P. Barbour, B. D. James, and F. D. Lomax (2000). "Analysis of Utility Hydrogen Systems and Hydrogen Airport Ground Support Equipment," Proceedings of the 1999 U.S. DOE Hydrogen Program Review, NREL/CP-570-26938.

6. Does the document include information on environmental, health or safety risks of H2 technologies?
(If yes give a brief description and list any primary sources)

Little apparent focus on these issues. Indeed one of the costs excluded from the analysis specifically was 'safety equipment costs'.

<u>Ten.</u>

1. Bibliographic information:

Title: 'Economics' (Chapter 11 of 'Hydrogen 2003').

Author(s) (whole report): Maddy, J., Cherryman, S., Hawkes, F., Hawkes, D., Dinsdale, R., Guwy, A., Premier, G., and Cole, S.

Date: 2003.

Source/Publisher: Hydrogen 2003 Report Number 1 ERDF part-funded project entitled: ‘A Sustainable Energy Supply for Wales: Towards the Hydrogen Economy’, University of Glamorgan, Hydrogen Research Unit.

2. Summary Information:

Type of study: Academic study, from Hydrogen Research Unit.
http://www.h2wales.org.uk/Assets/Documents/Chap%2011%20(3.9MB).pdf

Methodology (if specified): This chapter offers a broad-ranging focus on the ‘economics of hydrogen energy’ largely through drawing on a range of secondary sources. ‘The information is based on recently published information, and is presented in a standardised form wherever possible. All costs have been converted to a lower heating value (LHV) basis for hydrogen. Currency used is pounds sterling for a UK/Wales audience. However, absolute values must be used with some caution. Dates of the cost estimates are given with each reference, so the impact of inflation must be considered. Conversely, greater experience levels would tend to reduce the costs’.

‘Whilst references include authors from several parts of the world, the majority of the cost survey work referred to is US based. This may have a tendency to under estimate the cost if applied in the UK, particularly in the case of larger plant installations, due to additional impact of, for example, UK health and safety legislation on project cost.

Alternatively, it may be fair to assume that costs are generic and not based on competitive quotations from suppliers. The market approach of competitive tendering would tend to reduce the costs, again for the larger plant installations’.

‘Despite these potential discrepancies, the costs are intended as an indication of the state-of-the-art or the current prediction of future cost’.

The focus of the chapter is in moves from outlining 'a comparison of costs for various energy sources, demonstrating the variation in cost of hydrogen based on current production technologies'. The suggestion is that 'the current costs do not give the whole picture'. A series of 'externalities' need to be 'internalised' in that an 'adequate comparison of the cost of energy technologies also needs to assess the environmental and social costs'. The difficulty with this is that: 'Clearly, many externalities such as costs of abatement can only be approximated, whilst social cost or climate change are difficult if not impossible to fully calculate. In the absence of broadly accepted norms for external costs, any comparison of technologies will understandably depend on whether high or low estimates for the externalities are used'.

A series of 'supply-side factors' are analysed through secondary literature. 'Production economics' draws on surveys conducted by Padro and Putsche (1999), Adamson and Pearson (2000), Dutton (2002), and Simbeck and Chang (2002), and addresses: steam methane reforming, partial oxidation of oil, coal gasification, hydrocarbon pyrolysis, biomass gasification, biomass pyrolysis, electrolysis, wind/electrolysis, solar electrolysis solar photovoltaic, concentrated solar energy, high temperature electrolysis, biological production and by-product hydrogen. 'Hydrogen storage economics' addresses: hydrogen storage costs, underground hydrogen storage, liquid hydrogen storage, metal hydride, carbon based systems, chemical hydrides and vehicle hydrogen storage. Whilst 'distribution economics' looks at: compressed hydrogen trailer distribution, liquid hydrogen distribution, pipeline distribution, pipeline transmission cost, transport in metal hydrides, 'other means' of hydrogen distribution and 'chemical intermediates'. 'End use economics' encapsulates issues of: fuel cells (a variety of types), fuel cells for vehicles, internal combustion engines and gas turbines.

Technological scope and focus of the document/study: A series of 'supply-side factors' are analysed through secondary literature including: 'production economics' (steam methane reforming, partial oxidation of oil, coal gasification, hydrocarbon pyrolysis, biomass gasification, biomass pyrolysis, electrolysis, wind/electrolysis, solar electrolysis solar photovoltaic, concentrated solar energy, high temperature electrolysis, biological production and by-product hydrogen); 'hydrogen storage economics' (hydrogen storage costs, underground hydrogen storage, liquid hydrogen storage, metal hydride, carbon based systems, chemical hydrides and vehicle hydrogen storage); 'distribution economics' (compressed hydrogen trailer distribution, liquid hydrogen distribution, pipeline distribution, pipeline transmission cost, transport in metal hydrides, 'other means' of hydrogen distribution and 'chemical intermediates'); 'end use economics' (fuel cells (a variety of types), fuel cells for vehicles, internal combustion engines and gas turbines).

Geographical scope and focus of the document/study: Wales/UK, although much of the literature is derived from the US context.

Temporal scope and focus of document: Not entirely clear although the study does draw on numerous secondary documents already highlighted (e.g. Padro and Putsch).

Institutional affiliations: Hydrogen Research Unit, University of Glamorgan.

3. Abstract or brief summary:

The wider report of which this chapter is part aims to 'provide a resource to enable the reader to understand the current state of hydrogen development. It is a summary of the state-of-the-art as seen by the authors and is the first stage in a project to examine the social, economic and technical implications of a move towards the hydrogen economy for Wales'. This is as a prelude to 'later identify[ing] the most viable demonstration projects for a second stage, including possible sources of funding'. The importance of this is that as 'the necessary technical, economic and social information will have been put in place by the project, it should be possible to implement these projects rapidly'. Furthermore: 'The project will also provide a framework of information to support decision-making by those responsible for developing a sustainable energy policy in Wales. It is hoped that this project may be of assistance to other regions which are also considering this transition'. This specific chapter (chapter 11) focuses on the 'economics' of hydrogen technologies in terms of the issues and scope highlighted above and below.

4. Does the document include technological performance data?
(If yes give a brief description and list any primary sources)

Yes in relation to the range of technologies highlighted above, but from secondary sources.

5. Does the document include cost estimates/economic performance data?
(If yes give a brief description and list any primary sources)

Yes in relation to the range of technologies highlighted above, but from secondary sources.

6. Does the document include information on environmental, health or safety risks of H2 technologies?
(If yes give a brief description and list any primary sources)

Health and safety issues are addressed in a separate chapter (chapter 9) of the overall document 'Hydrogen 2003'. This focuses on: 'health hazards', 'safety procedures', 'industrial safety codes' and 'component safety standards and compatibility'.

Acknowledgements
We would like to thank colleagues at Salford and the Policy Studies Institute for general discussions around some of the ideas presented here. We also acknowledge the financial support of the UK Sustainable Hydrogen Energy Consortium.

Annex A

1. Bibliographic information:

Title:

Author(s):

Date:

Source/Publisher:

2. Summary Information:

Type of study:

Methodology (if specified):

Technological scope and focus of the document/study:

Geographical scope and focus of the document/study:

Temporal scope and focus of document:

Institutional affiliations:

3. Abstract or brief summary:

4. Does the document include technological performance data?
(If yes give a brief description and list any primary sources)

5. Does the document include cost estimates/economic performance data?
(If yes give a brief description and list any primary sources)

6. Does the document include information on environmental, health or safety risks of H2 technologies?
(If yes give a brief description and list any primary sources)

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Chandra, P., (1995), 'Technology Characterization: Explaining a Few Things', June 8. Requested by e-mail from the author.

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