Australian Government

Department of Resources
Energy and Tourism

HYDROGEN TECHNOLOGY ROADMAP

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Prepared for the
Australian Government
Department of Resources, Energy and Tourism

by

WYLD GROUP PTY LTD

in conjunction with

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ENHANCING AUSTRALIA'S ECONOMIC PROSPERITY

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ABBREVIATIONS

AFC	Alkaline Fuel Cell
ARC	Australian Research Council
AU	Australia
CA	Canada
CBD	Central Business District
CCS	Carbon Capture and Storage
CFCL	Ceramic Fuel Cells Limited
CH_4	Methane
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2-e	Carbon Dioxide Equivalent
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DE	Germany
DFC	Direct Fuel Cell
DG	Distributed Generation
DMFC	Direct Methanol Fuel Cell
DOE	United States Department of Energy
DOT	United States Department of Transport
DWPI	Derwent World Patent Index
EERE	Energy Efficiency and Renewable Energy
EC	European Commission
EU	European Union
FC	Fuel Cell
FCHV	Fuel Cell Hybrid Vehicle
FCV	Fuel Cell Vehicle
FY	Fiscal Year
GB	Great Britain
GHG	Greenhouse Gas
GJ	Gigajoule
GST	Goods and Services Tax
H_2	Hydrogen
H2FC	Korea's National RD&D Organization for Hydrogen and Fuel Cells
HCG	High-level Coordination Group
HERC	Korea's Hydrogen Energy R&D Center
HHV	Higher Heating Value
ICE	Internal Combustion Engine
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IGFC	Integrated Gasification Fuel Cell
IP	Intellectual Property
IPHE	International Partnership for the Hydrogen Economy
JP	Japan
JTI	European Union's Joint Technology Initiative on Hydrogen and Fuel Cells
kg	Kilogram
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt-hour
L	Litre
LEC	Levelised Energy Cost
LPG	Liquefied Petroleum Gas
LRMC	Long-Run Marginal Cost
MCFC	Molten Carbonate Fuel Cell
METI	Japanese Ministry of Economy, Trade and Industry
MJ	Megajoule
MOCIE	Korean Ministry of Commerce, Industry and Energy
MW	Megawatt
NAS	United States National Academy of Sciences
NG	Natural Gas
NHMA	National Hydrogen Materials Alliance
OECD	Organisation for Economic Co-operation and Development
PAFC	Phosphoric Acid Fuel Cell
PCT	Patent Cooperation Treaty
PEMFC	Proton Exchange Membrane Fuel Cell
PLE	Petrol Litre Equivalent
RAPS	Remote Area Power Supply
R&D	Research and Development
SEFCA	Sustainable Energy Fuel Cells Australia Pty Ltd
SOFC	Solid Oxide Fuel Cell
SWOT	Strengths, Weaknesses, Opportunities and Threats
TCO	Total Cost of Ownership
ULP	Unleaded Petrol
US or USA	United States of America
V	Volt
VC	Venture Capital or Venture Capitalist
WTT	Well to Tank
WTW	Well to Wheel

EXECUTIVE SUMMARY

On 13 April 2007, the Council of Australian Governments (COAG) announced that four energy technology roadmaps would be developed: coal-gasification, geothermal, hydrogen and solar thermal. The objectives of the hydrogen roadmapping process were to assess Australia's hydrogen research capabilities and strengths and to identify what actions Australia could take to prepare for the possible emergence of a hydrogen economy.

To this end, the roadmap identifies, among other outputs, the suggested role of Australian governments, industry and researchers in enabling and facilitating the development of a hydrogen economy in Australia. It recommends a range of strategies and initiatives, suggests responsibilities for implementation and proposes a time frame for implementation.

As noted in the literature and through the extensive stakeholder consultations conducted for this roadmap, it is important to treat hydrogen separately from fuel cells. Discussions of the hydrogen economy often do not adequately distinguish between these two.

First and foremost, hydrogen is not an energy source—it is an energy carrier that is produced from other substances using primary energy resources. Fuel cells, on the other hand, are energy conversion devices that utilise hydrogen. The emergence of a substantial stationary fuel cell market does not require the development of a hydrogen fuelling network—although such a network could speed the deployment of fuel cells. Similarly, hydrogen does not need fuel cells for its utilisation, although fuel cells offer some particular attractions for the efficient utilisation of hydrogen in electricity generation.

While many previous market predictions over the last decade have been overly optimistic, it appears that the long-term and substantial public and private sector investments in Europe, Japan and the USA in hydrogen and fuel cell research, development and demonstration (RD&D) over the last decade are beginning to generate economic opportunities.

Stationary, transport and portable fuel cell products are entering niche (but nonetheless potentially large) commercial markets and meeting customer requirements for product lifetimes and total cost of ownership (TCO) hurdles. Meanwhile, investment in hydrogen fuelling infrastructure is growing in the USA (particularly California), Europe, China, Korea and Japan if only, at this stage, to ensure large-scale demonstration trials of hydrogen-fuelled vehicles can be supported.

There are competitive energy carriers to hydrogen (i.e. electricity and liquid fuels) and energy converters to fuel cells (e.g. internal combustion engines and gas turbines)—and governments and industry are investing heavily in all of them to position their economies for a clean energy future and to reap the social, industrial and economic returns from that positioning. However, it is likely that a number of advanced economies overseas will develop significant industry sectors based on one or both of hydrogen and fuel cells.

Large sums of money have been, and continue to be, invested overseas in hydrogen related RD&D—the International Energy Agency, for example, estimated in 2004 that public and private sector RD&D funding was $1 billion and $3–4 billion per year, respectively. To date Australia has not invested comparably to investigate the opportunities that hydrogen and fuel cells may offer for a clean energy future here—hydrogen currently is positioned as a low priority in Australia's energy policy. Other advanced, and developing, countries are investing to prepare their economies and their people for hydrogen and fuel cells as one of the components of a clean energy future.

Australia risks significant competitive disadvantage in the global hydrogen and fuel cell markets and industry growth if it is simply left to market forces to prepare for their introduction locally. Overall, the economic benefits to Australian governments and industry of early preparation for hydrogen and fuel cell deployment, as proposed in this roadmap, are likely to exceed the costs of implementation because:

- Australia will be able to move earlier and more efficiently to benefit economically and environmentally from deployment of products and services based on fuel cells and/or hydrogen.
  - Carbon abatement is a high need in Australia's future energy pathways to contribute to global efforts to reduce the impacts of climate change; there is a high need to maintain Australia's international competitiveness as a low-cost energy supplier in global markets; and Australia has a high energy security vulnerability to particular, imported liquid fuels, the loss of which would cause severe disruption to the mining, agriculture and freight transport sectors.
- Australian companies and researchers will be better positioned to participate successfully in global supply chains for hydrogen and fuel cell components, systems and technology.
  - There is a high need to grow Australia's international competitiveness and participation in global supply chains for new energy technologies.

With an emissions-trading scheme in Australia, fuel-cell stationary power systems for distributed generation applications may become a technology-of-choice in Australia's residential and commercial sectors. Deployment of IGCC for large-scale electricity generation together with wide-spread use of fuel cell DG systems will lead to an increasing 'hydrogenation' of Australia's electricity generation. There also appear to be prospects for hydrogen and fuel cells in portable energy applications (laptop computers, video cameras, mobile phones) and some near-term commercial transport energy applications (e.g. forklifts and buses).

Australia will primarily be a taker (i.e. importer) of hydrogen and fuel cell technologies given our relative economic scale and industry structure. However, there must be local, independent technical capability and capacity to evaluate new energy technologies for application in Australia. Further, Australia has some world-class technology strengths in specific hydrogen, fuel cell and system integration areas, but the ability of Australia to exploit these is compromised by current energy market and innovation system weaknesses.

The primary need for Australia regarding hydrogen and fuel cells—at least in the near to medium term—is to ensure that both are actively maintained as options for a future low-carbon economy and society. Active maintenance will require:

- development of a favourable policy framework for clean energy in Australia;
- knowledge building in consumers, utilities, financiers, industry, regulators and governments about hydrogen and fuel cells;
- market development efforts to promote the sector and to remove barriers to deployment;
- development of Australian supply-chains for viable near-term applications and large-scale demonstration programs; and
- training and competence building in human resources and technology capability and capacity.

The vision for hydrogen and fuel cells in Australia therefore is:

By 2020 Australia is effectively exploiting emerging hydrogen and fuel cell market and supply-chain opportunities, locally and globally.

Key strategies to implement this vision, options for activities, indicative timeframes and suggested organisations responsible for their implementation are summarised in the table over. Investing in these activities will enable Australian governments, industry, researchers and the broader community to position Australia for the potential emergence of hydrogen and fuel cells as a key component of Australia's energy future.

Ultimately, the choice whether to embrace or reject the move to a 'hydrogen economy' will require compelling underpinning arguments. The recommendations in this roadmap will enable any ultimate decisions to be well informed ones.

While acknowledging the importance of building on and extending the R&D capability and capacity for hydrogen and fuel cells in Australia, stakeholders' top five priorities focused on market and supply-chain development activities, as follows:

- Large-scale demonstration projects, which stakeholders noted would pull and underpin: R&D; technology, industry and policy development; regulations, codes and standards; and overseas interest in Australia as a market.
- Establishment of an advocacy group in Australia (the proposed hydrogen and fuel cell industry association) which is comprehensive and widely supported. An important function for this group will be education and outreach to a wide range of parties but particularly to end-users and project/venture financiers.
- Accelerated development of regulations, codes and standards in Australia that facilitate the market uptake of non-industrial hydrogen use and of fuel cell products.
- Systems analysis modelling, including further cost modelling and comparative analysis, to guide and prioritise policy and industry development efforts.
- Establishment of public policy that both pulls and pushes progress in Australia in hydrogen and fuel cells, particularly market-support mechanisms such as pricing carbon emissions and establishment of government purchasing policies favourable to hydrogen and fuel cell products.

Learning from joint technology initiative approaches taken overseas, a High-level Coordination Group (HCG) comprising Australian government, industry and research sector representatives should be established to oversight the start-up and progress of the activities under this roadmap with the aim of ensuring that its vision is achieved and that by 2020 well informed and credible decisions about the future of hydrogen and fuel cells in Australia's energy mix can be made, taking into account competing options.

Rules of Thumb for Hydrogen

The energy content of 1 kg of hydrogen is equivalent to approximately 3.8 litres (approximately 1 US gallon) of petrol.

The energy content of 1 cubic metre of hydrogen (at atmospheric pressure) is equivalent to approximately 0.34 litres of petrol.

The energy content of 1 litre of liquid hydrogen is equivalent to 0.27 litres of petrol.

Summary of key strategies, options for activities and implementation

Key Strategies	Options for Activities	Indicative Time-Frame for Implementation	Responsibility for Implementation
Policy Framework: Market Support Mechanisms	• Ensure Australia's national emissions trading scheme does not inadvertently create barriers for fuel cells or hydrogen.	2008 – 2010	• Australian, State and Territory governments
	• Gain a thorough understanding of the GHG benefits of fuel cells and hydrogen in different stationary and transport applications.	2009 – 2012	• Industry, researchers and emissions-trading operator
	• Devise and implement policy mechanisms that will promote deployment in Australia of high efficiency DG systems, particularly for CHP applications.	2008 onwards	• Ministerial Council on Energy's Renewable and Distributed Generation Working Group
	• Extend, as appropriate, other clean energy market support mechanisms at State, Territory and Australian government levels to include high efficiency DG.	2008 onwards	• Australian, State and Territory governments
Policy Framework: Options Analysis Modelling	• Stay abreast of international modelling efforts; undertake modelling for Australia when appropriate; and compare international and Australian results.	2008 onwards	• Australian governments in conjunction with High-level Coordination Group (HCG)
Knowledge Building: Active in International Forums	• Continue / enhance involvement in multilateral (e.g. IEA, IPHE, APEC, APP) and bilateral forums.	2008 onwards	• Australian governments in conjunction with the HCG
Knowledge Building: Education and Outreach	• Develop education and outreach tools, including an up-to-date database of RD&D activities in hydrogen and fuel cells in Australia, to meet the information and knowledge needs of educators, researchers, government and industry.	2009 onwards	• Hydrogen & Fuel Cell (H&FC) Industry Association
	• As a follow-up to the WHEC 2008 in Brisbane, hold an annual national hydrogen and fuel cells conference with invited international participation.	2009 onwards	• H&FC Industry Association
Market Development: Coordinated Sector Representation	• Establish a hydrogen and fuel cell (H&FC) industry association.	2008 – 2009	• Hydrogen and fuel cell industry
Market Development: Regulations, Codes and Standards	• Industry demonstrates the need to accelerate the development of regulations, codes and standards in Australia for non-industrial hydrogen use and fuel cell products.	2008 onwards	• Industry suppliers of hydrogen and fuel cells
	• Ensure that Australia's regulations, codes and standards for hydrogen and fuel cells are developed in a timely manner, and in harmony with international best practice.	2008—2012	• Standards Australia; State and Territory governments; industry-sector regulators

Key Strategies	Options for Activities	Indicative Time-Frame for Implementation	Responsibility for Implementation
Supply-Chain Development: Viable Near-Term Applications	• Industry promotes uptake in Australia of economically competitive fuel cell and hydrogen products. • Australian governments promote participation by Australian companies in global supply chains for fuel cell and hydrogen products or services to maximise local industry development and employment growth.	2008 onwards 2008 onwards	• Industry suppliers of hydrogen and fuel cells • Australian, State and Territory governments
Supply-Chain Development: Large Scale Demonstrations	• National and international companies, in collaboration with Australian governments, support large-scale demonstrations in Australia of pre- or early-commercial fuel cell and/or hydrogen products in a small number of near to medium term economic applications. • Ensure, where possible, that such demonstration projects are linked into international trials and that data is shared as a key input into modelling and analysis of energy system options for Australia.	2009 – 2015 2009 – 2015	• HCG/H&FC Industry Association • HCG/H&FC Industry Association
Competence Building: World-Scale Collaborative R&D Projects	• Building on areas of technical strength identified in this roadmap, strengthen public-sector and promote private-sector funding support for world-class R&D applied to commercially-important technical problems in hydrogen and fuel cells, and their applications. • As a complementary or additional option, establish a joint initiative among national and international companies, Australian governments and researchers to fund and undertake world-scale, collaborative, focused R&D efforts in Australia in two areas of local technology strength and high, global, commercial opportunity where Australia could take a technology leadership position.	2009 onwards 2010 – 2012	• Australian, State and Territory governments in conjunction with the HCG • Australian, State and Territory governments in conjunction with the HCG
Competence Building: Capacity and Capability Building	• Encourage and work with tertiary and secondary educational institutions to develop relevant technical and business courses incorporating hydrogen and fuel cells as key teaching topics and foster postgraduate research opportunities in these and allied technical fields.	2009 onwards	• H&FC Industry Association

1 INTRODUCTION

On 13 April 2007, the Council of Australian Governments (COAG) announced that four energy technology roadmaps would be developed, coal-gasification, geothermal, hydrogen and solar thermal[1]. The objectives of the hydrogen roadmapping process were to assess Australia's hydrogen research capabilities and strengths and to identify what actions Australia could take to prepare for the possible emergence of a hydrogen economy.

To this end, the roadmap identifies, among other outputs, the suggested role of Australian governments, industry and researchers in enabling and facilitating the development of a hydrogen economy in Australia. It recommends a range of strategies and initiatives, suggests responsibilities for implementation and proposes a time frame for implementation.

1.1 Background to this roadmap

The National Hydrogen Study[2] put forward a vision for the future that

> "would have Australia among the world leaders in hydrogen technology. Australian renewable energy/hydrogen hybrid power supply systems, developed to address local needs, could be exported all over the world. Our fossil fuel resources would continue to sustain major export industries, but in many instances coal exports would now be converted to hydrogen at their destination and flue gases would be sequestered. 'Hydrogen economy' power plants and related sequestration infrastructure could be founded on international technological R&D in which Australian input and collaboration played an important and influential role.
>
> In short, there is opportunity, in this future, for hydrogen to meet Australia's own and much of the world's energy needs for a very long time, underpinning a secure economic future for the people of this country. In that world there would be few of the environmental problems currently associated with energy production and distribution—and anxiety about key concerns, like greenhouse emissions and air quality would be greatly diminished. Those opportunities should not be missed, either by inadvertently putting obstacles in its way, or by failing to take the necessary actions now that may be needed to ensure any future hydrogen economy that emerges has characteristics which benefit, rather than detract from, Australia's economic and environmental interests."

This study went on to recommend (Recommendation 9) that "to assist in better targeting available R&D funding, technology road maps should be commissioned for areas of hydrogen R&D identified as capitalising on Australia's competitive advantages."

The field of interest for this project is hydrogen and fuel cells in Australia. For hydrogen, its production, delivery and storage, as well as its use in stationary, transport and portable applications, are included in this roadmapping project. For fuel cells, the use in stationary, transport and portable applications are included.

1 http://www.coag.gov.au/meetings/130407/index.htm#climate, last accessed 27 March 2008.

2 *National Hydrogen Study*, A report prepared by ACIL Tasman and Parsons Brinckerhoff for the Department of Industry, Tourism and Resources, 2003.

1.2 The methodology for this roadmap

Roadmapping is traditionally a technology planning process to help identify, select, and develop technology alternatives to satisfy a set of product needs.[3] It starts with needs, not solutions.[4] The main benefit of technology roadmapping is that it provides the information that is necessary to help make better technology investment decisions.

In developing this Australian roadmap for hydrogen and fuel cells, this needs-driven approach has been kept foremost. That is, the development of this roadmap did not start with the end-point of a desirable hydrogen future already defined—in contrast to many similar planning processes elsewhere[5,6].

It is important to note that the set of needs, as discussed in Section 2.3, can also be satisfied by technologies that do not involve hydrogen and fuel cells.

To develop a credible and defensible roadmap for use by Australian governments and researchers, together with suppliers and customers in the hydrogen and fuel cell value chains, Wyld Group, in conjunction with its partners McLennan Magasanik Associates (MMA) and b*wise*IP Pty Ltd have:

- Undertaken bottom-up data gathering through extensive and direct consultation with stakeholders by:
  - Preparing a discussion paper for targeted use with key stakeholders to focus the consultation process and responses[7];
  - Carrying out one-on-one interviews with stakeholders from industry, research and government—nationally and internationally—about opportunities and constraints facing hydrogen and fuel cell technologies.
  - Conducting workshops in Melbourne, Perth and Brisbane with cross-sectional representation to enable sharing of views and cross-fertilisation of ideas;
  - Attending the IEA/IPHE Workshop on Building the Hydrogen Economy: Enabling Infrastructure Development in Shanghai from 22–24 October 2007; and
  - Holding meetings in New Zealand to discuss the development and progress of, and outcomes from, the current New Zealand hydrogen technology roadmapping project.
- Undertaken desktop research in order to:
  - Collect and review relevant national and international publications and the outputs of similar roadmapping projects overseas;
  - Model costs in Australia of production of hydrogen and of stationary power generation using fuel cells to provide a forecast of uptake of each in competitive markets here; and
  - Identify, at a high level, the international and national intellectual property (IP) landscape for hydrogen and fuel cells.
- Completed a draft roadmap document, and tested it and the analyses behind it through further key stakeholder consultation, including one additional stakeholder workshop in Sydney.

It is emphasised that development of any technology roadmap is done with the best data available at the time to optimise the factors that affect a technology's development. The practitioners in the field, however, will still have to deal with day-to-day successes and set-backs to reach their and the roadmap's goals.

3 M.L. Garcia and O.H. Bray, *Fundamentals of Technology Roadmapping*, Sandia National Laboratories Report No. SAND97-0665, April 1997

4 Industry Canada, *Technology Roadmapping—A Strategy for Success*, available at **http://strategis.ic.gc.ca/epic/site/trm-crt.nsf/en/rm00064e.html.**

5 W. McDowall and M. Eames, *Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature*, Energy Policy, Vol. 34, 1236–1250, 2006.

6 T. Clemens et al, *Transitioning to a Hydrogen Economy: Issues Document*, CRL Energy Limited Report No 07/11009, May 2007.

7 Discussion Paper—*Hydrogen Technology Roadmap: Market Potential and Challenges, Innovation Opportunities and Policy Issues*, prepared for the Australian Government Department of Resources, Energy and Tourism, October 2007.

1.3 Distinguishing hydrogen and fuel cells

As noted in many papers on hydrogen and by participants in the workshops conducted for stakeholder consultation for this roadmap, it is important to treat hydrogen separately from fuel cells. Discussions of the hydrogen economy often do not adequately distinguish between the two.

First and foremost, hydrogen is not an energy source— it is an energy carrier. Just like today's commonplace energy carriers—electricity and liquid fuels (petroleum products and biofuels)—hydrogen is "manufactured" from other substances using primary energy resources. That is, it takes energy to produce hydrogen from a range of hydrogen-containing materials (i.e. water, natural gas, liquid hydrocarbons, coal and biomass). It is important to note that:

- As illustrated in Figure 1, there are a wide variety of hydrogen production routes—and these range from large-scale, centralised production to medium, small and micro-scale distributed production.

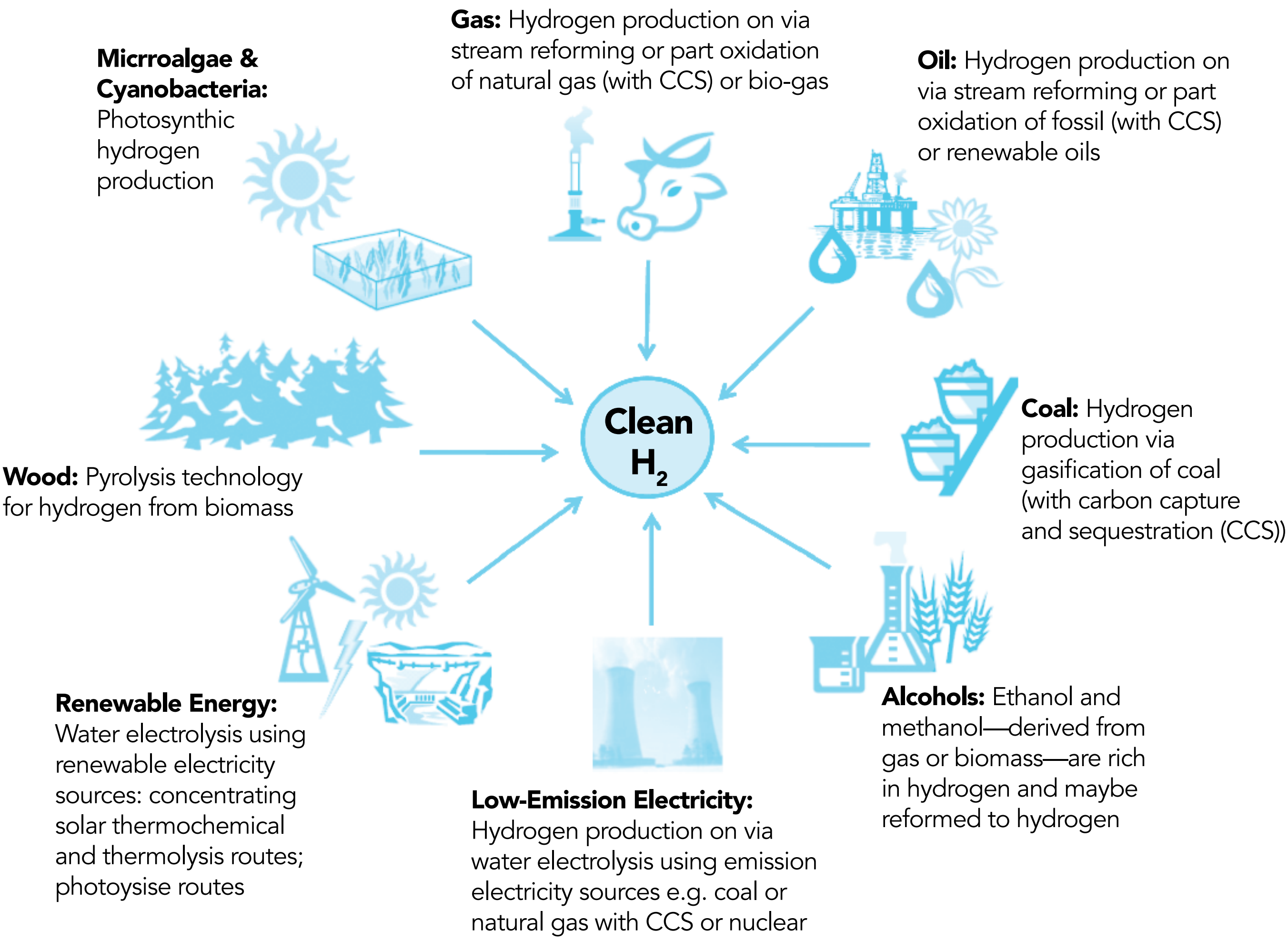


FIGURE 1: Production routes for clean hydrogen[8] (adapted from Riis et al[9])

8 The diagram uses 'clean' as describing the hydrogen produced by the various routes albeit, as shown, using fossil fuels depends upon utilisation of carbon capture and storage (CCS). Using wood or other biomass forms depends upon replanting and other measures for the hydrogen to be 'clean'.

9 T. Riis et al, *Hydrogen Production and Storage: R&D Priorities and Gaps*, International Energy Agency Hydrogen Implementing Agreement, 2006.

- Creation of a hydrogen fuelling system introduces multiple losses of efficiency from points of production through delivery and storage to its ultimate use.
- While hydrogen can be complementary to the other major energy carriers, in many cases they will be competitors to supply energy services to end users.
- As with any fuel, hydrogen can be utilised directly in internal combustion engines (ICEs), gas turbines and for industrial process heat applications.
  – That is, hydrogen does not need fuel cells for its utilisation, although fuel cells offer some particular attractions for the efficient utilisation of hydrogen in electricity generation.

Fuel cells, on the other hand, are energy conversion devices that utilise hydrogen. Some types of fuel cells lend themselves to the direct (internal) production of hydrogen from other fuels such as natural gas or biofuels while others require pure hydrogen as the fuel input (see Figure 2).

All fuel cells generate electricity—highly efficiently—with heat as a by-product of the generation process. While fuel cells in some applications are complementary to existing means of providing electricity and heat, in some they will be competitive and in others they provide options not currently available.

Most importantly, the emergence of a substantial fuel cell market does not need the development of a hydrogen fuelling network—although the former may be enhanced by the latter.

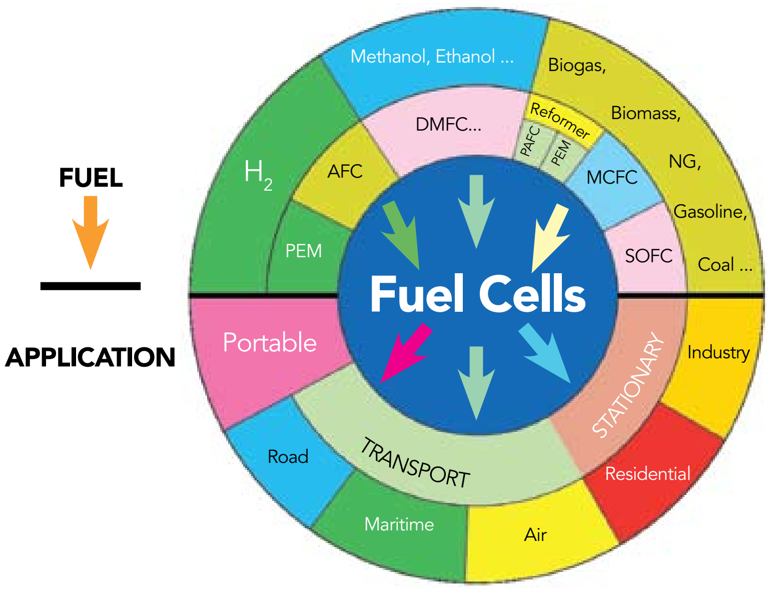


FIGURE 2: Fuel cell technologies, possible fuels and applications (from European Commission[10])
[PEM = Proton Exchange Membrane Fuel Cell; AFC = Alkaline Fuel Cells;
DMFC = Direct Methanol Fuel Cell; PAFC = Phosphoric Acid Fuel Cell;
MCFC = Molten Carbonate Fuel Cell; SOFC = Solid Oxide Fuel Cell]

10 European Commission, *Hydrogen Energy and Fuel Cells: A vision of our future*, Publication No. EUR 20719 EN, Directorate-General for Research and Directorate-General for Energy and Transport, 2003.

2. HYDROGEN AND FUEL CELLS – GLOBAL ACTIVITIES

2.1 Hydrogen production and use

2.1.1 Captive use

Hydrogen production is a large and growing industry today. Globally, some 50 million tonnes of hydrogen, equal to about 170 million tonnes of oil equivalent[11, 12] are produced annually almost wholly for captive use as a reagent in industrial and chemical processes. As of 2005, the economic value of all hydrogen produced worldwide is reported as being about US$135 billion per year.[13]

There are two primary uses for hydrogen today. Approximately one half is used to produce ammonia, which is then used directly or indirectly as fertiliser. Because both the world's population and the intensive agriculture used to support it are growing, ammonia demand is growing. Most of the balance of current hydrogen production is used to convert heavy petroleum fractions into lighter fractions suitable for use as refined fuels[14]. Such conversion processes represent an even larger growth area because rising oil prices are encouraging oil companies to use poorer, heavier source materials such as tar sands and oil shale.

The scale economies inherent in large-scale oil refining and fertiliser manufacture make possible on-site production and captive use of hydrogen in these industrial chemical processes. Currently, global hydrogen production is reported[15] to be 48 per cent from natural gas, 30 per cent from oil, and 18 per cent from coal with water electrolysis accounting for only 4 per cent.

A new, and potentially very large, captive use of hydrogen is in integrated gasification combined cycle (IGCC) power generation using black and brown coals as fuels. In this application, which has been demonstrated at commercial scale in a number of locations worldwide, the hydrogen produced from the coal gasification process is burnt in a combined cycle gas turbine for electricity generation. IGCC offers a route to efficient, pre-combustion capture of CO_2 for sequestration—and thus low GHG emission ('clean') power generation. IGCC also offers opportunities for polygeneration, i.e. production of both clean electricity and hydrogen, the latter for application in industrial processes or merchant use as a fuel.

2.1.2 Merchant use

Smaller quantities of "merchant" hydrogen are manufactured (or tapped off current captive use facilities) and delivered today to customers for a wide variety of applications. However, the merchant use of most prospective interest is hydrogen's utilisation as a transportation fuel. As Jeremy Bentham, Chief Executive Officer of Shell Hydrogen was reported as saying in a recent article "What is new is hydrogen being used as a fuel, rather than for its chemical purposes." [16]

11 Hydrogen has more than three times the heating value of a typical crude oil. Currently, however, almost all hydrogen is produced for use as a chemical reagent, rather than as a fuel, using fossil fuels as the feedstock by carbon emission intensive processes.

12 Global oil consumption in 2006 was about 3,900 million tonnes, BP Statistical Review of World Energy 2006.

13 **http://reporter.leeds.ac.uk/press_releases/current/biodiesel.htm**, last accessed 28 March 2008

14 Due to the importance of the Australian mining industry, a significant proportion of ammonia produced in Australia is converted to ammonium nitrate explosives (see Section 3.1.1).

15 **http://www.airproducts.com/Products/MerchantGases/HydrogenEnergyFuelCells/FrequentlyAskedQuestions.htm**, last accessed 27 March 2008.

16 D. Stanley, *Shell Takes Flexible Approach to Fueling the Future*, 2007 (available at **http://www.hydrogenforecast.com/ArticleDetails.php?articleID=250**, last accessed 07 October 2007).

Notwithstanding the research, development, demonstration and policy interest in many countries for utilisation of hydrogen as a fuel, the quantities of hydrogen currently used in this application are still negligible, worldwide. A number of fuel cell vehicle and refuelling system demonstration programs are underway around the world including passenger vehicles and buses. At the current time over 600 light duty fuel cell vehicles, 62 fuel cell buses and 100 operating hydrogen fuelling stations to support these transport sector demonstration programs are in place globally.[17] It is likely that very little, if any, of the hydrogen produced to support these demonstration projects is 'clean'.

2.1.3 Cost

The current cost of hydrogen production in high volumes is approximately two to three times higher than the United States' Department of Energy's (DOE) untaxed target of 50 to 75 US cents per petrol litre equivalent (PLE)[18], the focus being on hydrogen's use as a transport fuel.

Producing hydrogen by reforming natural gas is a well established process and large scale production facilities of 330,000 kg H_2 per day can achieve a hydrogen cost approaching the DOE target, albeit accompanied by CO_2 emissions. However, hydrogen delivery is costly and may more than double the cost of the fuel once it is delivered to the point of consumption. Therefore, an alternative approach is to develop a distributed network of smaller (1,500 kg H_2 per day) distributed hydrogen production facilities that would avoid the higher transportation costs of a centralised system.

Hydrogen production is capital intensive—the contribution of capital to the cost of hydrogen produced by reforming is estimated to be 21 per cent for a 330,000 kg per day plant, but approximately 54 per cent for a distributed hydrogen generation facility.[19] In the longer term, hydrogen production has to be by means entailing low CO_2 emissions (see Figure 1 earlier), i.e. either from fossil fuel sources accompanied by capture and sequestration of CO_2 emissions ('clean' hydrogen) or using renewable energy sources ('green' hydrogen).

Hydrogen must be transported from the point of production to the point of use, unless it is manufactured on a distributed basis at the refuelling point. It also must be safely compressed, stored and dispensed at refuelling stations or stationary power facilities. Due to its relatively low volumetric energy density, the transportation, storage and final delivery of hydrogen to the point of use can incur significant inefficiencies leading to a more than doubling of the cost of the fuel from its production to the point of consumption.

With no existing large scale distribution networks for hydrogen in place, the cost of network development is an additional impediment to large scale adoption. As noted by Stanley in his recent article,[20]

> "initial investments may continue to be expensive, especially in the early demonstration projects such as Shell Hydrogen's Washington, D.C. station, which was built in partnership with [General Motors], but not the DOE. An existing Shell gas station was chosen from 50 potential sites then retrofitted with a hydrogen fuelling pump, fed by a relatively small 1,500-gallon hydrogen tank. The overall cost for the project topped $2 million.
> ... A recent study commissioned by industrial gas giant, Linde AG, stated the cost of building 2,800 hydrogen stations across the European continent was "manageable," at about US$4.6 billion over the next 15 years. The Linde figure is significantly less than Shell Hydrogen's November, 2003, estimate of $20 billion."

Hydrogen may, of course, be reticulated by pipeline, like natural gas. However, there are questions as to the long-term compatibility and reliability of the natural gas reticulation systems with the introduction of hydrogen.

17 *Hydrogen and Fuel Cell Brief for Policymakers*, International Partnership for the Hydrogen Economy, Final Draft, 18 April 2007.

18 1 kg of hydrogen has approximately the same energy content as 4 litres (or 1 US gallon) of petrol.

19 *Roadmap on Manufacturing R&D for the Hydrogen Economy*, Based on the Results of the Workshop on Manufacturing R&D for the Hydrogen Economy, Washington, D.C., July 13–14, 2005, December 2005, US Department of Energy.

20 **http://www.hydrogenforecast.com/April2005/hf_shellinterview042205.html**, last accessed 5 November 2008

2.1.4 Competitive position and timeframe

Hydrogen is unlikely to compete with other energy carriers—liquid fuels and electricity—in any segment until the costs of its production, transport, storage and use (particularly use in fuel cells, which currently themselves are high cost) are significantly reduced. Although hydrogen production can result in a zero emission fuel, the technologies associated with this are less developed and the costs currently are too prohibitive for widespread uptake.

A complementary issue to cost is the time that it will take to establish a wide-spread hydrogen infrastructure. As Gether and Korpass noted in 2004, "All told, the historical experience with infrastructures suggests that it is unlikely that hydrogen will diffuse as a dominant energy carrier more rapidly than about four decades – about the same time as railroads or the natural gas system."[21] Of course, if climate change mitigation measures and fuel supply constraints lead to policy decisions by governments to support rapid deployment of hydrogen fuelling infrastructure then these historically-long timeframes will be significantly shortened.

The history of the roll-out to enable liquefied petroleum gas (LPG) to be available nationwide in Australia is consistent, however, with these long-time scales to establish a new fuelling infrastructure—indeed Australia is one of the few nations in the world that has done so even for LPG, a complementary fuel to petrol and diesel. LPG is a noteworthy example as it was, and remains today, effectively subsidised.

2.2 Fuel cells

2.2.1 Types

Fuel cells are classified primarily by the kind of electrolyte they employ. This determines the kind of chemical reactions that take place in the cell, the kind of catalysts required, the temperature range in which the cell operates, the fuel required, and other factors. These characteristics, in turn, affect the applications for which these cells are most suitable. There are several types of fuel cells currently under development, each with its own advantages, limitations, and potential applications (see Table 1).

Using pure hydrogen as a fuel, all fuel cell systems have similar efficiencies of electricity generation, namely in the range 45—55 per cent. However, with commonly available fuels such as natural gas (which is primarily methane (CH_4)) the lower temperature fuel cells (PEMFC, AFC and PAFC) have additional fuel processing inefficiencies that reduce their electrical generation efficiency to 30—40 per cent.

2.2.2 Portable power applications

A survey on the portable fuel cell market segment was published recently by *Fuel Cell Today*.[22] Specific applications include consumer electronics (e.g. laptop computers, mobile phones and cameras), hand tools and portable generators with the fuel cell technologies of choice for these portable applications being proton exchange membrane (PEMFC) and direct methanol (DMFC) fuel cells, although solid oxide (SOFC) fuel cells remain of interest for military applications.

21 Gether, K. and Korpass, M, *Lock-ins and Vested Interests that Hamper Transition to Hydrogen-Based Energy Futures*, 15th World Hydrogen Energy Conference, Yokohama, Japan, June 27 - July 2, 2004 (available at **http://www.h2foresight.info/Publications/WHEC_Kaare%20Gether2.pdf**).

22 G. Frawley, *Portable Survey*, Fuel Cell Today, December 2006 (available at **http://www.fuelcelltoday.com/media/pdf/surveys/2006-Portable.pdf**).

Table 1: Types, properties and main applications of fuel cells[23]
[DMFC = Direct Methanol Fuel Cell; PEMFC = Proton Exchange Membrane Fuel Cell; AFC = Alkaline Fuel Cells; PAFC = Phosphoric Acid Fuel Cell; MCFC = Molten Carbonate Fuel Cell; SOFC = Solid Oxide Fuel Cell]

	DMFC	PEMFC	AFC	PAFC	MCFC	SOFC
Electrolyte type	Polymeric ion exchange membrane	Polymeric ion exchange membrane	Immobilised alkaline salt solution	Immobilised liquid phosphoric acid	Immobilised liquid molten carbonate	Ceramic
Operating temperature	20—90 °C	30—100 °C	50—200 °C	~220 °C	~650 °C	500—1000 °C
Charge carrier	H^+	H^+	OH^-	H^+	CO_3^{2-}	O^{2-}
Fuel	H_2 (internal oxidation of methanol)	High purity[24] H_2	High purity[23] H_2	High Purity[23] H_2	H_2, CO (internal reforming of methane)	H_2, CO (internal reforming of methane)
Power range	1—100 W	1W—100kW	500W—10kW	10kW—1MW	100kW—10+MW	1kW—10+MW
Applications and main advantages:						
Portable power	Higher energy density than batteries and faster recharge.					
Transport		Zero tail-pipe emissions and high efficiency.				
Stationary power		Efficiency, emissions, reliability and/or low noise				

Portable fuel cell systems are being developed, fabricated and tested by a wide variety of large and small companies in the USA, Europe, Japan, Korea and China. This survey report concludes that

> "With over 3,000 new units introduced to the market in 2006, the past twelve months have been very encouraging for the portable fuel cell sector. Despite the lack of announcements regarding firm dates for commercialisation from big electronics companies, most of the players in this sector retain the view that a tangible commercial market will begin in 2007 and will be fully underway by 2008. This market will be driven by a strong and rapidly rising demand for portable power that has already outstripped the capability of traditional batteries.
>
> Going forward, the next five years will be very exciting for the portable fuel cell community. Several key companies are expecting to achieve commercial production and sales of their products in the timeframe 2007–2008 (and by doing so achieve first mover advantage) and beyond this point (one) can expect to see several more manufacturers introducing products on a mass commercial scale. Consumer pull remains strong for electronic goods with longer lifetimes and higher efficiencies than are provided by traditional batteries and military interest in fuel cells remains high."

23 Adapted from **http://www.doitpoms.ac.uk/tlplib/fuel-cells/types.php**, last accessed on 13 January 2008.

24 Praxair, for example, specifies its fuel cell grade hydrogen at 99.995 per cent purity but most importantly with extremely low levels of particular impurities (e.g. ammonia (NH_3), carbon monoxide (CO) and sulphur compounds) that can harm the catalyst-coated membranes inside the fuel cell. Further information is available at **http://www.praxair.com/praxair.nsf/7a1106cc7ce1c54e85256a9c005accd7/b2973104a60bf94685256ce3007bbaef?OpenDocument**

2.2.3 Transport applications

Two main routes to the adoption of hydrogen as a transport fuel are either using hydrogen directly as a combustion fuel in an ICE or using hydrogen in a fuel cell to generate electricity that drives electric motors to propel the vehicle. Major auto manufacturers, fuel cell companies and many governments are investing in the research, development and demonstration of fuel cell powered vehicles using hydrogen as the fuel. However, BMW is investing heavily in the development of hydrogen-fuelled internal combustion engine (ICE) powered vehicles, which are currently in limited production.

A number of fuel cell vehicle and refuelling system demonstration programs are underway around the world including passenger vehicles and buses. At the current time over 600 light duty fuel cell vehicles, 62 fuel cell buses and 100 operating hydrogen fuelling stations to support vehicular applications are reported to be in place globally.[25] In Australia, a trial of three fuel cell buses in Perth, along with the associated refuelling infrastructure, ran from September 2004 to mid-2007. Such long term trials provide valuable information on the reliability and operability of these power plants.

Two transport application areas that may provide near-term commercial market opportunities are in industrial vehicles (e.g. forklifts, automated guided vehicles and ground support equipment) and buses. A recent study by Battelle for the US DOE[26] concluded that "PEM fuel cells can provide value over battery-powered forklifts in high productivity environments. When forklifts are operated under conditions of near continuous use, fuel cell vehicles are significantly less expensive than similar battery-powered systems from a lifecycle cost perspective." A number of fuel cell companies including Ballard Power Systems, Nuvera Fuel Cells, Hydrogenics and Plug Power are working with system integrators in these industrial vehicle application areas.

Transit bus demonstration projects also are growing in number and in the number of deployed buses. As Ballard Power Systems has noted,

> "buses rely on centralized fuelling depots that simplify the hydrogen infrastructure requirements. Transit buses are government-subsidized, enabling the purchase of pre-commercial fleets. In addition, their design volume and drive cycle requirements are less restrictive. On August 3, 2007 BC Transit announced the contract award for the supply of up to 20 fuel cell hybrid buses to be delivered in late 2009. These buses will begin revenue operation in Whistler, British Columbia just before the 2010 Winter Olympic Games. The consortium of New Flyer Industries (coach manufacturer), ISE Corporation (hybrid drive integrator) and Ballard (HD6™ fuel cell module supplier) will build the buses. On November 13, 2007 the City of London, England announced the contract award for the supply of five fuel cell hybrid buses to be delivered in 2009. These buses will begin revenue service in London in 2010. The consortium of Wrights Bus Ltd. (coach manufacturer), ISE Corporation (hybrid drive integrator) and Ballard (HD6™ fuel cell module supplier) will build the buses."[27]

The first shipment of Ballard's sixth generation HD6™ fuel cell module occurred at the end of November 2007. It is reported [28] that the HD6™ module for bus applications carries a 12,000 hour warranty, a significant improvement over earlier fuel cell modules in these applications and an indication of the positive technical advancements being made.

25 IPHE (2007), *Hydrogen and Fuel Cell Brief for Policymakers*, International Partnership for the Hydrogen Economy Final Draft, 18 April 2007.

26 Battelle Memorial Institute, *Identification and Characterization of Near-term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets*, US Department of Energy Contract No. DE-FC35-03GO13110, April 2007.

27 **http://www.secinfo.com/d14qfp.tAy.c.htm**, last accessed 27 March 2008.

28 *Ballard to Power London Fuel Cell Buses*, Media Release 13 November 2007 (available at **http://phx.corporate-ir.net/preview/phoenix.zhtml?c=76046&p=irol-newsArticle&ID=1077676&highlight=**) and personal communication, Jamie Ally, Ballard Power Systems, Inc.

2.2.4 Stationary power applications

The segmentation of fuel cell stationary power applications in terms of unit capacity and input voltage (for Australia) are shown in Table 2.

Table 2: Stationary Energy Fuel Cell Market Segmentation

Generator Size	< 10 kW	10 kW to 1 MW	> 1 MW
Connection Voltage	240 – 415 V	11 kV	11 or 22 kV
Application	Domestic	Commercial	Industrial
		Industrial	Commercial
			Utility

One of the key advantages of fuels cells in distributed generation applications is the modularity of the design, and the fact that efficiency is largely independent of the size of installation. This means that installations can target all the key market segments in Table 2.

Over the past five years a number of stationary fuel cell systems have become available commercially and by 2006 the fuel cell industry had delivered approximately 800 large stationary fuel cell units and over 3000 small stationary units.[29]

One of the stakeholders interviewed for this roadmap noted to us that the recent USA Fuel Cell Conference showed that large, stationary, fuel cell systems are undergoing a revival. Fuel Cell Energy (a USA company) is now getting 30,000 to 40,000 hours fuel cell stack life and believes it can reach $2,500 per kW pricing for its molten carbonate systems. It has some 70 MW of orders on its books and is offering systems in the capacity range 300 kW to 3 MW. Also reported to be doing well is CFC Solutions GmbH that is reporting 30,000 hour stack life and high efficiency of 50 per cent on natural gas fuel for its 300 kW molten carbonate systems.

Also undergoing a revival are PAFCs—the first stationary fuel cells units deployed commercially. The 200 kW PAFC produced by UTC Power is now in operation in over 270 real-world installations and UTC Power has announced that its latest PAFC technology can deliver 80,000 hours stack life; the availability of its PAFC systems is in the 90 per cent range; and these systems are now doing better at heat recovery. Further, UTC Power believes it has ways to reduce the capital cost down to $2,500 per kW in reasonably low numbers of systems. It was noted to us that if they really can achieve this cost goal then payback periods would be less than 4 years, and there is still potential to lower capital cost that will get MCFC and PAFC systems into payback periods of less than 2 years.

A second significant semi-commercial release has been that of the Ballard Systems Mark 1030 V3. These 1 kW residential cogeneration systems provide 1 kW of electricity to individual dwellings as well as all required hot water. Ballard, in a Joint Venture with Ebara Corporation of Japan, sold 102 systems in 2005 and 168 units in 2006 to Japanese homes under the residential fuel cell cogeneration program sponsored by the Ministry of Economy, Trade and Industry (METI). These units are manufactured in small quantities and are heavily subsidised by METI in the vicinity of $US40,000 per unit. Based on planned unit production volumes this subsidisation is planned to fall to about $US10,000 per unit by 2008.

Overall, the commercial interest in fuel cells for stationary power applications is rising as they demonstrate commercial operation in a range of commercial and residential distributed generation applications.

2.2.5 Cost

Current costs for fuel cell power plants are extremely high for transport or stationary power applications. However these costs are expected to fall substantially when production volumes become large.

If a power plant is to gain acceptance in vehicle use it must be competitive with current ICEs that

29 IPHE (2007), *Hydrogen and Fuel Cell Brief for Policymakers, International Partnership for the Hydrogen Economy Final Draft*, 18 April 2007.

are routinely produced at a cost of about $US50 to $US100 per kW for the entire drive-train system (engine plus gear box). Due to the large number of vehicles produced each year (currently more than 40 million globally), substantial economies of scale are achievable in the manufacture of the fuel cell power plants even if only a small fraction of new vehicles are powered by fuel cells. The US DoE's Hydrogen Program has recently estimated[30] that, based on 2005 fuel cell technology and production of 500,000 units, the cost of production would be $US108 per kW. A detailed analysis in 2004 by Tsuchiya and Kobayashi[31] concluded that

> the cost reduction (for PEMFC stacks) to the level of internal combustion engine is possible from the viewpoint of learning curve when mass production would occur.

The key characteristic of the auto industry that enables rapid reduction in production costs is manufacturing scale. That is, when the estimated production costs reach the target level the introduction of only one or two fuel cell powered models could justify the investment in a 500,000 unit per year capacity plant.

However, if the production of fuel cells is driven only by the distributed generation market, an initial production scale plant would more likely have a capacity of about 1,000 to 5,000 units per year per production plant. At these lower production rates the unit cost likely will initially remain substantially above $1,000/kW and will reduce only slowly as demand increases.[32]

In both transport and distributed generation applications of fuel cells, the unit cost reduction will depend on the scale of production—recognising though that the cost goals and required manufacturing volume-cost learning rates are quite different for these two applications.

2.3 Alternate market views

While there is clearly great interest worldwide for the potential of hydrogen and fuel cells to meet a wide range of energy supply needs in a broad range of applications (see Section 2.4), there is not universal agreement that they either are the best option for all applications and/or that they will come to market rapidly. That is, there are other options to deliver the energy services consumers demand that can achieve the same or better greenhouse gas abatement in many applications than hydrogen and fuel cells.

2.3.1 Hydrogen production and delivery

Kreith and West point out in a 2004 paper

> "a technically feasible option is not necessarily the most efficient, the most economical, or the most environmentally benign choice to meet the need for heat and electricity."[33]

They cite Dr Joseph Romm from his testimony in 2004 to the USA House of Representatives that

> "Probably the biggest analytical mistake made in most hydrogen studies"… is failing to consider whether the fuels that might be used to make hydrogen [such as natural gas or renewable] could be better used simply to make electricity."

In a more recent paper,[34] Bossel notes that

> "the technology needed to establish a hydrogen economy is available or can be developed. Two comprehensive 2004 studies by the U.S. National Research Council and the American Physical Society summarize technical options and identify needs for further improvements. They are concerned with the cost of hydrogen obtained from various sources, but fail to address the key question of the overall energy balance of a hydrogen economy. Energy is needed to synthesize hydrogen and to deliver it to the user, and energy is lost when the gas is converted back to electricity by fuel cells. How much energy is needed to liberate hydrogen from water by electrolysis or high temperature thermodynamics or by chemistry? Where does the energy come from and in which form is it harvested? Do we have enough clean water for electrolysis and steam reforming? How and where do we safely deposit the enormous amounts of carbon dioxide if hydrogen is derived from coal?"

30 US Department of Energy Hydrogen Program, *"Fuel Cell System for Transportation – 2005 Cost Estimate: Independent Review"*, October 2006.

31 H. Tsuchiya and O. Kobayashi, *Mass production cost of PEM fuel cell by learning curve*, International Journal of Hydrogen Energy, Vol. 29, 985—990, 2004.

32 Based on experience of Wyld Group and MMA.

33 F. Kreith and R. West, *Fallacies of a Hydrogen Economy: A Critical Analysis of Hydrogen Production and Utilization*, J Energy Resources Technology, Vol. 126, 249–257, December 2004.

34 U. Bossel, *Does a hydrogen economy make sense?*, Proceedings of the IEEE, Vol. 94, No. 10, October 2006.

He notes that

> "It takes about 1 kg of hydrogen to replace 1 U.S. gal of gasoline. About 200 MJ (55 kWh) of dc electricity are needed to liberate 1 kg of hydrogen from 9 kg of water by electrolysis. Steam reforming of methane (natural gas) requires only 4.5 kg of water for each kilogram of hydrogen, but 5.5 kg of CO_2 emerge from the process. One kilogram of hydrogen can also be obtained from 3 kg of coal and 9 kg of water, but 11 kg of CO_2 are released and need to be sequestered. Even with most efficient fuel cell systems, at most 50 per cent of the hydrogen HHV energy can be converted back to electricity."

Bossel's efficiency analysis of the energy losses within a hydrogen economy shows that a hydrogen economy is an inefficient proposition for the distribution of electricity from renewable sources to useful electricity from fuel cells. Under this scenario only approximately 25 per cent of the power generated from wind, water, or sun is converted to practical use whereas if the original electricity from these renewable resources had been directly supplied by wires, as much as 90 per cent could have been put to service.

Mazza and Hammerschlag reached the same conclusion in their 2004 analysis,[35] concluding that

> "The use of renewable electrical generation that generates the greatest cuts is displacement of coal-fired generation. An equal amount of renewable energy yields 2.7 times the CO_2 cuts when used to displace IGCC "clean coal" plants instead of fueling FCVs, and 3.4 times as much when used to displace current coal technologies. Until a surplus of renewable generation exists, most new renewable electricity should go to meeting standard power grid needs. Natural gas also eliminates 2.7 times the CO_2 when displacing coal instead of running FCVs on NG-derived H_2. This raises concerns about the envisioned use of NG as a transition hydrogen source.
>
> These conclusions are not favorable for the proposed "hydrogen economy." More energy efficient alternatives exist to H_2 in transportation and energy storage that might preclude mass-scale emergence of H_2 technologies in these areas. Even when renewable electricity becomes cheap and abundant, it might be more effectively employed in advanced direct electricity applications. Land use and other environmental impacts of major renewables installations will continue to be a concern."

2.3.2 Transport applications

A recent, comprehensive, European evaluation of the Well-to-Wheels (WTW) energy use and greenhouse gas (GHG) emissions for a wide range of potential future fuel and powertrain options for vehicles[36] reached the following conclusions for hydrogen as a transport fuel:

- "Many potential production routes exist and the results are critically dependent on the pathway selected.
- If hydrogen is produced from natural gas:
  - WTW GHG emissions savings can only be achieved if hydrogen is used in fuel cell vehicles.
  - The WTW energy use / GHG emissions are higher for hydrogen ICE vehicles than for conventional and [compressed natural gas] CNG vehicles.
    - In the short term, natural gas is the only viable and cheapest source of large scale hydrogen. WTW GHG emissions savings can only be achieved if hydrogen is used in fuel cell vehicles albeit at high costs.
    - Hydrogen ICE vehicles will be available in the near-term at a lower cost than fuel cells. Their use would increase GHG emissions as long as hydrogen is produced from natural gas.

35 P. Mazza and R Hammerschlag, *Carrying the Energy Future: Comparing Hydrogen and Electricity for Transmission, Storage and Transportation,* Institute for Lifecycle Environmental Assessment, June 2004 (available at **http://www.ilea.org/downloads/MazzaHammerschlag.pdf**).

36 European Commission, *Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*, Joint Research Centre, Version 2c, March 2007.

- Electrolysis using [European Union] EU-mix electricity results in higher GHG emissions than producing hydrogen directly from [natural gas].
- Hydrogen from non-fossil sources (biomass, wind, nuclear) offers low overall GHG emissions.
  - Renewable sources of hydrogen have a limited potential and are at present expensive.
  - More efficient use of renewables may be achieved through direct use as electricity rather than road fuels applications.
- Indirect hydrogen through on-board autothermal reformers offers little GHG benefit compared to advanced conventional powertrains or hybrids.
  - On-board reformers could offer the opportunity to establish fuel cell vehicle technology with the existing fuel distribution infrastructure.
  - The technical challenges in distribution, storage and use of hydrogen lead to high costs. Also the cost, availability, complexity and customer acceptance of vehicle technology utilizing hydrogen technology should not be underestimated.
- For hydrogen as a transportation fuel virtually all GHG emissions occur in the [Well to Tank] WTT portion, making it particularly attractive for CO_2 Capture & Storage."

Another recent and comprehensive evaluation of electric drivetrain options for the USA in 2030 for light duty vehicles[37] also has been undertaken and reaches the following conclusions:

> "Over the next several decades, conventional technologies – vehicles using a spark-ignition or diesel engine – are likely to continue to dominate the in-use vehicle fleet. As such, it is vital that technological development focus on improving the fuel efficiency of conventional technologies over this period. … While conventional technology is likely to continue to dominate for the next two decades, continued technical development and increasing sales volume of hybrid vehicles are likely to drive down costs and improve performance. … In this analysis, the hybrid vehicle plays a critical role as a bridging technology to transition from the near-term reliance on incremental efficiency improvements in conventional technology (and continued use of petroleum) to an eventual goal of non-GHG emitting, domestic transportation energy sources.
>
> The evolution of battery and fuel-cell technology over the next 10-20 years will likely dictate whether the plug-in hybrid or the fuel-cell vehicle succeeds the hybrid vehicle. … The fuel-cell, which faces significant technical and infrastructure hurdles, is likely to have minimal impact over the 30-year time horizon of this study, even with successful development."

Toyota Motor Corporation of Japan, one of the earliest developers of fuel cell vehicles (FCVs), also notes that while the fuel cell hybrid vehicle (FCHV) is the closest to its view of the ultimate eco-car there are many paths to achieving this goal that will be utilised by it and other auto manufacturers over the coming decades (Figure 3).

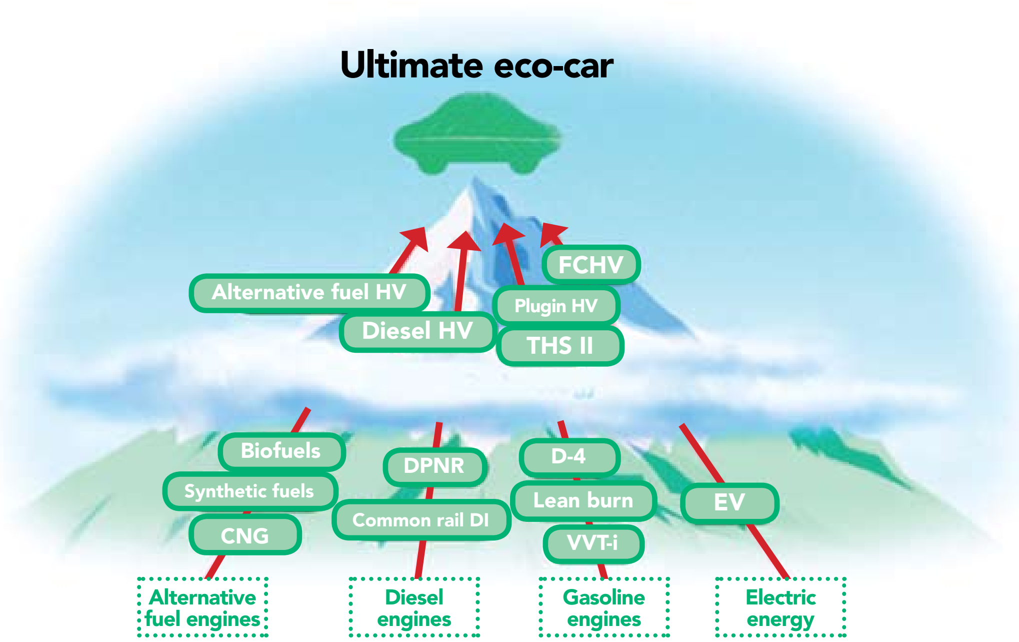
However, progress is being made with its FCHV developments, with Toyota recently announcing[38] that an improved version of its fuel cell hybrid vehicle successfully completed a long-distance road test today by travelling from Osaka to Tokyo (560 km) on a single fuelling of hydrogen.

More examples of the variety of drive-train approaches being explored for vehicles by the global auto manufacturers were on display at the North American Motor Show in Detroit, USA in January 2008.[39] Many of these are planned for market introduction soon.

37 M. A. Kromer and J. B. Heywood, *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet, Sloan Automotive Laboratory*, Laboratory for Energy and the Environment, Massachusetts Institute of Technology, Publication No. LFEE 2007-02 RP, May 2007.

38 http://www.japancorp.net/Article.Asp?Art_ID=15584, last accessed 03 December 2007.

39 Reported at http://www.eere.energy.gov/news/enn.cfm, last accessed 17 January 2008.



CNG: Compressed Natural Gas **DPNR:** Diesel Particulate and NOx Reduction system **THS:** Toyota Hybrid System **D-4:** Direct Injection 4-Stroke Gasoline Engine **VVT-i:** Variable Value Timing, intelligent **FCHV:** Fuel Cell Hybrid Vehicle **DI:** Direct Injection

Figure 3: Toyota's paths to the ultimate eco-car[40]

2.4 Supporting hydrogen and fuel cells to market

Section 2.3 makes it clear that governments and industry sectors have options available to them to deliver low GHG emission energy services to consumers. The discussion in Sections 2.1 and 2.2 also makes it clear that hydrogen as an energy carrier and fuel cells as an energy conversion device are undergoing significant consideration and development as one of these options.

As noted in a recent brief for policymakers submitted to the Steering Committee of the International Partnership for the Hydrogen Economy (IPHE), governments (see below) and industry in many countries are increasing investments in research and development to meet cost and performance requirements for technologies that produce, deliver, store, and use hydrogen in fuel cells for stationary, portable, and transportation applications.

These investments are being made to address technical and market barriers in order to build a hydrogen delivery infrastructure; develop safety codes and standards; and educate decision-makers, customers, and the future workforce about hydrogen and fuel cell technologies.

Global public and private R&D investment for hydrogen and fuel cells is estimated to be US$1billion and US$3-4 billion per year, respectively. Ongoing demonstration projects are assessing hydrogen and fuel cell technologies, helping identify key issues to feed back to research and providing an opportunity to familiarise and educate the public on hydrogen and fuel cell technology. [41]

This investment activity is stimulating market growth in hydrogen and fuel cells. A recent Clean Edge market report [42] estimated that the fuel cell

40 From **http://www.toyota.co.jp/en/tech/environment/fchv/index.html**, last accessed 03 December 2007.

41 *Hydrogen and Fuel Cell Brief for Policymakers*, **International Partnership for the Hydrogen Economy, Final Draft, 18 April 2007.**

42 J Makower, R Pernick and C Wilder, *Clean Energy Trends 2008*, Clean Edge, March 2008.

and distributed hydrogen market will grow from a $1.5 billion industry in 2007 (primarily for research contracts and demonstration and test units) to $16 billion over the next decade to 2017.

2.4.1 National programs

In a first-of-its-kind attempt at providing an overview of what is being done, by whom and in which country, for each R&D and policy topic, the International Energy Agency (IEA) in 2004 published a review of the R&D programs and policy strategies in Member countries to map the national, governmental efforts to research, develop and deploy the interlocking elements that constitute a hydrogen-based energy system, including CO_2 capture and storage when hydrogen is produced using fossil fuels.[43]

This review highlighted a significant number of ongoing, national activities and projects that reflect the vast array of technologies, logistics and policy issues required to build a hydrogen-based energy system. It also provided individual country profiles of activities for twenty-three IEA countries, including Australia.

In virtually all these countries, the review noted that R&D and policy efforts on hydrogen and fuel cells are expanding, ranging from fully integrated, government-funded programs to strategies spread in multiple public and private initiatives. Figure 4 provides a summary of these initiatives and an estimated public and private-sector spending on them then.

The enthusiasm of these national governments to invest in hydrogen and fuel cell development and deployment efforts has not diminished. A few examples include:

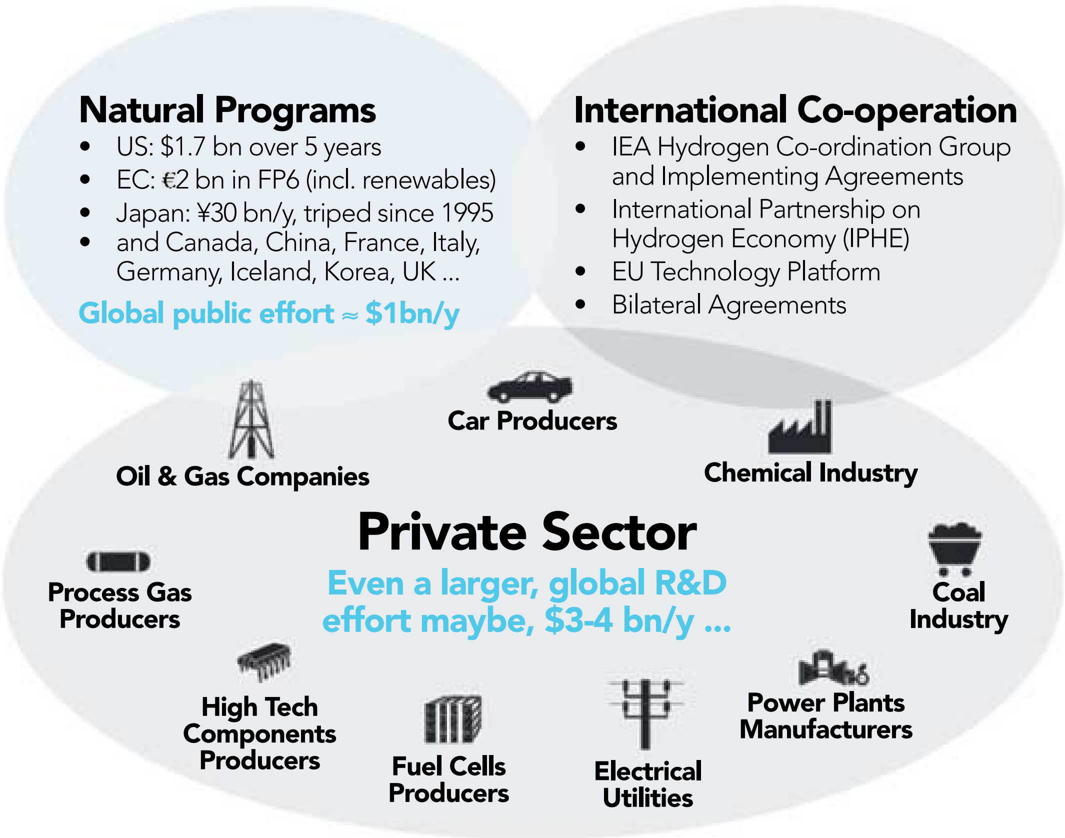


Figure 4: Hydrogen and Fuel Cells – National R&D Efforts and International Co-operation[44]

43 *International Energy Agency, Hydrogen & Fuel Cells: A Review of National R&D Program*s, 2004 (available at http://www.iea.org/textbase/nppdf/free/2004/hydrogen.pdf).

44 Ibid.

- The USA's Hydrogen Posture Plan published in December 2006[45] was prepared by the U.S. Department of Energy (DOE) Offices of Energy Efficiency and Renewable Energy (EERE); Fossil Energy; Science; Nuclear Energy, Science and Technology; and the U.S. Department of Transportation (DOT) to outline the activities, milestones, and deliverables that the USA's Federal government plans to pursue to support the development of hydrogen-based energy systems. The Plan integrates the planning and budgeting for program activities, in accordance with the USA's National Hydrogen Energy Vision and Roadmap.

  As an indication of the continuing support in the USA, the fiscal year 2008 budget approved for the DOE's EERE Office's hydrogen and fuel cells program is US$213 million[46], up nearly 10 per cent on the previous year.

- With the 7th European Union (EU) Research, Technology and Demonstration (RTD) Framework Programme (FP7, 2007-2013), the European Commission has introduced the concept of Joint Technology Initiatives (JTI) as a new way of realising public-private partnerships at European level, in order to define and implement a programme of research, technological development and demonstration in a more efficient manner.[47] JTIs target well-defined areas where existing programmes and instruments, which often follow a project-oriented approach, cannot cater for the scale and scope needed.

Outlining the development of a Joint Technology Initiative (JTI) for hydrogen and fuel cell technology in Europe at a conference in 2006, [48] Professor Lars Sjunnesson, Director R&D for E.ON Nordic AB and Chair of the European Hydrogen Association, described the needs for this JTI now as:

– "Need to accelerate the transition towards a sustainable energy economy and take a lead role in global technology development.

– Need to equally compete with major competitors like Japan and the US and match funding levels of € 400 to 600 million/year respectively.

– Need to establish public - private partnership to move technology faster, more efficient and with better focus.

– Need coherent research and deployment activities with clear commercialisation targets and avoid fragmentation of investment.

– Need to allow participation by a wide range of stakeholders including SMEs and research institutes.

– Need to build on existing momentum of industry and the European Commission and avoid further delay."

On 10 October 2007 it was announced that the proposal for a Fuel Cells and Hydrogen JTI had been adopted by the European Commission. It will be a public private partnership with industry in the lead. The Commission will fund € 470 million from the FP7 programme with at least a matching amount from private industry. This level of Commission funding is an increase of nearly 50 per cent on that committed under FP6 and this JTI overall is expected to contribute to reduced time to market for hydrogen and fuel cells technologies by between 2 and 5 years.[49]

- Japan was the first country to undertake a large-scale hydrogen and fuel cell R&D program—a ten-year, ¥18 billion effort that was completed in 2002. The New Hydrogen Project, commenced in 2003, focuses on commercialisation. Funding has been raised

45 *Hydrogen Posture Plan—An Integrated Research, Development and Demonstration Plan*, prepared by United States Departments of Energy and Transportation, December 2006.43

46 **http://www.rules.house.gov/110/text/omni/jes/jesdivc.pdf,** pages 30—32d, last accessed 10 January 2008.

47 **http://www.eubusiness.com/Rd/jet-guide/**, last accessed 14 January 2008.

48 Sjunnesson, Lars (2006), *European situation and perspective of the hydrogen and fuel cell technology,* presented at International Hydrogen Forum, Budapest, 9-10 October 2006 (available at **https://www.hfpeurope.org/uploads/1871/Presentation_LarsSjunnesson_Budapest_09OCT2006.pdf**).

49 **http://europa.eu/rapid/pressReleasesAction.do?reference=MEMO/07/404&format=HTML&aged=0&language=EN&guiLanguage=en**, last accessed 14 January 2008.

each year, reaching ¥35 billion in FY2005 and ¥35 billion in FY2006.[50]

- In Korea the National RD&D Organization for Hydrogen and Fuel Cells (H2FC) was founded in 2004 with the support of the Ministry of Commerce, Industry and Energy (MOCIE) to promote overall R&D, validation, demonstration and commercialisation of hydrogen refuelling station and fuel cells (stationary, transportation, portables, etc.) technologies. In 2006, H2FC supported 31 hydrogen and fuel cell projects with the total budget of about US$16 million. Thirty-seven hydrogen and fuel cell related companies, including Hyundai-Kia Motors, POSCO, SK, LG Chem, Ltd., Samsung SDI, GS Caltex, Doosan Heavy Industries & Construction Co. Ltd., and national research institutes and universities are participating.

  Another initiative, Korea's Hydrogen Energy R&D Center (HERC), was established in 2003 under the 21st Century Frontier Program of the Ministry of Science and Technology (MOST). The 2nd phase of this program (3 years) started in 2006. HERC supported the projects of hydrogen production, storage, and utilisation technologies in 2006 with a total budget of approximately US$10 million.[51]

2.4.2 Multilateral international programs

The following is a synopsis of the major multilateral, international programs in place to support hydrogen and fuel cells to market:

International Partnership for the Hydrogen Economy

The IPHE was launched in November 2003 as a mechanism to coordinate international hydrogen research and hydrogen technology development and deployment. The intention is to allow members to organise, coordinate and implement effective, efficient, and focused international research, development, demonstration and commercial utilisation activities related to hydrogen and fuel cell technologies. There are currently 18 member countries, including Australia.

The IPHE provides a mechanism for partners to organise, coordinate and implement effective, efficient, and focused international research, development, demonstration and commercial utilisation activities related to hydrogen and fuel cell technologies.[52] The IPHE provides a forum for advancing policies and common technical codes and standards that can accelerate the cost-effective transition to a hydrogen economy. It also educates and informs stakeholders and the general public on the benefits of, and challenges to, establishing the hydrogen economy.

International Energy Agency

The IEA's Hydrogen Implementing Agreement was established in 1977 to pursue collaborative hydrogen R&D and information exchange among its 21 member countries. Over this time it has established 25 Tasks (i.e. collaborative R&D agreements) on a wide range of hydrogen production, delivery and storage topics.[53]

The IEA's Advanced Fuel Cells Implementing Agreement[54] was established in 1990 with the primary aim being to advance the state of understanding of its 17 member countries (including Australia) in advanced fuel cells. It achieves this through a co-ordinated programme of research, technology development and system analysis Tasks on MCFC, SOFC and PEMFC systems. It also has a strong emphasis on information exchange through Task meetings, workshops and reports.

50 http://www.fuelcells.org/InternationalH2-FCpolicyfunding.pdf, last accessed 14 January 2008.

51 Personal communication, Dr. Seong-Ahn Hong, Director of National RD&D Organization for Hydrogen & Fuel Cell in Korea, 05 November 2007.

52 http://www.iphe.net/

53 http://www.ieahia.org/

54 http://www.ieafuelcell.com/

3 HYDROGEN AND FUEL CELLS – AUSTRALIA

3.1 Commercial activities

3.1.1 Hydrogen

Most of the hydrogen produced in Australia is consumed on-site for the production of ammonia that is used mostly for fertiliser production, with the majority of the remainder used for ammonium nitrate (mainly for mining explosives) and hydrogenation of heavier crude oil components to produce liquid hydrocarbons that are suitable for further processing to transport fuels. The hydrogen is all produced via reforming of natural gas, and almost all on a reasonably large scale. Ammonia capacity in Australia is about 1.7 million tonnes per year, requiring about 300,000 tonnes per year of hydrogen. Ammonia/hydrogen production is distributed among Queensland, Western Australia and New South Wales. Refinery production also is conducted in these states plus Victoria.

There is small scale hydrogen production via electrolysis at almost all large power stations in Australia (and elsewhere). It is used, in closed systems, for cooling of the generators themselves and is the preferred medium due to its low viscosity and other properties that result in high heat transfer efficiency. The electrolysis plant provides make-up hydrogen to compensate for losses through leakage and is, therefore, quite small. The plant and cooling systems have piping and fittings designed for hydrogen and appropriately qualified personnel maintain them. This hydrogen production and use at power stations is as, or more, relevant to progressing towards a significant impact of hydrogen as is large scale reforming of natural gas.

Some of the existing and new companies operating specifically in hydrogen production, delivery and/or storage are:

- **BOC Australia** is a member of the worldwide Linde group that supplies industrial gases and engineering services.[55] BOC has provided technical support to the Australian Antarctic Division on hydrogen storage and safety reviews for a project using wind power to generate hydrogen which as a fuel can be transported for remote applications. It also is in a strategic partnership with SEFCA (see Section 3.1.2) for the implementation of commercial fuel cell systems for stationary power generation.
- **Hydrexia Pty Ltd** is a hydrogen storage systems company commercialising technology based on novel magnesium alloys. It is a start-up company out of the University of Queensland and has a dedicated hydrogen laboratory located at the University's St Lucia campus. Its alloys have demonstrated a hydrogen storage capacity of up to 7 weight percent while operating at low pressures (15-20 bar) that remains consistent over many absorption/desorption cycles. Hydrexia is currently developing prototype storage systems demonstrating that this storage capacity can be achieved with a significantly larger amount of alloy.[56]
- **Eden Energy Ltd** is a listed company with interests in hydrogen production, storage and transport fuel systems, including a low emission Hythane (hydrogen-methane) blend and low temperature pyrolysis research into hydrogen production. It is particularly focussing on the clean energy transport market, producing hydrogen without any carbon emissions, transporting the hydrogen to markets and providing the engines to power hydrogen-based transport and energy solutions.[57]

55 https://boc.com.au/irj/portal/anonymous?guest_user=australia, last accessed 14 January 2008.
56 http://www.hydrexia.com.au/, last accessed 14 January 2008.
57 http://www.edenenergy.com.au/, last accessed 14 January 2008.

- **Hydrogen Technology Ltd**[58] is a public, unlisted company that has developed a gas generation electrolyser system, with the current prototype undergoing industry trials.
- **Hydrogen Energy International Ltd** is a new, joint venture company formed in May 2007 by BP and Rio Tinto. Its primary objective is to produce low-carbon electricity supply from carbon feedstocks. Both parent companies are committed to technologies and businesses that reduce carbon emissions, and will use their combined skills to accelerate the deployment of hydrogen-fuelled power plants and carbon capture and storage (CCS) projects.[59]

3.1.2 Fuel cells

Australia's largest fuel cell company, **Ceramic Fuel Cells Limited** (CFCL), has trialled in Europe, New Zealand and Australia a number of demonstration micro-combined heat and power (micro-CHP) systems based on its proprietary SOFC and system technologies. It has recently released a new generation of SOFC stack technology and is planning trials of pre-commercial, micro-CHP systems commencing in 2008. It is targeting Europe as its prime target market because of government market-support measures in a number of countries. In February 2008 CFCL signed an agreement to provide 50,000 fuel cells systems to Dutch energy company Nuon over a 5 year period and is constructing the corresponding manufacturing plant in Heisenberg, Germany.[60] Additionally, CFCL are also targeting promising Asian markets.[61]

SEFCA (Sustainable Energy Fuel Cells Australia Pty Ltd) is an importer of fuel cell products whose core activity is the promotion, supply, installation and support of a range of hydrogen-based solutions to its customers.[62]

Oreion Energy Pty Ltd has exclusive worldwide rights to advanced direct hydrogen fuel cell and PEM electrolyser technologies licensed from CSIRO. It is developing the direct hydrogen fuel cell technology as a viable replacement for batteries currently used to power small scale electronic devices, such as mobile phones and laptops, needing power sources of less than 500W. Oreion aims to advance this technology to provide a commercial solution to the power capacity and life expectancy constraints that apply to current battery technology for such devices. It also aims to develop derivative technology from the PEM electrolyser to exploit additional markets. One such market is the application of a portable PEM electrolyser to generate oxygen for medical uses at home and in remote areas such as field hospitals that lack access to existing sources of oxygen supply.[63] Oreion also is developing a fuel cell test station with operating power ranges of up to 250W, based on CSIRO's technology.

3.1.3 Sector representation

Within Australia the following organisations have been established to support and promote the hydrogen and fuel cell sectors:

- The **Australian Institute of Energy's Hydrogen Division** was established with the mission to promote the responsible development of hydrogen energy. Its objectives are:
  - "To offer information and provide a focal point pertaining to hydrogen technology
  - To promote inter-disciplinary discussion of hydrogen technology and research
  - To assist in the promotion of Australian hydrogen projects and studies undertaken
  - To demonstrate hydrogen technology to the Australian community

58 **http://www.hydrogentechnology.com.au/index.html**, last accessed 14 January 2008.

59 **http://www.hydrogenenergy.com/FullStory.aspx?m=14**, last accessed 14 January 2008.

60 *€12.4M Investment in Manufacturing Facility and Commercial Order from Nuon*, Announcement on 27 February 2008 (available at **http://www.cfcl.com.au/Assets/Files/20080227_CFCL_Capex_investment_and_Nuon_order.pdf**, last accessed 28 March 2008).

61 B. Dow, *Ceramic Fuel Cells Limited FY07 Results—Investor Presentation*, October 2007 (available at http://www.cfcl.com.au/Assets/Files/20071002_Roadshow_Statutory_accounts[1].pdf).

62 **http://www.sefca.com.au/page/sefca_solutions.html**, last accessed 14 January 2008.

63 **http://www.oreion.net/about**, last accessed 14 January 2008.

- To encourage hydrogen energy studies in educational curricula."[64]

- The **National Hydrogen Association of Australia** was established in 2001 "to advance the research and awareness into hydrogen as an alternative energy source".[65]
- **Fuel Cell Institute of Australia Pty Limited** was established in September 2003 as "the first dedicated organisation focusing on fuel cells science and technology within Australia".[66]
- The **National Hydrogen Institute of Australia** was established in 2004 "to go beyond association and promotion, and into leadership, policy creation and a systems approach to advance hydrogen within Australia".[67]

3.2 Innovation activities

3.2.1 Research and development

The 2005 Australian Hydrogen Activity report[68] identified more than 120 hydrogen and fuel cell R&D projects underway across the country involving over 30 different organisations. The range of projects identified includes but is not limited to:

- Hydrogen production from natural gas reforming (including solar reforming and high efficiency, compact, micro-channel reformers), coal gasification and biomass gasification, as well as projects on gas cleaning and separation.
- Hydrogen production from water by:
  - electrolysis using renewable (solar, wind, water) energy, both at room-temperature and at high temperatures;
  - direct solar-electro-chemical splitting (photolysis); and
  - polymer electrolyte membrane (reverse fuel cell) electrolysis;
- Bio-production of hydrogen.
  - Microalgal bio-H2 processes are reported to be currently at ~1 per cent efficiency, with a maximum efficiency of 10 per cent theoretically achievable. At 7 per cent efficiency, which should be attainable, the process could be economically viable (depending on oil price, bioreactor costs, etc).[69]
- Hydrogen storage using nano-materials and metal-hydride systems; and
- Nano-materials research in developing higher efficiency fuel cells of several types including PEMFCs, DMFCs, and SOFCs.

Since the release of this Activity report, an on-line database has been available[70] to provide R&D practitioners in Australia an opportunity to register and maintain the currency of their activities in hydrogen, fuel cells and associated fields.

The National Hydrogen Materials Alliance (NHMA) was established in 2006[71] with the aim of coordinating the development of new materials that improve the efficiency and economics of hydrogen generation, storage and end use. The Alliance includes a total of 12 participating universities and publicly funded research agencies in two aligned, research areas: hydrogen generation and end use; and hydrogen storage. It will receive $3 million from the CSIRO Energy Transformed collaboration fund, with a further $6.6 million of in-kind contributions from the participating organisations.

The Australian Academy of Science is completing an Australian Research Council (ARC) funded project analysing Australian hydrogen energy research publications and funding. A major component of this project was a symposium held in May 2006, followed by a report based on the

64 http://www.aie.org.au/hydrogen/, last accessed 14 January 2008.

65 http://www.hydrogen.org.au/nhaa/, last accessed 14 January 2008.

66 http://www.fuelcells.org.au/, last accessed 14 January 2008.

67 http://www.hydrogen.asn.au/, last accessed 14 January 2008.

68 *Australian Hydrogen Activity Report*, A report prepared by Dr D.A.J. Rand of CSIRO Energy Technology and Dr S.P.S. Badwal of CSIRO Manufacturing and Infrastructure Technology, for the Department of Industry, Tourism and Resources, 2004.

69 Hankamer, B., Lehr, F., Rupprecht, J., Mussgnug, J. H., Posten, C. and Kruse, O., *Photosynthetic biomass and H2 production by green algae: From bioengineering to bioreactor scale u*,. Physiologia Plantarum 131:10-21 (2007).

70 *Australian Hydrogen Activity Database*, at http://www.ret.gov.au/Industry/Energy/Documents/Australian_Hydrogen_Activity_Database.xls

71 http://www.csiro.au/partnerships/ps2lq.html#1, last accessed on 16 October 2007.

outputs of the symposium and a bibliometric assessment of science activities in the field in Australia.[72] The Academy's analysis shows that:

- There are a number of active hydrogen research groups in CSIRO and the universities. These include the Australian Research Council (ARC) Centre for Functional Nanomaterials at the University of Queensland, and the National Hydrogen Materials Alliance (NHMA) which comprises a consortium of 11 universities, the Australian Nuclear Science and Technology Organisation and CSIRO.
- A review of basic hydrogen energy-related research funded by the ARC and announced from 2002 to 2008 shows an allocation of $22,642,712 for 48 projects and four fellowships. This funding level is only moderate when compared to nanomaterials that received $50 to $70 million in ARC funding over the same period, not including additional funding from other sources.
- Australia is the 16th largest producer of hydrogen energy research publications. Major collaborators with Australian scientists in the field are in the USA, UK, Germany and China. With regard to hydrogen publications, while these started to increase in Australia in 2003-04, in comparison to Canada and the Netherlands (two countries that Australia often is compared to) the rate of growth is much less.
- Overall, the R&D profile in Australia for hydrogen and fuel cells is not strong—notwithstanding that there is some world-class research in Australia in a number of hydrogen and fuel cell fields.

It can also be observed, based on stakeholder consultations for this roadmap, that there are very few world-scale R&D[73] projects in Australia in hydrogen and fuel cell fields—Ceramic Fuel Cells Limited, the Solar Biofuels Consortium at the University of Queensland and one or two CSIRO initiatives being the main exceptions.

3.2.2 Demonstration

Transport

The only transport demonstration of hydrogen and fuel cell vehicles in Australia has been the Perth fuel cell bus trial. With the support of the Australian and Western Australian governments, the Department for Planning and Infrastructure purchased three fuel cell buses for operation as part of the Transperth public transport system, participating in an international fuel-cell bus trial in collaboration with similar trials in Europe and America.

The buses were part of a limited series of Mercedes-Benz Citaro fuel cell buses being manufactured in Mannheim, Germany by EvoBus (a subsidiary of Daimler) for a series of international trials. Ballard Power Systems supplied the fuel cell engines for the buses and BP supplied the hydrogen fuel for the trial, produced from their oil refinery at Kwinana.

The purpose of the trial, which ran from September 2004 to mid-2007, was to determine the critical technical, environmental, economic, and social factors that need consideration in the introduction of hydrogen fuel cell buses. The Perth trial was also structured to examine the Government and private sector systems needed to support a hydrogen-based energy system as well as identifying industry development opportunities for Western Australian and Australian industries. The trial was evaluated through seven projects, which were independently managed by Murdoch University.[74]

72 *Towards development of an Australian scientific roadmap for the hydrogen economy—Analysis of Australian hydrogen energy research publications and funding*, Australian Academy of Science, Draft 12 February 2008.

73 For clarity, the term 'world-class' is used in relation to the quality of outputs of individual R&D projects while the term 'world-scale' refers to the scale of human resources, physical infrastructure and funding (often referred to as 'critical mass') available and needed to achieve timely solutions to technology challenges.

74 **http://www.dpi.wa.gov.au/ecobus/1727.asp**, last accessed 14 January 2008.

Stationary

A 200 kW PAFC system from UTC Power was installed at the Australian Technology Park in Sydney in 1998. Natural gas, which is passed through a steam reformer to produce hydrogen, was the fuel for this commercial fuel cell. It produced electricity (backed up by a diesel generator) and hot water (at 65 °C), which was used at a nearby hotel.

Western Australia's first fuel cell was installed at the Research Institute for Sustainable Energy's Renewable Energy Systems Test Centre (ResLab) at Murdoch University in 2003. This small 5 kW alkaline system was designed to prove the concept of remote area power supply (RAPS) in a test facility with a 30 kW wind turbine. The prototype alkaline fuel cell system was replaced with a commercial 5 kW PEMFC in late 2004. The most recent fuel cell successfully tested at ResLab was a 1.2 kW alkaline fuel cell in January 2006.[75]

As part of the ongoing, international program of development and demonstration of its micro-CHP SOFC systems, Ceramic Fuel Cells Limited (CFCL) installed one of its early demonstration units in Melbourne. This unit was installed at Energy and Telecommunications Training Australia's premises in Chadstone, Melbourne in August 2005, before being moved into Szencorp's energy efficient commercial office building at 40 Albert Road, South Melbourne. The unit was installed there in late 2005 and commissioned in January 2006.[76]

3.3 Intellectual property landscape

To gain an understanding of Australia's relative position globally an analysis has been undertaken of the intellectual property (IP) landscape for hydrogen-related technologies. IP landscaping is a broad term that covers, as it suggests, any review of the topography or position relative to competitors (countries and companies) afforded by IP. Patents, as a major component of intellectual property and a primary source of technological information, offer a unique resource for analysing the process of technological change and measuring the knowledge base and competitive position of a given industry or country.

The analysis, conducted by b*wise*IP Pty Ltd, has used both statistical methods and a subjective technical review of patents.

3.3.1 Statistical analysis

The statistical analysis includes data up until early November 2007 based on patent applications by "Publication Year". It should be noted, however, that the actual patent filing (for example an Australian (AU) provisional patent) would generally be 18 months prior to the publication date so it will be 2009 before complete 2007 filing trends are available (which is why the data in the following figures tend to drop for 2007). Notwithstanding, the overall trend is clear—patent filings in hydrogen and fuel cells have exploded between 2001 and 2006, dominated by the trio of USA, Japan and generally one or other of Germany or Great Britain.

75 http://www.rise.org.au/info/Tech/fuelcells/index.html, last accessed 15 January 2008.
76 http://www.cfcl.com.au/Assets/Files/Smart_Power_Newsletter_06-02.pdf, last accessed 14 January 2008.

Overall, and not surprisingly, the findings based solely on statistical analysis are:

- The global level of IP activity in hydrogen technologies is rapidly increasing, particularly in the area of fuel cells.
- Australia does not feature highly in the number of global patent applications.
- Whilst there is minimal volume of Australian-based IP that is relevant to the global IP landscape for hydrogen, Australia does have important IP that could play a role in developing hydrogen-related solutions for Australia.

For the purposes of this analysis, the IP space was segregated into three main areas: hydrogen use – fuel cells; hydrogen production; and hydrogen storage (and distribution).

Hydrogen use – fuel cells

The increase in patent applications (PCTs) from 1996 to 2006 is greater than tenfold for fuel cells (see Figure 5). If the market players continue to follow this trend then one would expect the 2008 data to show patent filings increasing further.

Previous studies into fuel cell IP trends such as the Thomson Scientific White Paper [77] in 2004 have shown that, based on the Derwent World Patent Index (DWPI) charts, the main IP activity is based in Japan. This is due to a statistical reliance on "Basic Applications", which is the first application received into the DWPI.

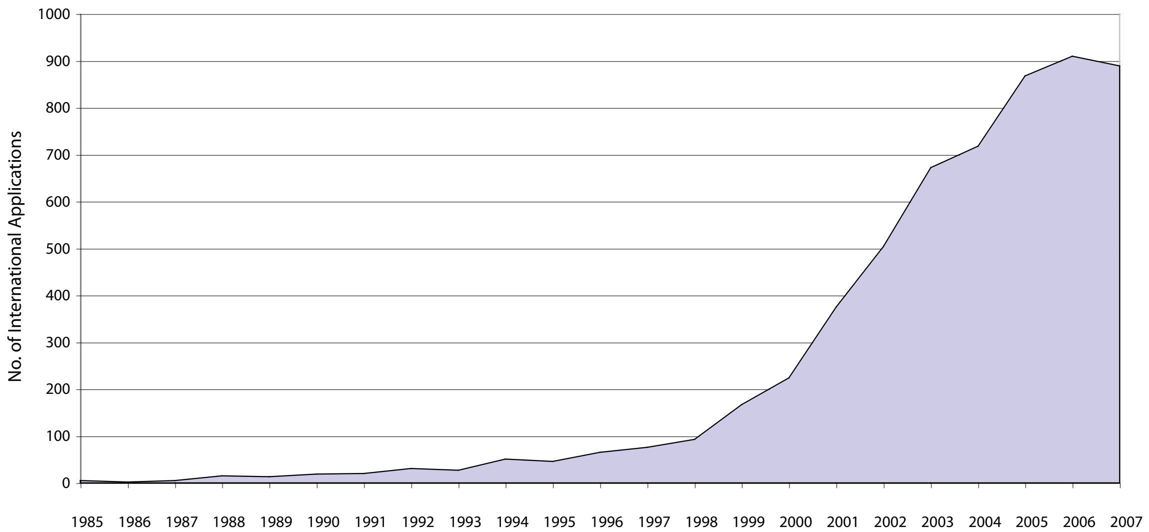


Figure 5: International patent applications by publication year (hydrogen use – fuel cells)

77 *The Hydrogen Revolution: An evaluation of patent trends in the fuel cell industry*, White Paper by Thomson Scientific Ltd, October 2004.

While Japanese applicants file more patent applications, the number progressing to PCT applications is dominated by the USA because a significant number of the Japanese applications are likely destined for the local Japanese market only. Thus while they are included in DWPI they skew the global results. This reasoning is further supported by a review of the number of granted patents in the USA and Europe only.

Using a keyword searching approach, 5,809 fuel cell-related PCT applications were identified while using a narrower patent class marks[78] approach, 3,508 PCT applications were identified. The analysis suggests the following conclusions:

- The IP Landscape according to PCT Applications is dominated by IP originating from the USA followed by Japan, Canada, Great Britain and Germany (Figure 6).
- Whilst the major car companies feature in the highest number of filed patent applications (Figure 7), the landscape includes the key market players focussed on fuel cells, for example Ballard Power Systems.
- The key market players also include major global manufacturing and/or chemical companies—such as 3M, DuPont, Matsushita, and Honeywell—with significant IP holdings (20-60 patents).
- Australia features in the country of origin listing with 1.3 per cent of patent applications, largely resulting from the IP holdings of listed company Ceramic Fuel Cells Limited.

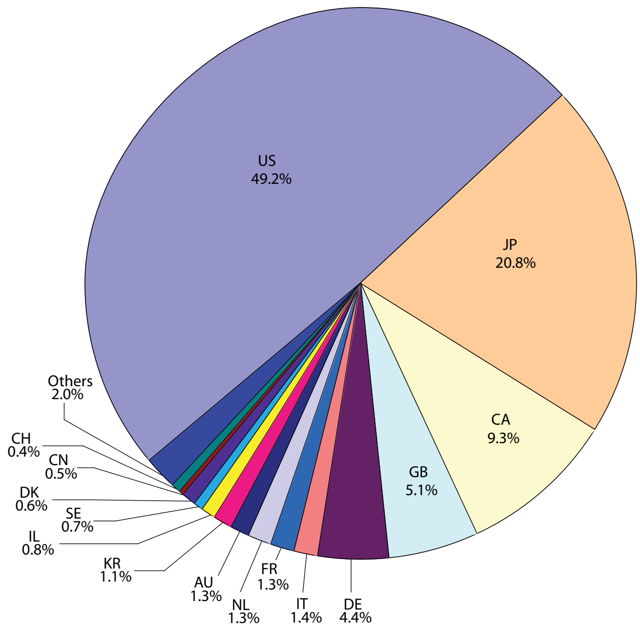


Figure 6: International patent applications by country of origin (hydrogen use – fuel cells)

78 All patents are classified according to an International Patent Classification system (IPC). In addition our analysis also uses the classification system provided by the United States Patent Office, the US Class Mark system (USCM).

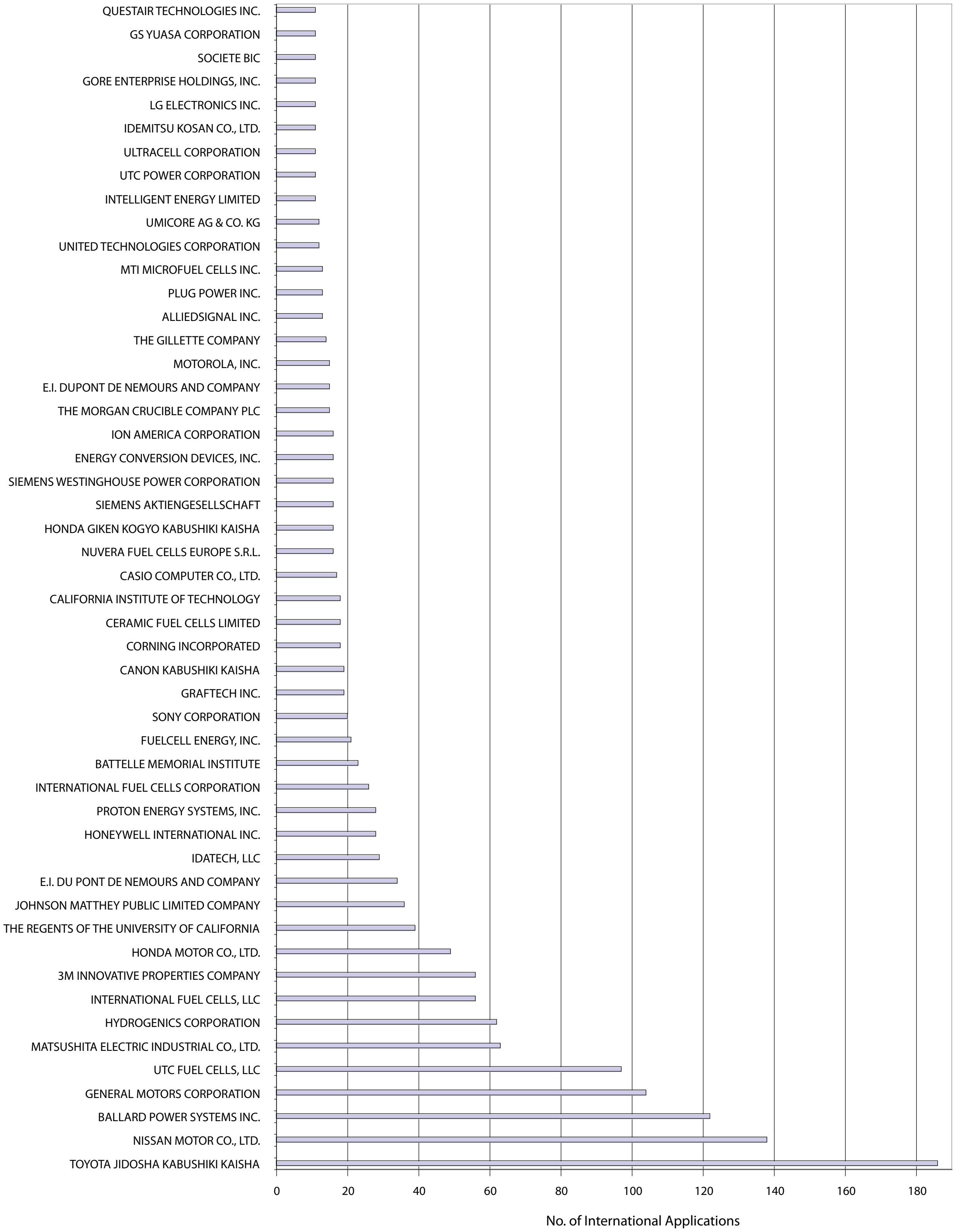


Figure 7: Top international patent applications by Assignee Name (hydrogen use – fuel cells)

Hydrogen production

The increase in patent applications (PCTs) from 1996 to 2006 is approaching tenfold for hydrogen production, although the number of applications is much smaller than for fuel cells. Using a keyword searching approach, 1,097 hydrogen production-related PCT applications were identified while using a narrower patent class marks approach, 256 PCT applications were identified. The analysis suggests the following conclusions:

- The USA holds approximately half these PCT applications followed by Japan, Canada and Great Britain (Figure 8).
  - One of the reasons for the USA dominance is that Nanologix Inc has filed many PCT applications (Figure 9) covering hydrogen production from microorganisms (bioreactor).
- Apart from Nanologix, the main market space is shared by a mixture of companies focussed specifically on hydrogen generation, the major car companies and universities.
- Figure 8 also shows Australia with 6.3 per cent of total patents in hydrogen production.
  - This is due to patent applications from the University of Queensland, the Australian National University and companies such as Technological Resources Pty Ltd (which comes under Rio Tinto).

Hydrogen storage

There are a limited number of patents directed at hydrogen storage, with the patent class mark search identifying 214 PCT Applications—a greater than fivefold increase from 1996 to 2006. This data:

- Did not identify any Australian IP in hydrogen storage (Figure 10)—although further searching based on technology/market keywords does identify Australian based IP in this area (see Section 3.3.2).
- Showed that the USA, and two USA companies (Energy Conversion Devices Inc and Advanced Technology Materials Inc), dominate the hydrogen storage IP Landscape.

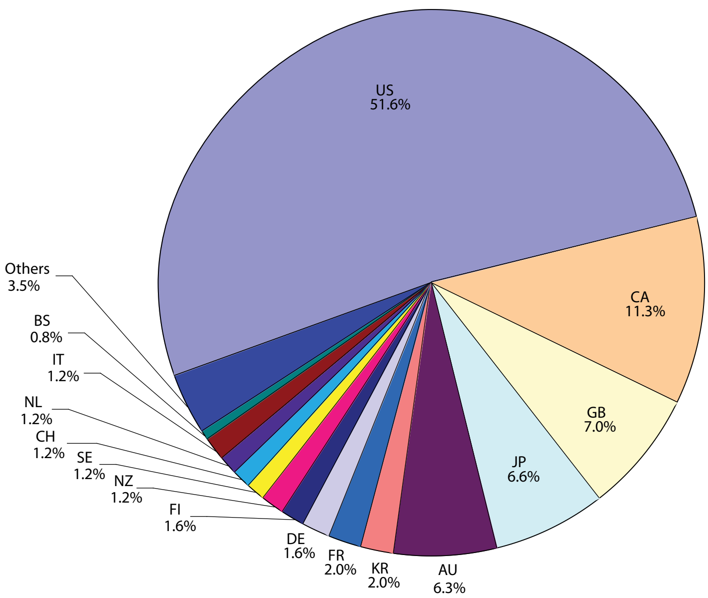


Figure 8: International patent applications by country of origin (hydrogen production)

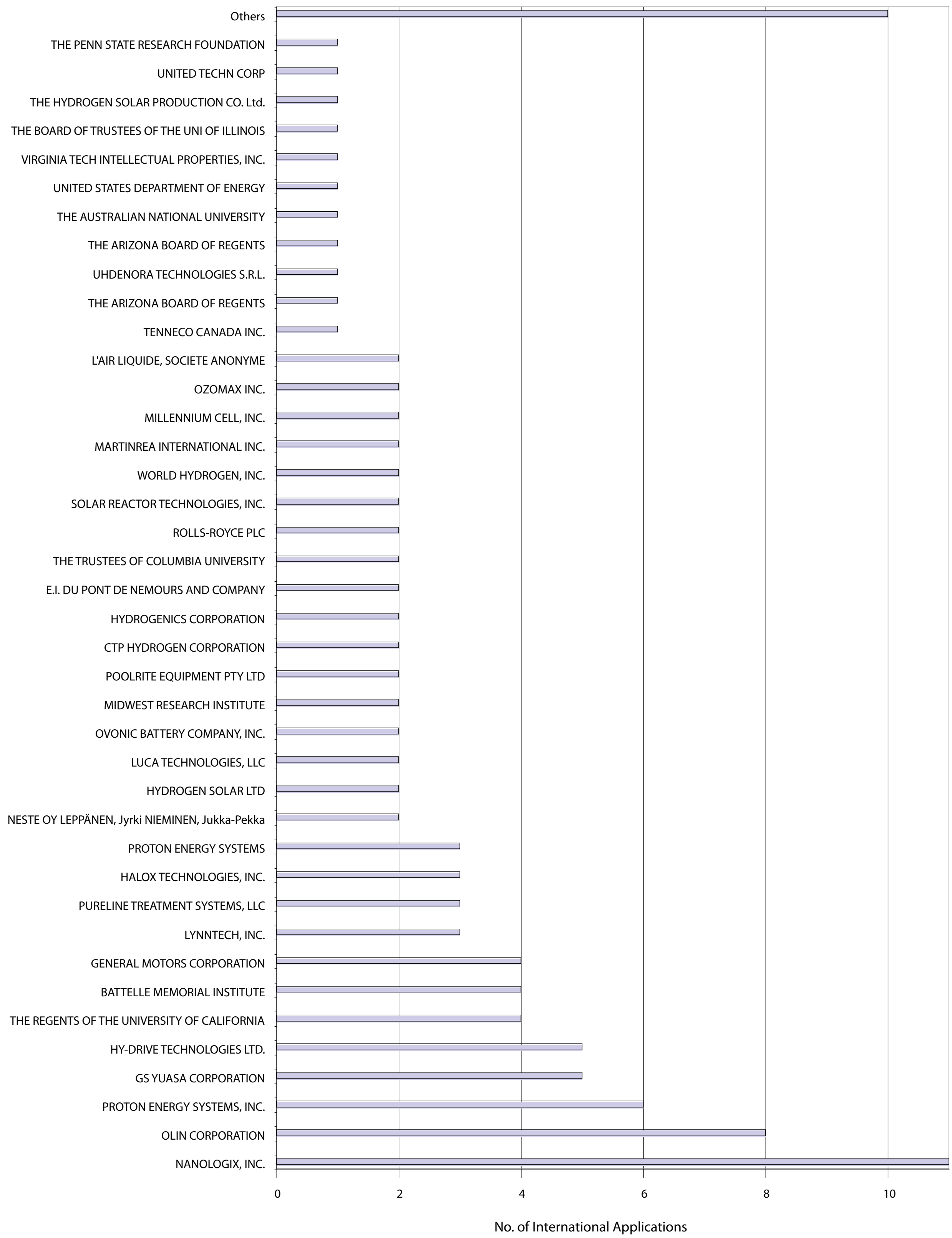


Figure 9: Top international patent applications by Assignee Name (hydrogen production)

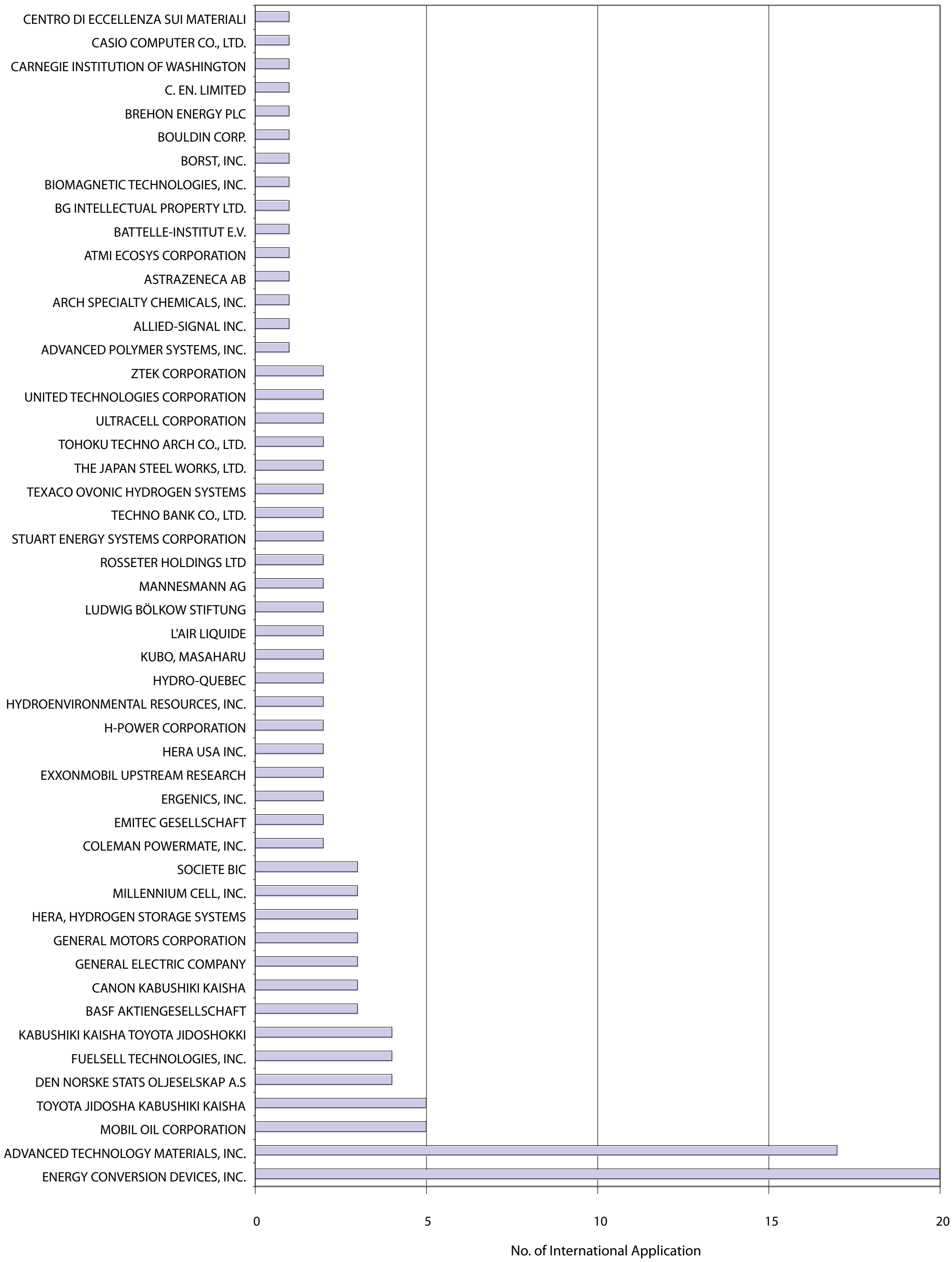


Figure 10: Top international patent applications by Assignee Name (hydrogen storage)

3.3.2 Technical/Market Based Analysis

In contrast to the previous statistical analysis, this technology-based survey used specific sets of keyword identifiers to undertake a subjective analysis (through internet and media searches) of the Australian hydrogen and fuel cell IP landscape. The main goals of this survey were to identify and categorise the potentially important Australian IP according to technical focus and scope and to analyse and correlate the IP landscape to show relationships.

The results indicate that the main players generally fall into four areas (see Table 3 and Appendix A):

- Established companies (or divisions of an established company) with well-advertised interest and investment in commercialising hydrogen-related technology;
- Smaller start-up companies focussed on commercialising new technology;
- Research organisations (semi-government or universities) where public funds support the development of H2 related technology; and
- Individuals.

Table 3: Australian Hydrogen IP Landscape

Owner/Holder of the IP Rights	Entity Type	IP Activity Level	Number of PCT Apps	Number of Granted Patents*
Albert Bow	Individual	Low	1	0
Allan Yeomans	Individual	Low	1	(1)
Casey, Alan Patrick Smith, Stewart	Individual	Low	1	1
CC Energy	Pty Ltd	Low	1	0
Ceramic Fuel Cells	Ltd	Medium	27	10
CSIRO	Res Org	Low	0	(1)
DUT	Pty Ltd	Low	1	0
Eden Energy	Ltd	Medium	9	1
Green Gas Generator (now based in Singapore)	Pte Ltd	Low	1	0
H.A.C. Technologies	Pty Ltd	Low	1	1
Hydra-Gas Racz, George	Multi	Low	1	0
Hydrogen Technology	Ltd	Low	2	2
Nicktown	Pty Ltd	Low	1	0
Orbital Engine Company	Pty Ltd	Low	1	1
Poolrite Equipment	Pty Ltd	Low	1	0
PowerGen International	Pty Ltd	Low	1	0
Rhyddings Pty Ltd, Renjean Pty Ltd Caesar, Marvyn Leonard	Multi	Low	1	1
RMG Services	Pty Ltd	Low	3	1
Solar Systems	Pty Ltd	Low	1	2
Technological Resources	Pty Ltd	Low	3	0
The Australian National University	Uni	Low	1	0
Toseski, Dimko	Individual	Low	1	0
University of Melbourne	Uni	Low	2	1
University of Queensland	Uni	Low	6	0
University of Wollongong	Uni	Low	1	0

* The number of granted patents is US patents except where there are granted Australian patents, which are shown in brackets.

Hydrogen use—fuel cells

As expected, there is no Australian-based IP in phosphoric acid or molten carbonate fuel cells. The IP space in these technologies is well covered by large overseas companies. It would be difficult for Australia to gain any hold in this space and it is probably not a wise use of R&D resources to try.

Ceramic Fuel Cells Ltd (CFCL) has a long history of R&D, with development of its planar SOFC technology commencing in 1991 (and earlier within CSIRO where the technology originated). CFCL's first patent was filed in 1995 and it has the largest fuel cell-relevant IP holdings in Australia with 27 PCT applications and 10 granted US patents over the last 14 years (see Appendix A). CFCL's target market is domestic combined heat and power production and distributed generation.
As the CFCL design utilises natural gas as the base fuel to produce hydrogen by internal reforming, some of the CFCL IP is also relevant to hydrogen production.

Hydrogen production

Through its wholly owned subsidiary Hythane Company LLC, Eden Energy Limited is progressing hythane (~90 per cent hydrogen and ~10 per cent methane) as an alternative fuel. According to Eden Energy, hythane offers ready-to-use technology that bridges the divide between today's engines and a future hydrogen economy.[79] Eden holds the IP rights to hythane through its acquisition of US based entities Brehon Energy PLC and HyRadix Inc. As a result Eden now has about 10 patents that protect its Hythane production, storage and dispensing systems (see Appendix A).

There are a small number of patents scattered across other Australian-based entities relevant to hydrogen production, but there are no standout market players. The IP of interest in this space stems from a related area of research where Australia has proved to be a major player, specifically photovoltaics and concentrating solar thermal. Several research groups in Australia are working on photo-electrolysis, microalgae and/or concentrating solar power for the production of hydrogen (see Appendix A) including the University of Queensland, Solar Systems Pty Ltd and Technological Resources Pty Ltd (a wholly-owned subsidiary of Rio Tinto).

Hydrogen Storage

There is minimal Australian-based IP related to hydrogen storage, although there are relevant patents (see Appendix A) from the University of Queensland and Technological Resources Pty Ltd.

3.3.3 Analysis of Australian IP landscape

From a global perspective, and using IP as the metric, development of commercially driven applications has been geared towards the use of hydrogen rather than its generation or storage. As evidenced by the volume of IP (numbers of patents) and subjective review, the majority of effort has focussed on the development of viable fuel cells. The optimisation of fuel cell design for performance versus costs is where much of the IP resides and this IP is usually design-specific in order to protect a particular fuel cell system.

The nature of the hydrogen IP landscape reflects the known implementation issues faced by advocates of a hydrogen economy. The lack of a commercially-viable hydrogen distribution infrastructure and storage solutions, or clear pathway towards overcoming this lack, has resulted in the IP focus on fuel cells. There are notable exceptions such as Canada where a mix of government and industry support has led to the development of a prototype hydrogen infrastructure. From an IP perspective this shows that Canada scores well above the mark in terms of IP volume and commercially-valuable IP, e.g. Ballard Power Systems in Canada are now seeing success, after a long R&D journey, with their technologies.

There is a minimal volume of Australian-based IP that is relevant to the global landscape and it is currently scattered with no national cohesion. However, Australia does have some important IP that could play a role in developing hydrogen and fuel cell solutions for Australia.

As is the case internationally, the area of greatest activity in Australia is fuel cells, largely due to the R&D, commercial and IP protection activities of Ceramic Fuel Cells Limited. Apart from the CFCL IP, no significant hydrogen or fuel cell IP holdings have originated from Australia. There are, however, several patents currently under prosecution that, if granted, may provide a basis for an investable IP position. It also is noted that some of the fuel cell IP is directed at system integration where the

79 http://www.edenenergy.com.au/, last accessed 28 January 2008.

generation of hydrogen, and to a lesser extent the storage of hydrogen, are part of a total fuel cell system.

While Australia is not strongly placed in hydrogen and fuel cells IP, there are no broad constraints to development and use in Australia because of the age of the basic technology, the abundance of published technical literature and the fact that the early patents in the key technical areas have all but expired.

The main IP barrier to entry for any new players to the market is on a technology-solution basis. For example, if a new market entrant was to choose a PEMFC or SOFC-based technical solution then the patents of the existing players in these areas may be a barrier for that new entrant's particular solution.

3.4 Market potential

To gain an understanding of their economic competitiveness and market potential, a study was made of the costs in Australia of production and delivery of hydrogen as a fuel and of electricity from stationary fuel cell systems as a distributed generation product.

This study, undertaken by McLennan Magasanik Associates (MMA), explored the market potential through the use of a model that determines the long run marginal cost (also known as levelised cost) of various hydrogen production and stationary fuel cell system generation options in Australia[80]. The full analysis of this study is provided in Appendix B to this roadmap.

A number of case studies—representative of the market opportunities available—were developed to examine the potential. The cost of hydrogen is compared to petroleum fuel for transport and the cost of stationary fuel cell system generation is compared to the cost of grid supply options. The basis of these analyses is that the least cost alternative will be selected to supply the market. On this premise, hydrogen as a transport fuel or fuel cell-based distributed generation systems will only have potential if their cost is lower than the incumbent alternatives.

The modelling has been undertaken as a high level exercise designed to capture the major trends and sensitivities to inputs on the cost of producing hydrogen and of generating electricity using fuel cells. As such, a number of factors are ignored or treated in a relatively non-detailed manner. In particular the following are important issues that should be considered in using the results of the modelling:

- Hydrogen production for transport fuel is only analysed to the point of vehicle refuelling. It was considered that the variables involved in analysing the transport component of the system were too great to include in the current study. Use of hydrogen for transport applications was therefore compared on a petrol litre equivalent (PLE) basis to unleaded petrol.
  - Clearly, if fuel cell vehicles become commercially available at the fuel efficiencies claimed, which are significantly greater than petrol fuelled vehicles, the costs for hydrogen as a transport fuel on the basis of kilometres travelled will improve relative to petrol.
  - The uncertainties associated with forecasting petrol-fuelled vehicle fuel consumption, which will significantly reduce as hybrid, plug-in hybrid and diesel fuelled vehicles increasingly penetrate the market, are particularly large.
- Costs for hydrogen production and delivery have been developed based on the best available published data for plants capable of producing the required quantities of hydrogen for particular applications. Detailed costs from small scale pilot trials were intentionally not utilised, such as the Perth bus trial as these are unlikely to be representative of the costs incurred when large scale adoption occurs.
  - The Perth bus trial reported[81] a hydrogen cost of \$21/kg H_2. This hydrogen was produced and purified at the Kwinana refinery, and this production route was not considered. Given that the trial employed three buses and a single fuelling station and the annual hydrogen consumption was about 18,000 kg/year (0.05 tonne/day) these costs were not considered to be representative of a larger plant and delivery

80 All costs in this Section 3.4 are in real terms as of mid-2007.

81 "STEP Fuel Cell Bus Trial - First Year Operating Summary 2004/05"

system supporting a significant fleet of vehicles.

– The distributed hydrogen production and supply stations for transport use modelled in this work are in the 1 to 3 tonne/day capacity range on the basis that significant numbers of vehicles could be supported.

3.4.1 Hydrogen production cost

A number of production and supply scenarios were analysed that cover the scale and technologies that would likely be required to supply hydrogen at 99.99 per cent purity to be used in the following applications:

- Large-scale fuel cell generation of around 300 kW
- Medium-scale fuel cell generation of around 30 – 50 kW
- Small-scale fuel cell generation in range 1 – 5 kW
- Supply to a large-scale service station for transport fuel
- Supply to a small-scale transport fuel dispenser for home use

Within each of these hydrogen demand categories, a number of potential production pathways may be utilised. A combination of natural gas reforming, electrolysis and coal gasification plant were selected that could be used to supply different levels of demand:

- A 380 tonne/day coal gasification plant
- A 1 tonne/day electrolysis plant
- A 240 kg/day electrolysis plant
- A 1 kg/day electrolysis plant
- A 380 tonne/day natural gas reforming plant
- A 27 tonne/day natural gas reforming plant
- A 3 tonne/day natural gas reforming plant

The sizing of these plants is roughly according to the sizes that would suit a centralised production facility with delivery to users; a service station sized unit; and a small size suitable for home fuelling of a vehicle or fuelling a commercial fuel cell. The underlying assumptions regarding the operating and capital costs and the efficiency of the systems are shown in Table 4.

Table 4: Key assumptions for hydrogen production cost modelling

Hydrogen Production System	Hydrogen Output (tonne/day)	Capital Cost 2010 ($/tonne/day capacity)[82]	Fixed Operating Cost 2010 ($/tonne/day capacity)	Variable Non-Fuel Operating Cost 2010 ($/tonne H_2)	Efficiency (GJ/kg H_2 Produced)
Large Scale Natural Gas Reforming	380	$483,000	$15,400	$4.64	0.20
Medium Scale Natural Gas Reforming	27	$650,000	$15,400	$4.64	0.21
Small Scale Natural Gas Reforming	3	$880,000	$15,400	$4.64	0.22
Large Scale Electrolysation	1	$5,800,000	$116,000	$0.57	0.18 (0.050 MWh/kg H_2)
Medium Scale Electrolysation	0.24	$7,300,000	$116,000	$0.57	0.18 (0.050 MWh/kg H_2)
Small Scale Electrolysation	0.001	$16,900,000	$116,000	$0.57	0.19 (0.053 MWh/kg H_2)
Large Scale Coal Gasification	380	$445,000	$15,400	$0.11	0.167

The levelised cost of producing hydrogen for the selected plant types is shown in Figure 11. As expected the use of electrolysis is the most expensive method to produce hydrogen, while large scale production using natural gas reforming results in the lowest cost, starting at around $2 /kg.

82 Capital cost and fixed operating costs are presented as "dollars per unit capacity" so the total plant cost is equal to the value in the table multiplied by the relevant capacity.

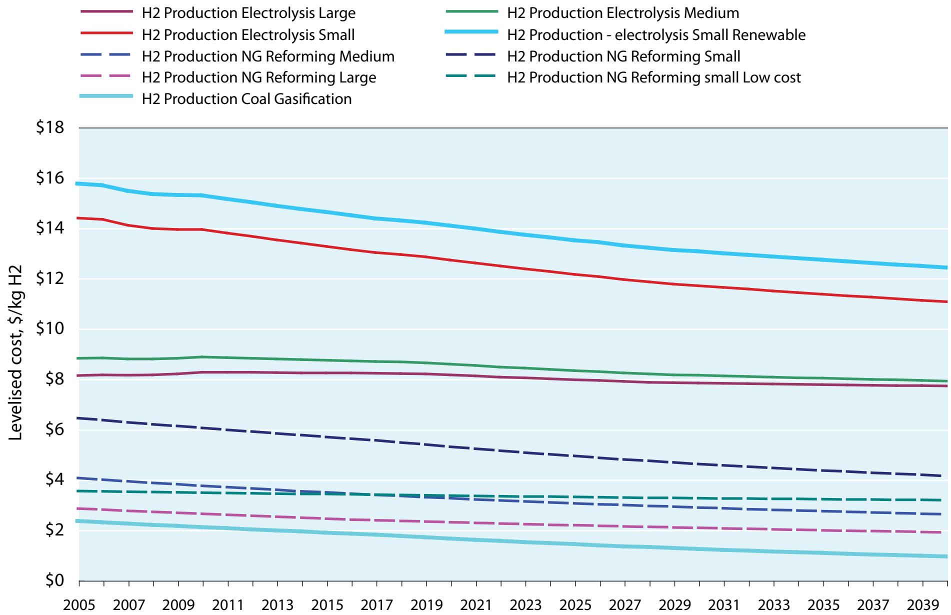


Figure 11: Levelised cost of hydrogen production for a range of capacities and methods

Significant reductions in capital cost for the electrolysis plants are assumed[83] as a function of projected, increased manufacturing volumes of such plants. This particularly applies for the small scale units that may in future be produced in large volumes. The impact on the final production cost of capital cost is relatively small however, because of the dominance of electricity cost in the total.

The impact of utilising renewable electricity for the production of hydrogen by electrolysis is also shown in this figure and adds approximately $2.00/kg to the cost. This additional cost of renewable electricity is assumed to be the equivalent of the cost of a renewable energy certificate, taken to be $40/MWh.

Also included in the analysis was an option for a small scale natural gas reformer that is produced in large numbers with significant economies of scale achieved in manufacturing, resulting in a cost 20 per cent lower than current costs. This results in a hydrogen production cost of less than $2/kg by 2020, which approaches that of the large scale NG reforming unit.

The effect of fuel price is shown in Figure 12 for changes from -20 per cent to +30 per cent of the modelled fuel cost. These data show that while reformation of natural gas and gasification of coal are relatively stable with respect to the fuel price, the production cost is much more sensitive to the cost of electricity for electrolysis. High electricity prices push the cost of hydrogen production from small scale electrolysis to about $13/kg.

83 *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, National Research Council and National Academy of Engineering, 2004.

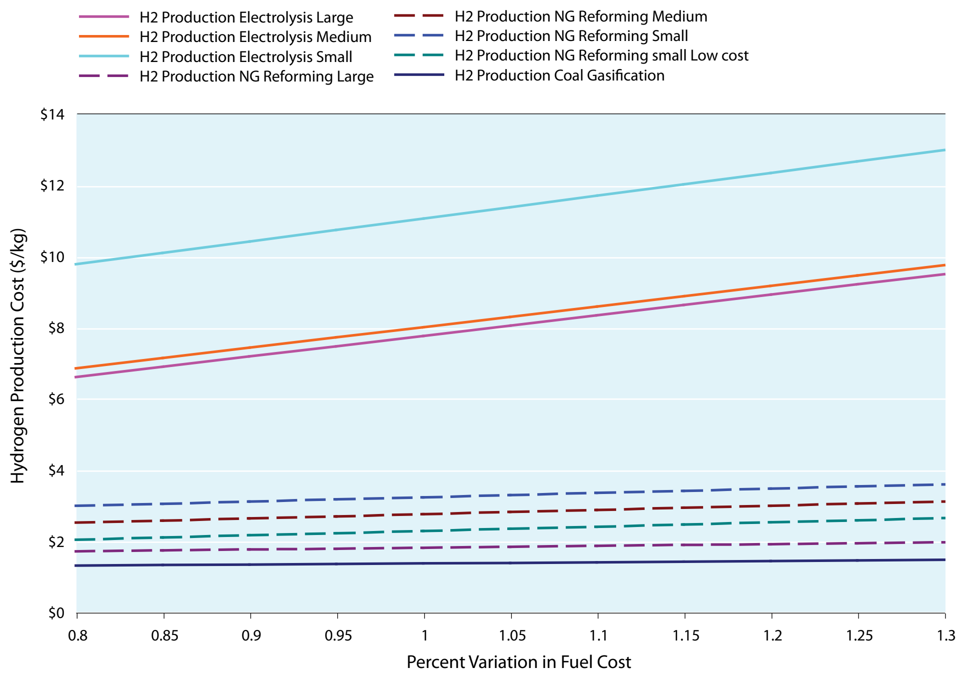


Figure 12: Sensitivity of hydrogen production cost to fuel cost

3.4.2 Market potential for hydrogen as a transport fuel

The potential for hydrogen to be utilised as a transport fuel is dependent on a number of factors including:

- The availability and cost of hydrogen fuelled vehicles
- The development and implementation of standards for these vehicles
- The availability of refuelling facilities
- The availability of economic hydrogen production facilities

If hydrogen is to be an acceptable fuel for transport applications, it needs to be produced, delivered and dispensed into the vehicle at a cost similar to that of petrol on an energy basis. In conducting this analysis the production costs of hydrogen in $/kg have been converted into delivered costs in terms of dollars per petrol litre equivalent (PLE). That is, the cost of the quantity of hydrogen that will deliver the same energy as a litre of petrol. There are three main scenarios for the delivery of hydrogen to a refuelling station:

- Hydrogen may be produced at a centralised location and piped to the refuelling station.
- Hydrogen may be produced at a centralised location and transported by road in high pressure or cryogenic tanks.
- Hydrogen may be produced and stored on site.

Pipeline delivery was not considered because it is unlikely that there will be sufficient demand to justify the infrastructure costs until a large proportion of the vehicle fleet is using hydrogen.

The cost of delivering hydrogen in tube tankers to a refuelling facility was estimated to be $2.10/kg based on US data from the NAS[84], utilising a 2 hour round trip including refilling and unloading. It was further assumed that 20 per cent of the delivered hydrogen cost is required for dispensing equipment, and the resulting delivered purchase price includes a petrol equivalent excise of 38.143 cents per PLE and GST at 10 per cent. An unleaded petrol price of $1.50/L increasing at 0.5 per cent/year, in real terms, was used as a comparison point for the dispensed hydrogen costs. As shown in Figure 13, the dispensed cost of hydrogen does not become lower than this petrol price until 2020 at the earliest.

84 Ibid.

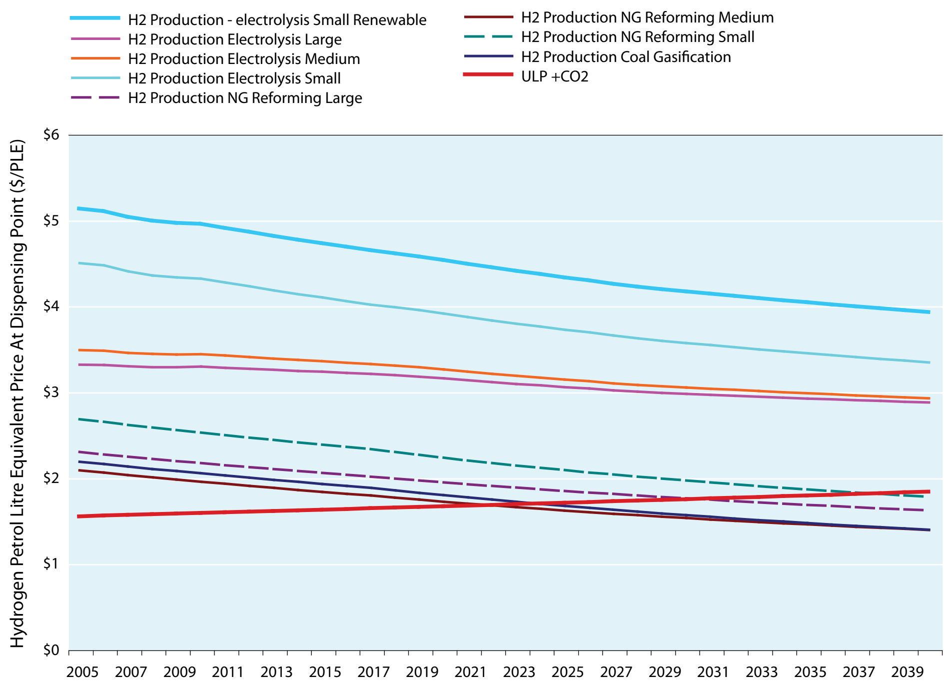


Figure 13: Comparison of delivered hydrogen to unleaded petrol

This comparison shows that electrolyser-produced hydrogen is not competitive with current petrol prices, with oil at around the $US100 barrel mark. However if petrol prices reach $2.50/L it would approach competitiveness.

Natural gas reforming, however, reduces in cost to around $1.50/PLE in 2020, which is likely to be competitive with petrol at that time. Further development and mass manufacture could

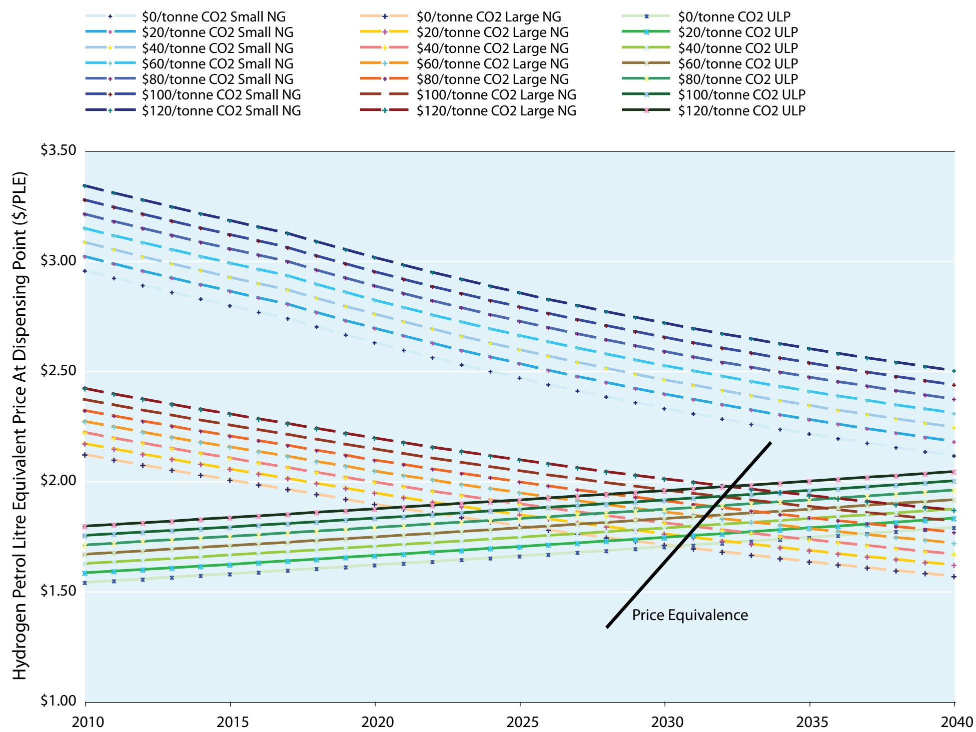


Figure 14: Comparison of delivered hydrogen to unleaded petrol under varying CO_2-e costs

significantly reduce the capital cost of production, delivery and dispensing equipment although this would be offset by the likely increase in natural gas costs as the demand for gas increases because of increasing demand for natural gas-fuelled electricity generation and the potential increase in demand for it for the production of hydrogen.

The impact of a range of carbon prices on the cost of producing hydrogen with natural gas reformation is shown in Figure 14, with the corresponding prices for unleaded petrol under the same carbon tax regime.[85]

The price equivalence line shown identifies the points at which hydrogen becomes a viable fuel purely on a delivered cost basis. In this example, the cost of hydrogen becomes competitive around 2030 and moves to later periods as the carbon cost is increased.[86] For large-scale coal gasification the competitiveness is reached a few years earlier than this while competitiveness is never reached for electrolysis. This is a result of the relativities in the carbon intensities of the ULP and the hydrogen by each of these production methods.

There are a few transport sectors where the need for widespread networks of refuelling stations is not a critical requirement. These include bus networks, public and private sector fleet operators and taxis. However these operators would, in general, only make a decision to use hydrogen fuel if it were economic to do so.

On the basis of this analysis, the economics will not be favourable for a number of years—although it is recognised that some government departments may choose to use hydrogen-fuelled vehicles for other, more altruistic reasons. Overall, the market potential for hydrogen as a transport fuel in Australia is considered to be low—at least until low-cost, clean or green hydrogen production and delivery routes are developed and commercialised.

3.4.3 Fuel cell distributed generation electricity costs

The stationary power costs and market potential was analysed of small to medium scale distributed generation (DG) systems that would be installed in the distribution system close to the customer load that they serve. Discussion of the Australian electricity generation and supply markets therefore is focussed on the retail market rather than on the wholesale market.

Generation costs have been estimated using MMA's GENCHOICE model. The model calculates the long run marginal cost for new generation plant[87], with the full costs of generation modelled for each option. To model the effect of a carbon price, the model adds a variable cost equal to the carbon price multiplied by the emission intensity of the generator. In examining the generation costs for fuel cell DG systems, a mixture of unit sizes were selected that could be used to supply different levels of demand. The plants examined were:

- For use in commercial buildings and/or clusters of individual homes:
  - A 300 kW PEM fuel cell using hydrogen fuel.
  - A 300 kW direct fuel cell[88] using natural gas fuel.
- For use in a single household environment:
  - A 3 kW PEM fuel cell using hydrogen fuel.
  - A 3 kW direct fuel cell (e.g. solid oxide) using natural gas fuel.

Key assumptions for these plants are shown in Table 5, with more detail in Appendix B.

85 It was noted to us by one the stakeholders interviewed for this roadmap that recent modelling of carbon prices in the electricity sector alone shows that it may rise to \$60 to \$80 per tonne CO_2-e reasonably quickly. However, if other sectors across the economy (e.g. transport) are required to achieve emissions targets then this will take carbon prices much higher, noting that the carbon price has to be >\$150 per tonne CO_2-e to have an equivalent cost to the current excise tax of 38c per litre. That is, the sensitivity of response to carbon prices is much higher in the stationary energy (particularly electricity) sector than the transport sector.

86 This is based on the carbon content of the petrol itself and excludes carbon emissions from the production, transport and refining of crude oil and the transport of the refined product. Any emissions associated with the production, processing and transmission of natural gas are also excluded. Emissions associated with the processing of natural gas are heavily influenced by the CO_2 content of the raw gas and its removal if required, the concentration CO_2 in the final product being limited to about 2 per cent.

87 *The long run marginal cost (or levelised energy cost) of a new generation option is equal to the present value of capital, fuel and operating costs divided by the present value of the output over the expected life of the plant.*

88 A Direct Fuel Cell (DFC) uses natural gas directly as the fuel and reforming occurs internally, within the fuel cell. To achieve internal reforming DFCs need to operate at high temperatures thus restricting them to solid oxide and molten carbonate fuel cell technologies.

Table 5: Key assumptions for fuel cell DG system cost modelling

Option	2010 Capital Cost ($/kW)	Fuel Supply	2010 Fuel Cost ($/GJ)
3 kW PEM Fuel Cell	$5,700	Small Electrolyser	$98/GJ H_2
3 kW PEM Fuel Cell Mass Produced [89]	$1,000	Small Electrolyser	$98/GJ H_2
3 kW PEM Fuel Cell	$5,700	Small NG Reformer	$42/GJ H_2
300 kW PEM Fuel Cell	$3,700	Small NG Reformer	$42/GJ H_2
300 kW PEM Fuel Cell	$3,700	Medium Electrolyser	$62/GJ H_2
300 kW PEM Fuel Cell	$3,700	Medium Electrolyser Low Cost [90]	$24/GJ H_2
300 kW DFC Fuel Cell Low Cost	$3,500	Commercial Natural Gas Supply	$8.60/GJ NG
300 kW DFC Fuel Cell High Cost	$5,200	Commercial Natural Gas Supply	$8.60/GJ NG
3 kW DFC Fuel Cell Low Cost	$3,700	Residential Natural Gas Supply	$13.00/GJ NG
3 kW DFC Fuel Cell High Cost	$5,500	Residential Natural Gas Supply	$13.00/GJ NG

The modelled cost of electricity generation for each of the fuel cell options examined is shown in Figures 15 and 16, along with the supply costs of grid electricity for residential and commercial customers.

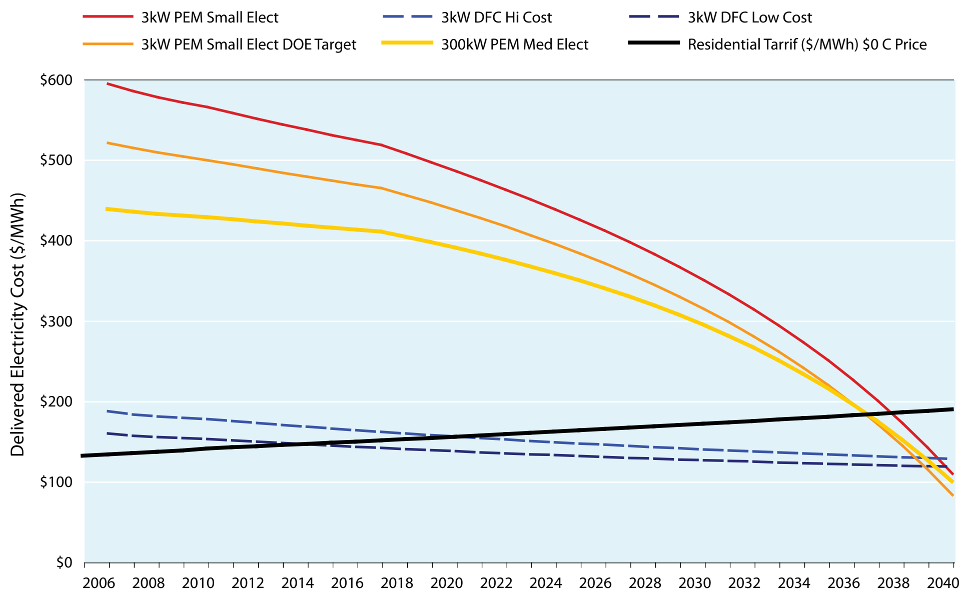


Figure 15: Comparison of fuel cell DG electricity cost to residential tariffs

89 *Costs for this option are the DOE target for mass-produced automobile power systems.*

90 *Costs for the low cost electrolyser assume significant improvements in efficiency and manufacturing economies of scale.*

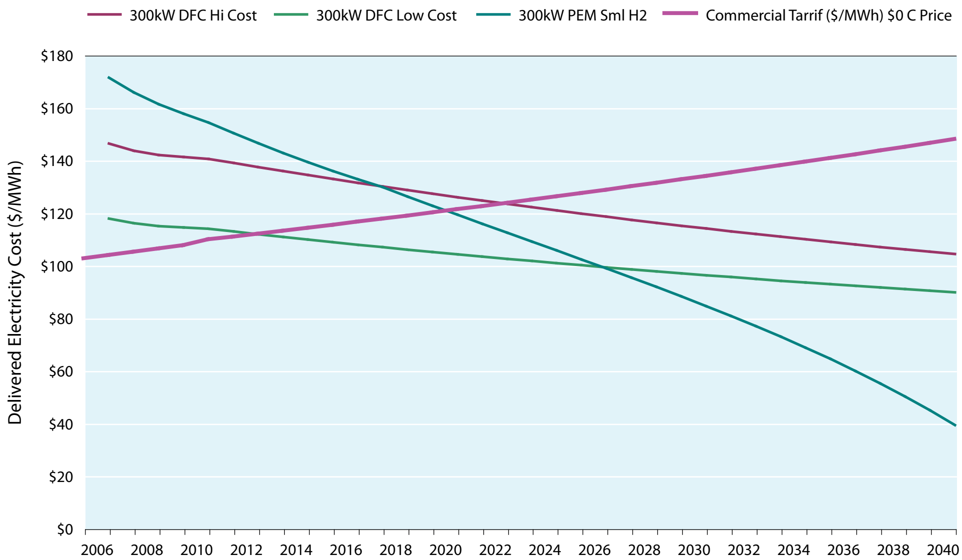


Figure 16: Comparison of fuel cell DG electricity cost to commercial tariffs

These charts show that the electrolyser hydrogen supply options are not viable—it is inefficient to use electricity to generate hydrogen to generate electricity. The only situation where this may be applied is as a method for storing intermittent renewable electricity generation in remote regions. These electrolyser options are not considered further in this roadmap.

The key parameter defining the success of a DG technology is whether the cost of supplied electricity from the fuel cell is less than the grid supply. The fuel cell options that are likely to become economic at a residential level are shown in Figure 17.

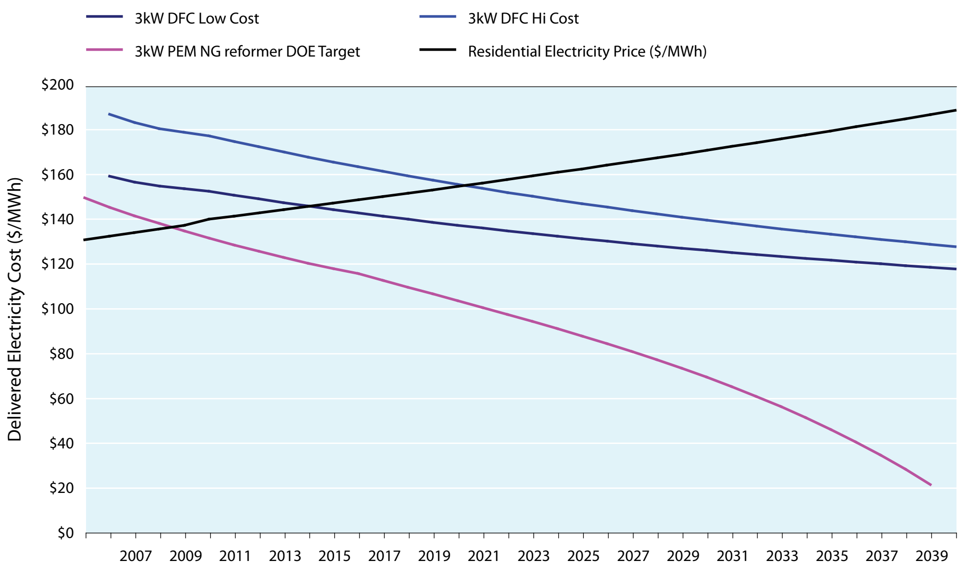


Figure 17: Comparison of viable fuel cell DG options at the residential level

Two of the options shown in Figures 16 and 17 are low cost scenarios that represent an optimistic outcome of development work being carried out, and should therefore be treated as possible outcomes that are not of high probability. More likely is that a number of these technologies become economic in the period leading up to 2020, as indicated by the generation costs of the higher cost 3 kW DFC and the 300 kW PEM fuel cell. In the case of the 300 kW units these would likely be installed in new residential estates to power clusters of new homes or in apartment buildings in order to compete against a residential tariff. Where waste heat can be harnessed for heating and/or cooling the economics will improve further.

The options that are likely to become competitive, as commercial electricity rates increase, are shown in Figure 18.

Not surprisingly, the fuel cell generation options that are competitive in this market are the larger 300 kW systems that do benefit from economies of scale. As was the case with the residential systems though, the low cost option for the 300 kW DFC unit should not be viewed as a likely outcome but a possible outcome.

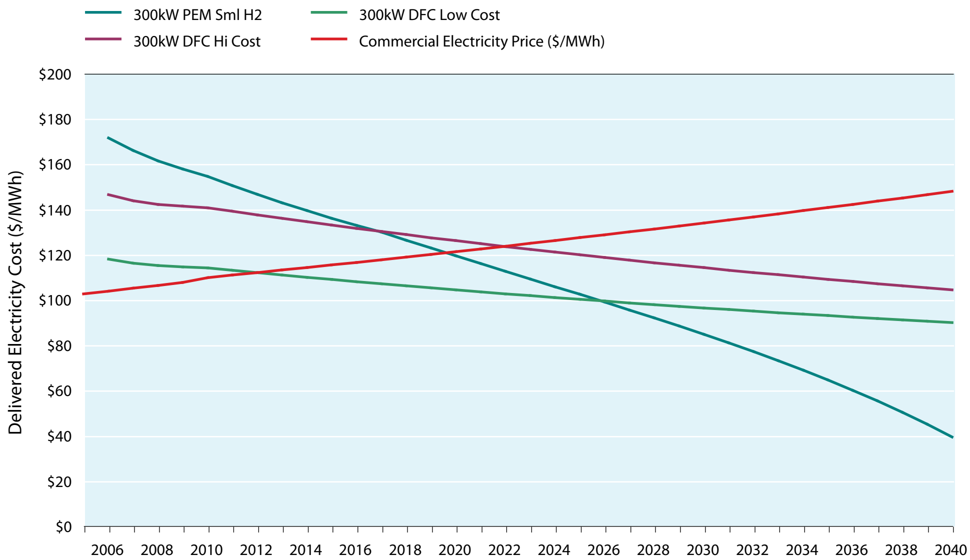


Figure 18: Comparison of viable fuel cell DG options at the commercial level

The high level of uncertainty in the costs associated with fuel cell generation means it is important to understand that different outcomes in capital and fuel cost parameters are likely and will affect the delivered electricity price. Our analysis shows that in most cases a 10 per cent increase in capital cost results in an increase of between 4 and 6 per cent in the electricity price[91]. The sensitivities to fuel costs are similar or higher.

The impacts of a carbon trading environment on the economics of these fuel cell DG systems also have been modelled over a carbon price range of $0 to $120/tonne CO_2-e. The outcome of this carbon price modelling for the 300 kW commercial sector options is shown in Figure 19 and for the 3 kW residential sector options in Figure 20.

In both the residential and commercial sectors, our analysis shows that even a modest carbon price would result in the DFC systems becoming progressively economically viable over the next decade but the PEMFC systems will take much longer or need a significantly higher price of carbon.

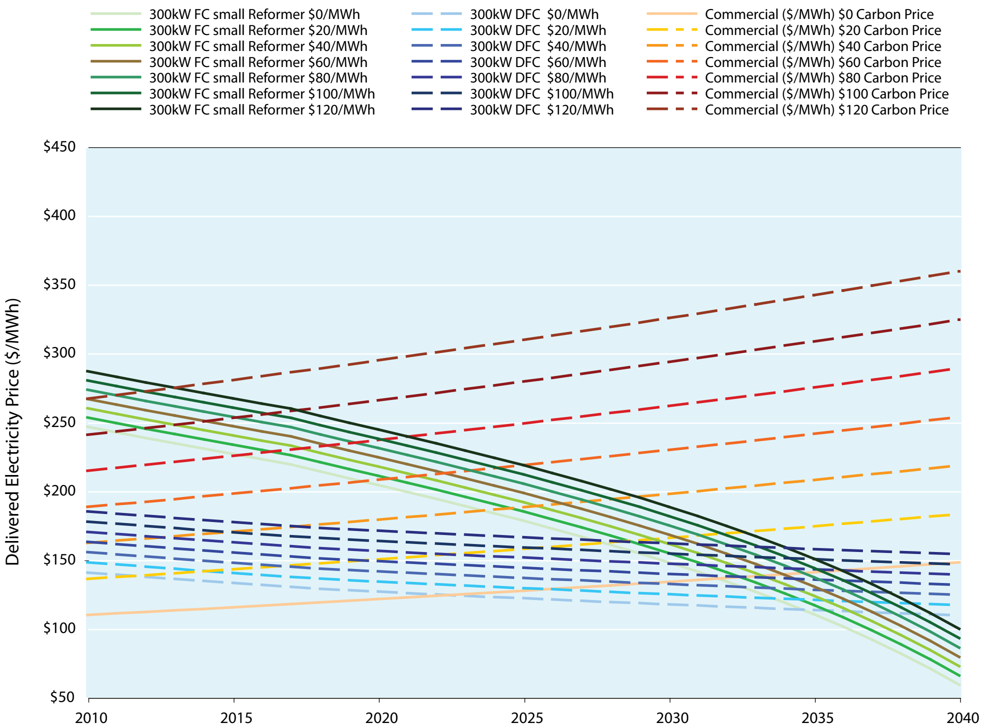


Figure 19: Comparison of viable fuel cell DG options at the commercial level under carbon pricing

91 In the case where the DOE target value for capital cost for a 3 kW PEMFC system is used, the electricity price is largely invariant to changes in the capital cost. This behaviour is attributed to the fact that at these low capital cost values the electricity price is largely dominated by the cost of fuel.

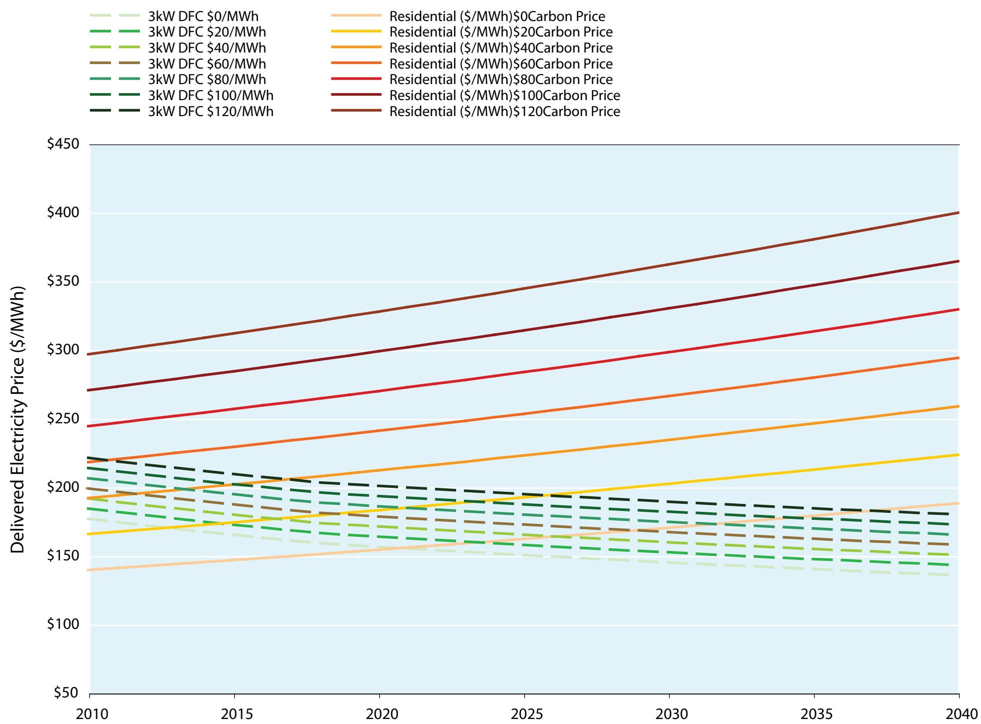


Figure 20: Comparison of viable fuel cell DG options at the residential level under carbon pricing

3.4.4 Fuel cell distributed generation market potential

The analysis shows that, on a delivered electricity cost basis, prior to about 2020 there is unlikely to be significant adoption of either direct or hydrogen-fuelled FC systems for distributed generation. However, they will start to make inroads in specialist applications where high reliability is a necessity—this has already occurred overseas in facilities such as data processing centres and hospitals.

After 2020 the cost of fuel cell electricity becomes comparable with that delivered from the grid and it is at this point that significant uptake could occur. However, this will—to a large degree—be dependent on whether the required policies and standards for connecting distributed generation to the electricity networks are adopted.

The adoption of a carbon trading scheme by the Australian government could accelerate the uptake of FC distributed generation systems. The analysis shows that even a modest carbon price improves the economics significantly for direct fuel cell systems because their delivered carbon intensity, using natural gas fuel directly, will be lower than grid-delivered power as a result of its higher efficiency and the avoidance of transmission and distribution losses. However, this trading scheme will need to recognise and include these forms of generation to achieve these economic benefits.

It also is noted that to achieve the full greenhouse benefit, and thus carbon offset contribution, of a hydrogen-fuelled fuel cell requires the production of greenhouse neutral hydrogen by means of either renewable electricity or through carbon capture at the point of production. Both, however, incur additional costs.

Residential

In Australia there are approximately 100,000 new houses and approximately 45,000 to 50,000 new non-house dwellings (largely apartments) built each year. If each new house built had 1 to 3 kW of DG capacity installed it would amount to an annual capacity increase of 100 to 300 MW. Incorporating DG into new apartment construction would increase this value to 150 to 450 MW or greater as apartment buildings could potentially utilise larger generating units.

This is a significant increase in DG capacity when compared to the annual average increase in peak demand over the past five years of 875 MW for the eastern states, where most of the new housing construction is occurring. However, this potential market will likely be shared between a variety of technologies that will compete on the basis of cost and environmental performance.

Commercial

There is significant potential for fuel cell generation in commercial buildings—particularly noting the economic competitiveness of larger DFC units under even a modest carbon price.

While it is difficult to determine a reliable figure of the potential capacity that could be installed, the number of high rise buildings in the central business district (CBD) in the major Australian cities allows a determination of a maximum potential penetration of larger fuel cell DG systems. These CBD locations are often tightly constrained in terms of electricity distribution and therefore may provide additional benefits to the installer, although the supply of natural gas to fuel these CBD-based systems could also prove to be difficult as distribution networks for gas have become constrained in some areas.

There are 1,800 high rise buildings in Sydney, Melbourne, Brisbane and Perth. If a 300 kW fuel cell DG system was placed in each of these a maximum of 550 MW of generation capacity would be installed. Many of these sites would use more than the 300 kW assumed so the potential capacity could be larger. Other potential facilities where units of this scale could be installed include hospitals, government buildings and industrial facilities. Including these facilities could easily double the potential in the commercial buildings market.

Overcoming barriers

The incumbent system of electricity generation has not, historically, been designed to allow the connection of a large number of small scale generators to the distribution system resulting in a number of barriers—technical, economic and regulatory in nature—when it is desired to utilise large numbers of small scale, distributed generators.

In particular, two additional policy considerations (apart from a carbon pricing regime) that would assist a significant proportion of this market potential to be realised (assuming that FC DG system cost targets are met over time) are:

- Enabling easy and low-cost connection to existing distribution systems; and
- Changing electricity market rules to allow for the full financial benefits of distributed generation (such as avoided transmission upgrades, lower losses and grid support) to be captured by the distributed generators as a matter of routine.

4 STRATEGIC ANALYSIS

4.1 Prime drivers of change on Australia's energy systems

In considering the development of a roadmap for hydrogen and fuel cells for Australia it is important to clearly identify the prime drivers of change to energy systems and their importance in Australia's particular environmental and economic circumstances today. Once these energy system needs are determined then the contribution of hydrogen and fuel cells to fulfilling them—that is, the 'need' for hydrogen and fuel cells—can be placed in context.

In a review of the hydrogen futures literature covering a total of 40 studies published between 1996 and 2004,[92] McDowall and Eames identified four overarching problems or policy objectives that consistently stand out in the literature as providing the underlying drivers of a transition to a hydrogen future, as follows and as depicted in Figure 21:

- "**Climate change:** Reducing carbon dioxide emissions is clearly considered to be the most important of these. Climate change is cited by all of the studies reviewed. Indeed, seven of the studies refer only to climate change as a reason for a transition to a hydrogen economy.
- **Energy security:** This encompasses a range of concerns over the finite nature of oil and gas reserves, their geopolitical sensitivity and location, energy prices, and vulnerability of centralised energy systems to attack. No studies focused exclusively on this aspect, and 18 made no mention of energy security at all. Of the studies that emphasise energy security, most are roadmaps or visions.
- **Local air quality:** Many studies cited reductions in local air pollution as a significant benefit of a transition to a hydrogen economy, though only regionally focused studies, such as those from London and California, gave this factor particular emphasis.
- **Competitiveness:** Seven studies refer to international (industrial and economic) competitiveness as an important driver in the transition towards a hydrogen economy."

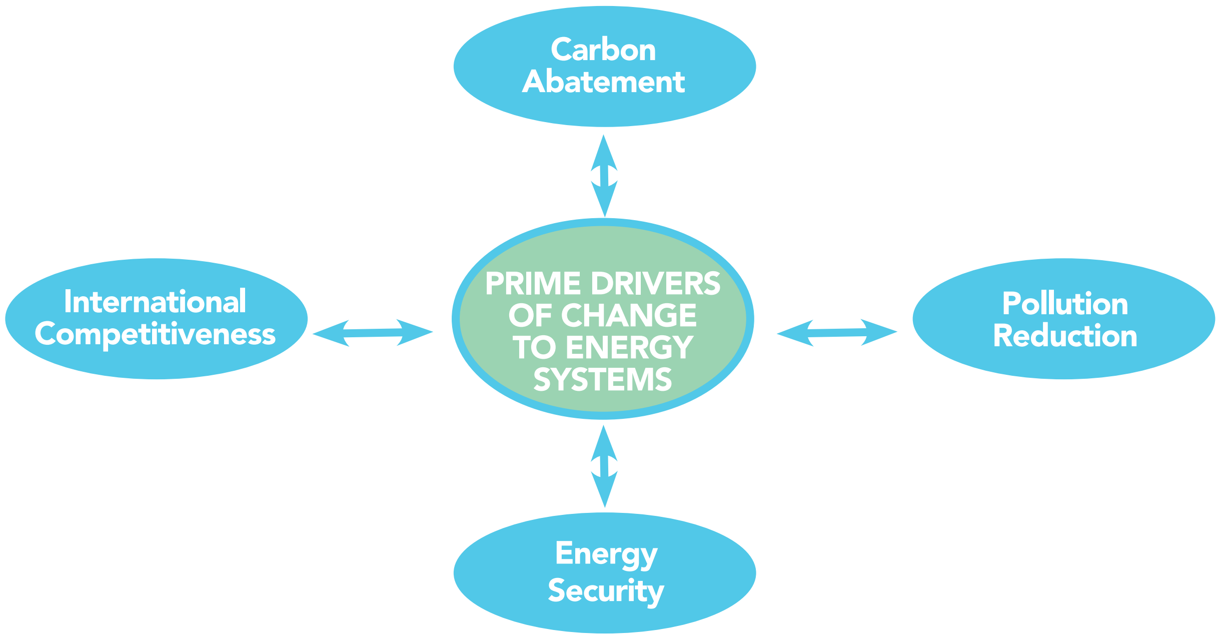


Figure 21: Prime drivers of change to energy systems

92 W. McDowall and M. Eames, *Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature, Energy Policy,* Vol. 34, 1236–1250, 2006

Carbon Abatement

As noted also by Mazza and Hammerschlag[93], arguably the most important criterion in determining future energy pathways is how rapidly, and to what extent, they will decrease global greenhouse gas emissions.

While Australia's total contribution to global GHG emissions is small, Australian governments have recognised that this is not a reason for inaction. Australia is a heavily carbonised economy—our end-use energy needs are satisfied primarily from fossil fuels[94], thereby making us one of the most intense GHG emitters per capita globally.

Choosing to play a constructive role internationally and being credible reflects a value judgement. For this reason, carbon abatement is considered a high need in Australia's energy systems so that a constructive role can be played in contributing to global efforts to reduce the impacts of climate change—as one stakeholder observed: "to be credible internationally (Australia needs) to do much more than our energy consumption relative to the world might suggest".

Recent important examples of Australian Government responses to this imperative are its commitments to: ratification of the Kyoto protocol; the introduction of a trading scheme in 2010 that will price carbon emissions; and the introduction of a National Renewable Energy Target for renewable electricity production.[95] Overall, as another stakeholder noted: "the national policy environment is evolving in a manner that is favourable for the development of clean energy technologies".

Pollution Reduction

Unlike many other regions and cities in the world, Australia is blessed in a relative sense with clean air in our cities and regions. However, that does not mean that Australia authorities should not take action to improve indoor and outdoor air quality. Local reduction of health-impairing pollutants such as diesel particulates, volatile organic compounds and smog-inducing chemicals (nitrous oxides) is important.

Pollution reduction remains, however, a low need in Australia compared to other localities internationally where the health benefits to be gained are relatively much greater.

Energy Security

Australia is a resource rich country with significant resources of coal, uranium and natural gas. It is one of the few OECD countries that is a significant net energy exporter. Since 1986, Australia has been the world's largest exporter of coal, and since 1989 has emerged as one of the largest exporters of liquefied natural gas (LNG) and uranium.[96] Australia is overwhelmingly a net energy exporter, with trade in energy dominated by coal, LNG and uranium. However, Australia is a net importer of liquid fuels, including crude oil and other refinery feedstocks and refined petroleum products, particularly diesel and gasoline.

Australia can be considered to have a low vulnerability in regard to energy security (i.e. Interruption to supply) due to our plentiful indigenous supplies of fossil and renewable energy sources. Our one area of current high energy security vulnerability is the liquid fuels that Australia imports, the loss or continuing rapidly-rising cost of which would cause severe disruption to key sectors including mining, agriculture and heavy-duty vehicle transport.

International Competitiveness

Fossil fuel energy exports are major contributors to Australia's economy, as is the competitive advantage Australia derives from its low-cost, indigenous, coal resources that are utilised

93 P. Mazza and R Hammerschlag, *Carrying the Energy Future: Comparing Hydrogen and Electricity for Transmission, Storage and Transportation*, Institute for Lifecycle Environmental Assessment, June 2004 (available at **http://www.ilea.org/downloads/MazzaHammerschlag.pdf**).

94 In the case of electricity, about 85 per cent is generated from coal. Transportation and mobile machinery rely almost entirely on hydrocarbon fuels.

95 **http://www.gg.gov.au/governorgeneral/speech.php?id=377**, last accessed 06 March 2008.

96 Australian Bureau of Agricultural and Resource Economics (ABARE), Energy in Australia 2006, published March 2007.

particularly for electricity generation. In a world economy in which the externalities of GHG emissions, particularly carbon dioxide, are internalised into energy prices Australia's international competitiveness may be threatened. Energy exports, particularly black coal, may be curtailed over the longer-term if customers move to alternate, lower GHG emission energy sources or carriers. Australia's manufacturing competitiveness, particularly for energy intensive processes such as metals production, also may decline over time if competitor countries can provide lower cost, low-emission energy supply. Australia also faces a growing liquid fuel import bill as demand for diesel and gasoline increases and as Australia's reserves of crude oil continue to run down.[97, 98]

In another aspect of competitiveness, the industrialisation and market penetration of new energy technologies also can drive change in energy systems as they displace less-competitive energy supply, delivery and use technologies. Reciprocally, as energy systems change then this market pull acts as a stimulus to develop and commercialise new, more competitive energy technologies.

Technological innovation is considered as a major driving force in long-term economic growth[99] and Australia should seek to capitalise on technology innovations that drive, or are driven by, change in energy systems, noting that pricing of GHG emissions is beneficial to these new technologies in that their price gap relative to incumbent, high-emission energy supplies is reduced. International competitiveness in new energy technologies, and particularly Australian industry competitiveness and participation in global and local energy supply chains, are important for the economic and social (particularly job creation) benefits that come from them.

International economic and industrial competitiveness therefore is considered to be a high need in Australia's energy systems.

4.2 The need for hydrogen and fuel cells in Australia

As noted in Section 1.2, roadmapping should be a needs-driven process and in the previous section the following needs related to Australia's energy systems were determined:

Carbon abatement—HIGH

Pollution reduction—LOW

Energy security—LOW, except in transport fuels where it is HIGH

International competitiveness—HIGH

The question now is what contribution hydrogen as an energy carrier and fuel cells as an energy conversion device could make to each of these needs, focusing particularly on their contributions in Australia to carbon abatement and international competitiveness.

4.2.1 Transport energy applications

Contribution to carbon abatement

The transport sector in Australia in 2005 contributed 80.4 Mt[100] of CO_2-e emissions, some 15.4 per cent of the estimated total net emissions in Australia in that year of 522 Mt. Road transport activities comprised the vast majority (70.7 Mt or 88 per cent) of the transport sector's emissions. The sub-sector contributions to the road transport total are: passenger cars 43.7 Mt, light commercial vehicles 11.3 Mt and heavy duty trucks and buses 15.7 Mt. It also is instructive to note that road transport contributes some 60 per cent of the emissions of nitrous oxide in Australia—a contributor to local atmospheric pollution concerns (smog) in our large cities.

The discussion in Section 2.3.2 and the references cited in that Section show that hydrogen as a fuel and fuel cell powered drive-trains for vehicles are only two of a number of options to achieve significant carbon abatement in the transport

97 *Queensland's Vulnerability to Rising Oil Prices*, Taskforce Report, April 2007 (available at **http://www.epa.qld.gov.au/publications/p02190aa.pdf/Queenslands_vulnerability_to_rising_oil_prices__taskforce_report.pdf**)

98 *Australia's future oil supply and alternative transport fuels - Final report,* The Senate Standing Committee on Rural and Regional Affairs and Transport, February 2007 (available at **http://www.aph.gov.au/Senate/committee/rrat_ctte/oil_supply/report/report.pdf**).

99 N Rosenberg, *Innovation and Economic Growth*, OECD 2004 (available at http://www.oecd.org/dataoecd/55/49/34267902.pdf, last accessed 28 march 2008).

100 Australia's National Greenhouse Accounts, *National Inventory Report 2005—Volume 1*, The Australian Government Submission to the UN Framework Convention on Climate Change, April 2007.

sector. Efficiency improvements via a range of techniques including smaller, lighter vehicles; efficiency improvements in conventional engines; and, particularly, hybridisation of drive-trains can deliver significant, on-the-road fuel consumption reductions and GHG emissions abatement.

It is important to note the growing trend to electric drive-trains—the plug-in hybrid, the fuel-cell and the electric vehicle[101], particularly in passenger cars. As Kromer and Heywood note[102]

> "Electric powertrains offer the opportunity to achieve a step-change reduction in petroleum use and GHG emissions in the United States light-duty fleet. However, it will be several decades before these technologies can penetrate the in-use fleet and are likely to come at a higher cost than conventional technologies. In addition, these technologies cannot meet long-term petroleum or GHG reduction targets by themselves. They must be deployed in combination with other aggressive measures such as improved conventional technology, development of low carbon fuels and fuel production pathways, and demand-side reductions. … There is a temptation to assume that deploying new powertrains with low in-use emissions will solve the GHG problem on their own, but the reality is that developing clean fuel pathways will require extensive technological and infrastructure development in their own right."

Hydrogen-fuelled FCVs or FCHVs for passenger cars, light commercial vehicles or buses therefore are not needed to deliver significant carbon abatement and reduction in petroleum use in the Australian transport sector—but they clearly are an option that needs to be well understood. Further, whichever combination of energy carriers among electricity, hydrogen and bio-fuels prevails in the long-term it is imperative that they be sourced from clean fuel pathways otherwise well-to-wheel carbon abatement will be minimal, at best. A concomitant challenge will be development of low-cost clean energy carriers to minimise economic impacts on vehicle owners and operators.

Therefore opportunities exist for Australia to develop and commercialise innovative, low-cost, clean and/or green hydrogen production technologies focused on Australia's abundantly-available, primary fossil and renewable energy resources, noting that any such use of fossil fuels implies the capture and storage of the co-produced CO_2.

Contribution to international competitiveness

Australia has three overseas-owned auto manufacturers making passenger vehicles here: General Motors Holden, Ford and Toyota. Each of these companies:

- is integrated into its parent company's global operations, with the output of the local vehicle plants supplying into the Australian and export markets;
- has local vehicle design and development capacity and capability; and
- is a significant employer directly and supports employment in many local supplier companies.

However, a reality of the Australian passenger vehicle market is that almost 80 per cent of the approximately 1 million new vehicles sold annually are imported. It also is clear that the Australian operations of these auto manufacturers are small by global standards. It is not unreasonable, therefore, to conclude that:

- If there is a shift by global auto manufacturers to hydrogen-fuelled FCVs or FCHVs then Australian consumers—who often are cited as early adopters of new technologies—will represent a demand for them that may be met via imports rather than local manufacture.
- The small scale of local operations; the large capital requirements to build new drive-train and vehicle assembly plants; and the yet-unresolved debate as to which drive-train

101 *Time's up for petrol cars*, says GM chief, The Age, 15 January 2008 (http://www.theage.com.au/news/technology/times-up-for-petrol-cars-says-gm-chief/2008/01/14/1200159401944.html).

102 M. A. Kromer and J. B. Heywood, *Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet*, Sloan Automotive Laboratory, Laboratory for Energy and the Environment, Massachusetts Institute of Technology, Publication No. LFEE 2007-02 RP, May 2007

platform(s) will prevail (HEV, PHEV, FCV, BEV or all of them) may mean that over time the current Australian drive-train manufacturing operations will close and they may not be replaced.

Even if next-generation drive-train manufacturing is not undertaken in Australia, they can be imported to enable local vehicle assembly to continue. Nonetheless, there could be opportunities for Australia to participate competitively in the global supply chain for, for example:

- Electric drive-trains (e.g. adaptation of the CSIRO/University of Technology Sydney developed high-efficiency, light-weight electric motor drives for solar cars[103]), whether or not hydrogen-fuelled FC engines prevail in the long-term.
- On-board storage for hydrogen.

Other considerations

In common with all other jurisdictions that are evaluating hydrogen as an energy carrier for the transport task in their country or region, Australia faces the 'chicken and egg' problem with regard to establishing a hydrogen fuelling infrastructure. That is, a hydrogen fuelling infrastructure is not a simple add-on to the current liquid fuel supply systems—to establish such a radically-different production, transport and delivery system is a major expense.

As a petroleum company interviewee commented, his company

> "follows the car companies, so if they change to hydrogen then the oil and gas companies will follow. However, his company sees the future as multi-fuel because the auto companies will go to multi-fuel drive trains, including electric vehicles. The other side of this is that if the car companies know that there will not be a fuelling infrastructure then they will not produce a drive-train for that fuel".

To overcome this 'chicken and egg' problem, a number of national and state governments are co-investing with private sector companies in the establishment of hydrogen highways—a chain of hydrogen-equipped filling stations and other infrastructure along a road or highway which allow hydrogen-fuelled cars to travel. British Columbia[104], California[105], Japan[106] and Norway[107] have, or are installing, hydrogen highways on particular driving routes.

4.2.2 Stationary energy applications

Contribution to carbon abatement

The stationary energy sector in Australia in 2005 contributed 279.4 Mt of CO_2-e emissions, some 53.5 per cent of the estimated total net emissions in Australia in that year of 522 Mt.[108] Within the stationary energy sector, emissions from electricity production dominate (194.3 Mt or approximately 37 per cent of total annual emissions for Australia in 2005), with other energy industries emitting approximately 20 Mt and the direct emissions from combustion in the manufacturing and construction sector reaching 43.7 Mt.

The contribution of hydrogen and fuel cells to carbon abatement in Australia's stationary energy sector, and particularly electricity generation, could be considerable.

- A move to gasification of coal and subsequent combustion of the produced hydrogen in gas turbines via integrated gasification combined cycle (IGCC) technology, with pre-combustion capture of CO_2 and assuming its successful, long-term sequestration, is one approach to delivering dramatic reductions in GHG emissions for large-scale electricity production.[109]
  - IGCC also gives the option for polygeneration, i.e. production of electricity and hydrogen, the latter available for chemical/industrial processes or merchant use as a fuel.
  - Utilisation of biomass, alone or co-fed with black or brown coal, in an IGCC process would lead to capture and sequestration of atmospheric CO_2.[110]

103 *The 'CSIRO advantage' increases motor efficiency, Manufacturers'* Monthly, 19 October 2007 (available at **http://www.manmonthly.com.au/articles/The-CSIRO-advantage-increases-motor-efficiency_z77380.htm**).

104 **http://www.hydrogenhighway.ca/code/navigate.asp?Id=265**, last accessed 28 March 2008.

105 **http://www.hydrogenhighway.ca/code/navigate.asp?Id=265**, last accessed 25 March 2008.

106 **http://www.jhfc.jp/e/station/index.html**, last accessed 25 March 2008

107 **http://www.hynor.no/english**, last accessed 25 March 2008.

108 Australia's National Greenhouse Accounts, *National Inventory Report 2005 Volume 1*, The Australian Government Submission to the UN Framework Convention on Climate Change, April 2007.

109 **http://www.ccsd.biz/factsheets/igcc.cfm**, last accessed 16 January 2008.

110 J. Rhodes and D. Keith, *Engineering economic analysis of biomass IGCC with carbon capture and storage*, Biomass and Bioenergy, Vol. 29, pp440–450, 2005.

– A longer-term option is to utilise large-scale, high temperature fuel cells (e.g. MCFC or SOFC) with a gas turbine (an integrated gasification fuel cell or IGFC system) to deliver even higher electrical generation efficiency.[111]

- Integrating a storage mechanism into intermittent renewable (e.g. solar, wind, wave) electricity supply systems will increase their supply capacity into electricity markets. While there are a number of battery options under development for this task, an alternate storage approach is to generate hydrogen on-site that is subsequently utilised in a stationary fuel cell system.
  – This combination is already utilised commercially in some high-value applications such as remote telecommunications installations.
- As discussed in Section 2.2.4 of this roadmap, stationary fuel cell systems ranging in capacity from 1 kW to over 1 MW are commercially available or in pre-commercial demonstration.
  – Applications include high-reliability, on-site power generation and combined heat and power (CHP), the total fuel conversion efficiency (power + heat) of the latter achieving or exceeding 80 per cent, with correspondingly low CO_2 emissions.
  – Such distributed generation applications of fuel cells can be significantly more efficient than electricity supply from conventional centralised generation + grid systems.

An increasing 'hydrogenation' of Australia's electricity supply system by these various means could contribute to significant carbon abatement—although it is recognised that such 'hydrogenation' will occur only slowly in Australia as existing generation assets are retired over the next 10 to 40 years.

Nonetheless, there are commercial and development opportunities for Australia to accelerate deployment of, particularly, distributed generation and CHP applications of fuel cell systems utilising natural gas fuel as well as coal-based IGCC power generation with CCS.

Contribution to international competitiveness

Australia's low electricity costs have been, and remain, a competitive advantage in a global context. As discussed earlier (Section 4.1), in a world economy in which the externalities of GHG emissions, particularly carbon dioxide, are internalised into energy prices our energy exports, particularly black coal, may be curtailed over the longer-term if our customers move to alternate, lower GHG emission electricity generation.

Our manufacturing competitiveness, particularly for energy intensive processes, also may decline over time if our competitors are better able to provide lower cost, low-emission electricity supply.

In both cases it is important economically and socially that Australia maintains its international competitiveness in energy exports and electricity costs as a key cost in our industrial, commercial and residential sectors. For large-scale power generation the cost of CO_2 capture and the efficiency and long-term effectiveness of very large-scale CO_2 sequestration are key determinants for the continued use of fossil fuels.

Therefore opportunities for Australia include:

- Development, demonstration and commercialisation of low-cost CO_2 capture and CO_2 sequestration, which are required as key enabling technologies for clean, large-scale hydrogen production from fossil fuels (as well as their use for electricity generation by other means).
- Participation in the global supply chains for stationary fuel cell systems, components and/or technologies.

4.2.3 Portable energy applications

The opportunity for fuel cells in portable energy applications is, as discussed in Section 2.2.2, to replace batteries. Both methanol and hydrogen-fuelled micro-FCs are being developed and trialled for these applications ranging in power output from 1 W to around 500 W.

111 *GE Wins Fed Contract For Fuel Cell-Gas Turbine System*, 17 August 2005 at **http://www.extremetech.com/article2/0,1697,1849269,00.asp**, last accessed 16 January 2008.

Contribution to carbon abatement

The opportunity for carbon abatement is to displace the electricity used to charge batteries in portable equipment. However, this is only a very small proportion of electricity use and thus the abatement potential from displacing electricity in these applications is minor. Further, the methanol or hydrogen used for the micro-FCs will need to be sourced from clean or green production facilities if the abatement is to occur, as discussed earlier.

Contribution to international competitiveness

Australia is not a manufacturing location for portable equipment such as mobile phones, personal digital assistants, laptop computers and portable tools or for the batteries that they utilise.

Nonetheless, there could be opportunities for relevant Australian-developed technology to participate competitively in the global supply chains for micro-FC systems, components and/or technologies—an example being the CSIRO-developed technology discussed in Section 3.1.2 of this roadmap.

4.2.4 Stakeholders' views

In the workshops held in Melbourne, Brisbane and Perth; the one-on-one interviews; and in responses to the Discussion Paper, stakeholder views were obtained on the need generally, and specifically in Australia, for hydrogen and fuel cells. A summary of the key points stakeholders made is provided over.

Hydrogen—generally

- There's no "golden bullet" to solve the world's energy problems—a sustainable mix of energy vectors is required.
- It is universal in its end-uses and this universality is attractive—however, options need to be kept open for different vectors.
- Fossil fuels, such as oil and natural gas, will eventually run out and hydrogen could replace these.
- Hydrogen provides solutions to fill gaps that exist today—therefore hydrogen is part of the solution set.
- Hydrogen is historically the end point of wood-peat-coal-oil-gas—history is pushing us towards hydrogen and there is a need in response to climate change. Again, this implies clean production of hydrogen.
- There are near-term applications cited to be available now that include industrial gas, mining sector, indoor air pollution reduction, RAPS; cost savings through on-site production plus workplace environment benefits; conversion of diesel to dual fuel of diesel/hythane (approximately 10 per cent diesel and 90 per cent hythane) provides a cost benefit by using low grade purity hydrogen as well as providing greenhouse gas abatement.

Hydrogen—for Australia

- Hydrogen distributed power is advantageous to Australia because of our unique situation of having a population spread over a large land mass. Hydrogen is especially appropriate for small isolated towns where shipping is difficult but on-site production of hydrogen is practical.
- Remote locations can use renewables, but they still need reliable back-up for permanent power and hydrogen solves those problems as it may be stored—it fills a niche market.
- Australia has vast quantities of coal and should find a way of using everything it has (with carbon capture and storage).
- If Australia does not do anything it will be a follower—there are niche markets on the supply and use side to exploit. Australia has to be in the game otherwise it will never get into the market.
- Mitigation of risk around climate change is needed in the agriculture and tourism sectors.
- Australia could be a test-bed for technologies in the southern hemisphere, e.g. in remote power—there is local expertise to develop and trial these kinds of technologies.
- Australia's import of oil is increasingly leading to rising energy security concerns and particular transport task challenges. However, hydrogen for transport is more difficult in Australia largely because of Australia's low population density.

- Hydrogen could provide a long-term competitive advantage for Australia, which could become an energy hub for global supply of hydrogen.

Fuel cells—generally

- Advantages for using fuel cells in distributed generation include lower pollution, lower noise and high electrical efficiency.
- In transport, fuel cells are part of efficiency improvement in drive-trains. Life cycle analysis on transport shows that efficiency of the vehicle really matters and fuel cell vehicles have high efficiency over a wide operating regime.
- They have lower pollution levels; use less water (theoretically should produce water); and offer easier CO_2 capture[112].
- Scalability is good and they maintain efficiency across wide range of sizes.
- Some stationary FC systems are ultra reliable, which has become a strong selling point.
- Fuel cells could replace batteries and they have greater reliability and disposability.

Fuel cells—for Australia

- Fuel cells have a place in Australia for large-scale stationary and distributed generation, to cover problems of losses through the electrical transmission and distribution system. This may be driven by a carbon tax.
- Near-term applications for FCs are growing – strong business cases can be made for use in forklifts; domestic CHP; reduction of local pollution in big, industrial cities; back-up power; mining; provision of high-quality ('digital quality') power.
- Fuel cells are inevitable because the United States, Europe and Japan are investing in them, whether Australia jumps on board or not.

4.3 Key barriers and challenges for hydrogen and fuel cells

McDowall and Eames' review of the hydrogen futures literature[113] draws out the key barriers and challenges for hydrogen and fuel cells, as follows:

"The literature recognises a diverse range of barriers to the development of a hydrogen economy. The three most prominent are:

- The absence of a hydrogen refuelling infrastructure—the difficulty of establishing a market for FCVs in the absence of a refuelling infrastructure—and vice versa.
- High costs: particularly of fuel cells and of low-carbon hydrogen production.
- Technological immaturity: hydrogen on-board storage and consequent limited current driving range of hydrogen vehicles; limited life-time of fuel cells."

"Other frequently cited barriers include safety, public acceptability, and the absence of codes and standards. There are also many barriers that are picked up by only a few studies, including: the absence of surplus renewable electricity; social values that disregard the environment; a regulatory framework that currently supports fossil fuels; ability of incumbent technologies to adapt in the face of competition from hydrogen; limited skills base; absence of global co-operation or plan of action; limited availability of fuel cell components, particularly platinum; difficulty of technological developers in accessing capital; lack of demand for hydrogen products; and, social opposition, uncertainty over viability and costs of carbon sequestration."

In the workshops held in Melbourne, Brisbane and Perth; the one-on-one interviews; and in response to the Discussion Paper, stakeholder views were obtained on key barriers and challenges for hydrogen and fuel cells generally and in Australia. A summary of the main points stakeholders made is provided following.

112 Although it is noted that such capture and transport to storage is easier said than done on a small scale as would be the case in DG.

113 W. McDowall and M. Eames, *Forecasts, scenarios, visions, backcasts and roadmaps to the hydrogen economy: A review of the hydrogen futures literature*, Energy Policy, Vol. 34, 1236–1250, 2006.

- **Regulatory:**
  - Hydrogen is regarded as an industrial gas in Australia and has to meet industrial regulations that are now archaic. The cost of current regulatory compliance can be very high—companies and their customers have to pay for this compliance.
  - The National Electricity Market (NEM) does not cater for distributed generation within grids.
  - Overseas, but not in Australia, certification is needed only once for an organisation, rather than for each product, which helps.
  - Industrial or semi-industrial and consumer markets are different and have different degrees of concern and issues—they should be treated separately in regulations.
  - Small and medium enterprises often represent lone voices for regulatory change to overcome technical issues specific to their needs.
  - There is a lack of consistency in standards around the world.
- **Public:**
  - There is still a public perception that hydrogen is dangerous.
  - Consumer functionality must meet consumers' "taught" expectations.
  - Consumer acceptance—a significant education and awareness issue which, in turn, affects the market timeframe and success of new business models.
- **Cost:**
  - The cost and source of production, compression and distribution of hydrogen are issues—clean and cheap hydrogen production is a challenge.
  - There are high costs associated with establishing fuelling infrastructure and demonstrations and hydrogen infrastructure costs are higher per driver/car in Australia than overseas.
  - The significant pre-investment costs for preparation for a hydrogen economy.
  - Fuel cells now have a path to cost-effectiveness and have matured to the point of market-entry. Many technical challenges have been overcome over the last 5 years, and FC developers and suppliers now are more focussed on the challenges of infrastructure (distribution and transportation), feedstock, etc.
- **Technical**:
  - Hydrogen infrastructure is lagging behind, for example, storage.
  - Storage has the biggest group of technical challenges.
  - Challenges of coupling intermittent renewable to hydrogen production.
- **Market-entry:**
  - There are substitute products in the market place in transportation, like hybrid cars, so hydrogen will have to overcome these competitor products, and go some way beyond, in order to compete.
  - There is an issue about getting to the stage where production has a significant volume, such as 200,000 systems per year, where it may be competitive. Incentives are needed to bridge that market gap from 100 to 200,000 units.
  - High-value niche markets do not usually provide opportunities for low-cost production.
  - Mindsets among people in the utilities industries are very conservative.
  - From a developer's point of view Australia and New Zealand are small economies.
  - There is minimal awareness across government, industry and community.
  - For fuel cells, overseas suppliers may not be interested—Australia is too far away and has 'cheap' energy.
  - Vested interests in existing infrastructure and the issue of stranded assets.
- **Policy and programs**
  - Fuel cells are rarely discussed or presented as an option to meet emission targets. They should be considered and written into policy documents.
  - In Korea, Germany and the USA there have been research and development programs to back up development—Australia does not have similar policies.

4.4 Australia as a 'taker' or 'maker'

Given these barriers and challenges, the current context for hydrogen and fuel cells in Australia and the high levels of activity in them overseas, stakeholders also were posed the question "should Australia be a 'taker' or 'maker' in hydrogen and/or fuel cell technology?" A summary of their responses is provided below.

- Australia may be a taker largely because of the size of our industry sectors but Australia can influence manufacturers and contribute to stimulating demand, as well as developing regulations, codes and standards.
- Australia is a small and remote market, so being a maker is more difficult because we lack the capacity for scale. However, an advantage is the ability to address our specific circumstances so there could be solutions and niche markets in the supply chain for application-specific systems.
- Australia's remoteness has some benefits, often forcing more innovative system solutions.
- Australia has expertise and technology in metallurgy, nanotechnology, biotechnology and other areas that are being utilised in world-recognised hydrogen storage and biofuels R&D areas, but does Australia have the critical mass required to enable it to be a maker?
- A critical issue for 'making' is the availability of venture capital in Australia. There are problems in the risk profile mentality, expertise breadth and depth of VCs here, although investment in the cleantech space is growing in Australia.
- Australia can contribute to collaborative programs with overseas groups and bring the technology back to Australia where it can be exploited.
- Australia has niche innovations in hydrogen and fuel cells, but technology developed in Australia tends to go overseas.
- Australia can build off the clean coal and CCS technology investment already happening; Australia is a world leader in solar technologies; and Australia has good capability in gas handling (compression, transport and processing) and management in quantity and scale.
- If Australia wants to be a maker it needs the ability and money to take technologies to the stage of large scale demonstration—lots of little groups doing good work do not make an industry.

In summary, stakeholders felt that Australia primarily will be a taker of hydrogen and fuel cell technologies from overseas suppliers given our relative economic scale and industry structure, but they also strongly felt that:

- To be a competent 'taker' there must be local, independent, technical capability and capacity to evaluate the hydrogen and fuel cell technologies that are needed; and
- Australia has opportunities to be a 'maker' in specific hydrogen, fuel cell or enabling technologies—notwithstanding the challenges in Australia, as in other countries, to successful local development and commercialisation.

4.5 SWOT analysis

Stakeholders were asked to provide their views on the Strengths and Weaknesses (i.e. the internal landscape) of Australia, and the Opportunities and Threats (i.e. the external landscape) facing Australia, in hydrogen and fuel cells (separately).

Consolidated SWOT analyses for hydrogen and for fuel cells are presented in the following sections.

4.5.1 Hydrogen

Strengths

- Australia has natural gas, coal and uranium, as well as renewable energy resources and technology, for large-scale hydrogen production.
- Public support for clean energy to decrease GHG emissions.
- Australia has experience in rolling out a new fuelling infrastructure—LPG.
- Australia has a strong capability and track record to do hydrogen research—pockets of excellence distributed across Australia.
  - Australia has niche problems to build on and solving them can build credibility.
  - Australian researchers are well respected in international and national networks.
  - There is a critical mass in gas liquefaction and gas technology in WA.
  - The NHMA as a researchers' network.
- Australians in senior positions in foreign companies who advocate for Australian technology and knowledge.
- Wealthy economy with clever people who have a diverse range of skills.
- Australians' willingness to be early adopters—Australia is a great test site.
  - Hydrogen bus trials in Perth.
  - Australian bus, locomotive and long haul sector industries to leverage.

Weaknesses

- Lack of strategic government investment and (consistent) policy making in the area.
- Regulatory structure in Australia is costly and not designed for hydrogen as a fuel.
- Lack of public and private investment in R&D.
  - Australia does not lack expertise but it does lack scale, and that takes money.
  - Australia cannot take up large R&D projects.
- Industry structure in Australia is mostly headquartered overseas and the local base is shallow.
- No hydrogen champions in the right places—political, industrial and financial sectors.
- Our fossil fuel endowment—there is a heavy investment in coal (which could get stranded).
- Small market in Australia means it's hard to grow volume production.
- Historically Australia is not as good at commercialisation as at R&D.
  - There is a lack of commercialisation expertise in Australia and an immature early-stage financing sector.
- Australia has a small hydrogen technology industry sector compared to Canada (and other countries).
- The lack of a focused industry body for the sector.

Opportunities

- Diversity of production sources for hydrogen.
  - Production of hydrogen from solar, biomass, geothermal and other renewable resources.
  - Clean hydrogen from fossil fuel with CCS.
- Create a hydrogen industry.
  - Hydrogen production industry could offset any potential future loss of market for coal—build on LNG export experience and capacity.
  - Australia can export products, technology, knowledge and R&D services.
- Hosting of demonstration trials and raising public awareness.
- Climate change results in attitudinal change generally and a changing political climate.
  - Leverage on industry's need to change to deal with GHG issues.
- Increasing cost of oil and it remains high.
- Solving the cheap hydrogen storage challenge.
- Reducing cost of liquid hydrogen through improved liquefaction and storage.

Threats

- Competitive technologies in incumbent and emerging areas that are or may be lower cost.
  - People do not know which fuel to back so a 'wait and see' approach is adopted.
- Accidents / safety concerns.
- Regulatory approvals processes cost time and money. Regulations do not change quickly enough and non-global standards create market barriers.
- Cost of hydrogen infrastructure establishment.
  - Australia has existing, and expanding, grids for electricity and natural gas, but no infrastructure for hydrogen.
- Climate change does not become visible and Australian consumers' attitudes do not change.
- Trapped capital leads to inertia to change by industry.
- If sequestration does not work, IGCC and clean hydrogen from fossil fuels are not available.
- Absence of political will to put market drivers in place e.g. GHG emissions are not priced highly enough.
- Financiers do not understand hydrogen and are reluctant to invest.

4.5.2 Fuel cells

Strengths	Weaknesses

• Australia has a good but small skill base in fuel cells research, existing technology and some commercial entities doing business in fuel cells.
  ◦ An ability to evaluate fuel cell technologies from our knowledge base.
  ◦ Experience in hydrogen fuel cell buses.
• There are synergies in Australia with other innovations (e.g. Solar Cities) and codes and standards are starting to be developed.
• Alternate energy companies are well established in Australia and specifically interested in distributed generation.
• Australia has some very large companies that could invest and have interest in fuel cells, such as mining and telecommunication companies.
• Australia has specialty minerals (rare earths) for more efficient and cheaper catalysts.
• Australians have a culture of early adoption.
	• Australia has a thin veneer of experts in fuel cells—there is no depth of capability here.
	• Australia is well behind in fuel cells relative to other countries.
	• Australia has a lack of policy drivers, so there is slower development of markets here.
	• Australian regulatory, planning and investment frameworks are not designed for DG.
	• Local fuel cell companies are small and vulnerable.
	  ◦ Lack of large companies to support long-term development opportunities.
	• Lack of manufacturing capability and presence in fuel cells, balance of plant components and system integration—an immature supply chain, including hydrogen supply.
	• Lack of education focus on, and political knowledge of, fuel cells.
	• No effective, united industry/lobby group.

Opportunities	**Threats**

• With pricing of carbon, higher efficiency (of fuel cells) is important.
• Conventional fuel prices keep rising and stay high.
• Utilise early adopters to drive demand and awareness.
  ◦ Remote DG (especially with renewables); high reliability power (banks, data services, hospitals, telecommunications and emergency services).
  ◦ The electricity grid is an available network and utilities are becoming more open to DG solutions e.g. supply for areas with low power quality and reliability issues.
  ◦ Early adoption in fleet vehicles; heavy duty transport applications (e.g. buses); underground mining vehicles; materials handling (forklifts in confined spaces), etc using centralised (hydrogen) refuelling.
  ◦ Use of "opportunity" fuels, e.g. bio-methane, coal seam methane and ethanol.
  ◦ Co-generation (particularly high temperature fuel cells) for heating and cooling.
  ◦ With lots of construction and expansion underway in Australia it is a good time to introduce stationary fuel cells.
• Fuel cells become a large scale, global business providing supply chain opportunities.
  ◦ Opportunities for integration of fuel cells into existing products and for development of new fuel cells system components.
	• The incumbent energy systems work well and Australia has inexpensive energy, so energy security is not a key driver here.
	  ◦ Cost of carbon stays too low to provide sufficient market pull for fuel cells.
	  ◦ Gas to liquids comes on and obviates need for any infrastructure change.
	• Currently no direct linkage between hydrogen/fuel cells and Australia's upcoming Emissions Trading Scheme or the National Renewable Energy Target.
	• Existing Australian fuel cell companies go offshore and the expertise base is lost.
	• The cost of (high purity) hydrogen remains high and supply is unreliable.
	  ◦ If CO_2 sequestration does not work the price of hydrogen may be even higher.
	• Lack of consumer knowledge and acceptance.
	  ◦ Media attention in Australia is primarily focussed on fuel cell vehicles rather than stationary or portable applications.
	• Improvements in other technologies make them more attractive e.g. battery technologies and new, more-efficient ICEs.
	• Cost of fuel cells is too expensive for them to be adopted on a wide scale.
	• Availability of key fuel cells and balance-of-plant materials (e.g. platinum).
	• New battery technology makes battery electric and plug-in hybrid vehicles more attractive.
	• Hydrogen storage challenge is not solved.

5 CONCLUSIONS

This hydrogen roadmap has two overarching objectives:

- To assess in what areas of hydrogen technology Australia currently has research capabilities and strengths compared to research overseas; and
- To identify what actions Australia should take to prepare for the possible emergence of a hydrogen economy, and the economic case for each of these options.

With these objectives in mind and based on the information and analyses in earlier Sections of this roadmap, the following key findings are drawn.

Hydrogen and fuel cell market growth

The public and private sector investment in hydrogen and fuel cell research, development and demonstration (RD&D) is still well in excess of any returns from sales of commercial or near-commercial products. In this respect, hydrogen and fuel cells are no different to other clean energy technologies such as wind turbines or photovoltaics that took a long time to reach industry-sector profitability. Indeed, most energy technologies will take some 10 to 20 years to move from discovery in a laboratory through to widespread market acceptance.

While many market predictions have been overly optimistic, it appears that the long-term and substantial public and private sector investments in Europe, Japan and the USA in hydrogen and fuel cell RD&D over the last decade are beginning to generate opportunities. Stationary, transport and portable fuel cell products are entering niche (but nonetheless potentially large) commercial markets and meeting customer requirements for product lifetimes and total cost of ownership (TCO) hurdles. Meanwhile investment in hydrogen fuelling infrastructure is growing in the USA (particularly California), Europe, China, Korea and Japan if only, at this stage, to ensure large-scale demonstration trials of hydrogen-fuelled vehicles can be supported.

There are competitive energy carriers to hydrogen (i.e. electricity and liquid fuels) and energy converters to fuel cells (e.g. internal combustion engines and gas turbines)—and governments and industry are investing heavily in all of them to position their economies for a clean energy future and to reap the social, industrial and economic returns from that positioning. As one stakeholder commented, there's no 'golden bullet' to solve the world's energy problems—a sustainable mix of energy vectors is required. However, it is likely that a number of advanced economies overseas will develop significant industry sectors based on one or both of hydrogen and fuel cells.

Positioning Australia in hydrogen and fuel cells

With the imminent introduction of an emissions-trading scheme in Australia, fuel-cell stationary power systems for distributed generation applications may become a technology-of-choice in Australia's residential and commercial sectors. Demonstration projects for production and captive use of hydrogen in large-scale IGCC power generation likely will proceed—albeit in the absence of carbon capture and storage at least initially. Deployment of IGCC for large-scale electricity generation together with wide-spread use of fuel cell DG systems will lead to an increasing 'hydrogenation' of Australia's electricity generation. There also appear to be prospects for hydrogen and fuel cells in portable energy applications (laptop computers, video cameras, mobile phones) and some near-term commercial transport energy applications (e.g. forklifts and buses).

Large sums of money have been, and continue to be invested overseas in hydrogen related RD&D—the International Energy Agency, for example, estimated in 2004 that public and private sector RD&D funding was $1 billion and $3–4 billion per year, respectively. To date Australia has not invested comparably to investigate the opportunities that hydrogen and fuel cells may offer for a clean energy future — hydrogen is currently positioned as a low priority in Australia's energy policy. Other advanced, and developing, countries are investing to prepare their economies and their people for hydrogen and fuel cells as one of the components of a clean energy future. Australia risks significant competitive disadvantage in the global hydrogen and fuel cell markets and industry growth if it is simply left to market forces to prepare for their introduction locally.

Australia will primarily be an importer of hydrogen and fuel cell technologies given our relative economic scale, industry structure and technology developments in these fields. However, there needs to be local, independent technical capability and capacity to evaluate new energy technologies for application in Australia.

Further, Australia has some world-class technology in specific hydrogen, fuel cell and system integration areas, but the ability of Australia to exploit these is compromised by current energy market and innovation system weaknesses.

Overall though, the economic benefits to Australia of early preparation, as proposed in the next chapter of this roadmap, are likely to exceed the costs of implementation because:

- Australia will be able to move earlier and more efficiently to benefit economically and environmentally from deployment of products and services based on fuel cells and/or hydrogen.
  - Carbon abatement is a high need in Australia's future energy pathways to contribute to global efforts to reduce the impacts of climate change; there is a high need to maintain Australia's international competitiveness as a low-cost energy supplier in global markets; and Australia has a high energy security vulnerability in particular, imported liquid fuels, the loss of which would cause severe disruption to the mining, agriculture and freight transport sectors.
- Australian companies and researchers will be better positioned to participate successfully in global supply chains for hydrogen and fuel cell components, systems and technology.
  - There is a high need to grow Australia's international competitiveness and try to ensure our participation in global supply chains for new energy technologies.

The need for hydrogen and fuel cells in Australia

It is clear that there are opportunities for hydrogen and fuel cells to contribute to Australia's carbon abatement and international competitiveness. However it also is clear that, notwithstanding the considerable investment overseas in hydrogen and fuel cell R&D, demonstration and near-term opportunities for commercial deployment, neither hydrogen nor fuel cells are yet 'mainstream' for transport, stationary or portable energy applications—although they could be and may become so in the future.

This strongly suggests that the primary need for Australia regarding hydrogen and fuel cells—at least in the near to medium terms—is to ensure that both are actively maintained as options for a future, low-carbon economy and society. Active maintenance will require:

- Development of a favourable policy framework for clean energy in Australia;
- Knowledge building in consumers, utilities, financiers, industry, regulators and governments about hydrogen and fuel cells;
- Market development efforts to promote the sector and to remove barriers to deployment;
- Development of Australian supply-chains for viable near-term applications and large-scale demonstration programs; and
- Training and competence building in human resources and technology capability and capacity.

Investing in these activities will enable Australian governments, industry, researchers and the broader community to position Australia for the potential emergence of hydrogen and fuel cells as a key component of Australia's energy future.

Ultimately, the choice whether to embrace or reject the move to a 'hydrogen economy' will require compelling underpinning arguments.

> "As the IEA noted in a 2005 review of the prospects for hydrogen and fuel cells … assessing the future of hydrogen and fuel cells without taking into account competing options would result in misleading conclusions. Development risks, uncertainty surrounding each technology and the competing options must be taken into account in setting energy policies and strategies. Picking "winners" at this stage is premature." [114]

The recommendations in this roadmap will enable any ultimate decisions to be well informed ones.

114 International Energy Agency, *Prospects for hydrogen and fuel cells*, Energy Technology Analysis, 2005.

6 A HYDROGEN AND FUEL CELLS ROADMAP FOR AUSTRALIA

6.1 Vision

Drawing from the key conclusions of the previous Section, Australian governments, industry, researchers and the broader community should collaborate and co-invest:

- To prepare technically and socially for possible widespread deployment so that Australia can easily leverage the rest of the world's considerable investments in hydrogen and fuel cells and that our uptake can be earlier, more efficient and lower cost.
- To foster local industry development opportunities as they arise in order to extract significant economic and industrial value from participation in the global supply chains for stationary, transport and portable energy applications that utilise hydrogen and/or fuel cells.

The vision for hydrogen and fuel cells in Australia therefore is:

By 2020, Australia is effectively exploiting emerging hydrogen and fuel cell market and supply-chain opportunities, locally and globally

6.2 Recommended strategies

Building off stakeholder input, ten inter-related strategies are proposed to achieve this roadmap vision, as depicted over and described below.

- **Policy Framework**
  - Australian government expedite market support mechanisms including the implementation of a national GHG emissions trading scheme and a national renewable energy target scheme to support deployment of clean energy carriers and high-efficiency distributed generation.
  - Australian governments invest in options analysis modelling to enable ongoing determination of the costs and benefits of hydrogen and fuel cells within Australia's economic, industrial, environmental, social and geographic contexts. This should take into account competing technologies and be kept up to date as circumstances change.
- **Knowledge Building**
  - Australian industry, researchers and government are active in international forums related to hydrogen and fuel cells to learn from and to contribute to global knowledge networks.
  - Industry, government (including regulators) and public education and outreach activities should be strengthened and expanded, building from credible international and national hydrogen and fuel cell data and activities.

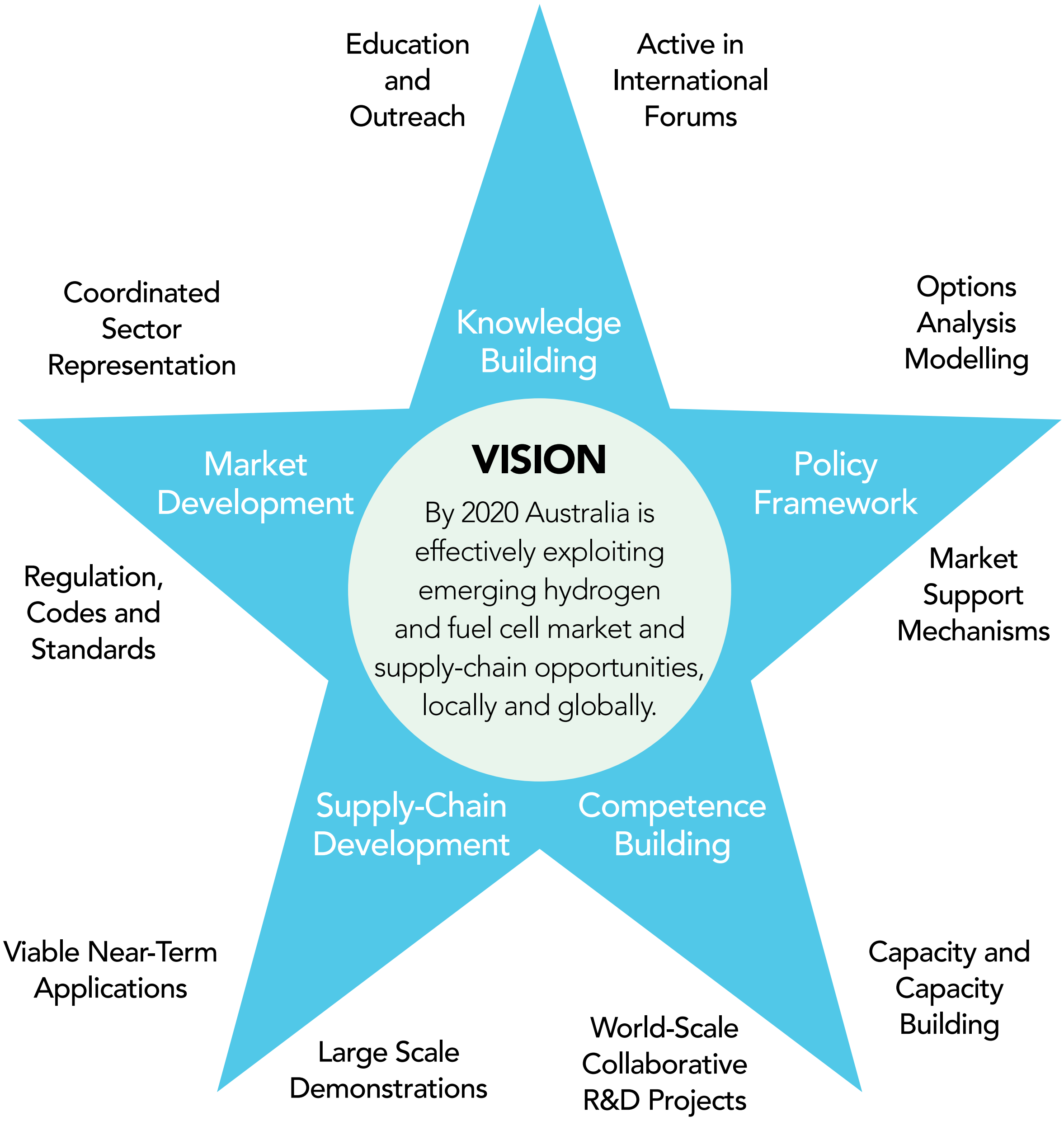


Figure 22 Proposed strategies toward the vision for hydrogen and fuel cells in Australia

- **Market Development**
  - Establish an appropriately-funded and well-managed, industry-led national body for coordinated sector representation and promotion of the interests of hydrogen and fuel cell-related industry and professionals.
  - Building off best-practice international activities and models, develop uniform regulations, codes and standards in Australia that enable timely and safe deployment of hydrogen and fuel cells in stationary, portable and transport energy applications.
- **Supply-Chain Development**
  - Australian companies identify and supply products, components and/or technology into viable near-term applications of fuel cells and/or hydrogen in stationary, portable and transport energy applications.
  - Australian industry and governments jointly invest in internationally-linked, large scale demonstrations in Australia of fuel cells and/or hydrogen in stationary and transport energy applications that will be economically viable in the near to medium term.
- **Competence Building**
  - Support world-class R&D in hydrogen and fuel cell areas, specifically encouraging world-scale collaborative R&D projects that build on technology strengths in Australia that are being, or could be, applied to commercially-important technical problems in hydrogen or fuel cells.
  - Educators, industry and governments actively support the capacity and capability building in Australia necessary to supply the skilled personnel needs of Australian industry and research organisations in key fields of importance to hydrogen and fuel cell technology development and commercial exploitation.

6.3 Options for key activities

Building on stakeholder input and the analysis in previous sections of this roadmap, options for key activities against each of these strategies are recommended. It is emphasised that these activities form a basis for consideration by government, industry and research stakeholders to commence implementation of this roadmap.

- **Market support mechanisms**
  - Ensure that the introduction of Australia's national emissions trading scheme does not inadvertently create barriers for fuel cells or hydrogen.
    - It will be important through systems analysis to gain a thorough understanding of the GHG benefits of fuel cells and hydrogen in different stationary and transport applications because these benefits will be an important consideration under the emissions trading scheme.
  - Devise and implement policy mechanisms that will promote deployment in Australia of high efficiency distributed generation systems[115], particularly for combined heat and power applications. Examples of such policy mechanisms that might be considered include, but are not limited to:
    - Enabling easy and low-cost connection to existing distribution systems;
    - Changing electricity market rules to allow for the full financial benefits of distributed generation (such as avoided transmission upgrades, lower losses and grid support) to be captured by the distributed generators as a matter of routine; and
    - A tax credit, which decreases over time in the level of support, that would enable lower total cost of ownership for early adopters of high efficiency DG systems.

115 It is noted that some such work has been completed under the Australian Energy Market Agreement between the Australian, State and Territory governments. Specifically, the Ministerial Council on Energy in 2007 agreed to new Rules governing economic regulation of distribution that removed many barriers to distributed generation. Further work is in progress to harmonise and simplify connection to distribution networks across jurisdictions, with the latest recommendations to the MCE published in *Network Planning and Connection Arrangements - National Frameworks for Distribution Networks*, available from **www.mce.gov.au**.

- Extend, as appropriate, other clean energy market support mechanisms at State, Territory and Australian government levels to include high efficiency, fuel cell-based distributed generation (particularly combined heat and power) and clean/green hydrogen-fuelled transport.
  - An example of such a mechanism is the use of government purchasing policies to create a consistent and early market demand that stimulates local supply-chain development of hydrogen and fuel cell products.

- **Options analysis modelling**
  - Stay abreast of international modelling efforts and when appropriate undertake analysis of the infrastructure challenges and of the economic and environmental costs and benefits of wide-spread deployment in Australia of captive and merchant use of hydrogen and of fuel cells in stationary and transport energy applications.
  - To the extent possible, compare the results of international analyses with similar ones for Australia that use competing technologies—different energy carriers and energy conversion devices—for the same stationary and transport energy applications.

- **Active in international forums**
  - Ensure Australia actively participates in, and where appropriate, takes a leadership role in, key multilateral forums relevant to hydrogen and fuel cells e.g. the IPHE; relevant IEA Implementing Agreements and similar high-level groups such as the Asia Pacific Economic Cooperation (APEC) Energy Working Group and the Asia Pacific Partnership for Clean Development and Climate (APP).
  - Utilise established bilateral links and forums together with growth of dialogue between interested parties to share knowledge and experience in hydrogen and fuel cells between Australia and New Zealand (particularly), USA, Japan, China and European countries.

- **Education and outreach**
  - Led by the proposed hydrogen and fuel cells industry association, develop education and outreach tools, including an up-to-date database of RD&D activities in hydrogen and fuel cells in Australia, to meet the information and knowledge needs of educators, researchers, government and industry.
  - As a follow-up to the World Hydrogen Energy Conference in Brisbane in 2008, the proposed hydrogen and fuel cells industry association hold an annual, national, hydrogen and fuel cells conference with invited international participation.

- **Co-ordinated sector representation**
  - Establish a hydrogen and fuel cell industry association that could work with established industry and professional representative organisations (e.g. Clean Energy Council; Australian Institute of Energy), hydrogen and fuel cell industry and research sector stakeholders to develop and agree on the scope, objectives, structure, funding sources and operational principles of a co-ordinated national representative organisation in Australia for them.

- **Regulations, codes and standards**
  - Industry demonstrates the need to accelerate the development of regulations, codes and standards in Australia that facilitate the market uptake of non-industrial hydrogen use and of fuel cell products in portable, stationary and transport applications.
  - All stakeholders work together to ensure that Australia's regulations, codes and standards are developed in a timely manner, and in harmony with international best practice so that local importers and exporters of fuel cell and hydrogen products and technologies can maximise global market opportunities at acceptable local adaptation costs.

- **Viable near-term applications**
  - Industry promotes uptake in Australia of fuel cell and hydrogen products that are economically competitive now, including but not limited to:
    - Portable fuel cell products for battery replacement in professional equipment;
    - Fuel cell powered transport vehicles in industrial applications e.g. indoor goods movement vehicles (forklifts);
    - Fuel cell stationary power systems for applications such as high reliability power for data processing.
  - Australian governments promote participation by Australian companies in global supply chains for fuel cell and hydrogen products or services to maximise local industry development and employment growth.
- **Large scale demonstrations**
  - National and international companies, in collaboration with Australian governments, should support large-scale demonstrations in Australia of pre- or early-commercial fuel cell and/or hydrogen products in a small number of near to medium term economic applications. Possible demonstration projects include, but are not limited to:
    - A large-scale trial of commercial-scale co-generation (electricity plus integrated heating and/or cooling) direct fuel cell systems coordinated across a range of Australian climatic regions.
    - A large-scale trial of residential-scale co-generation (electricity plus integrated heating and/or cooling) direct fuel cell systems coordinated across a range of Australian climatic regions.
    - A large-scale trial over 5 years of operation of heavy duty vehicles (buses) utilising hydrogen-fuelled drive-trains coordinated across private and public sector fleet operators in Melbourne, Sydney, Adelaide, Perth and Brisbane to enable the gathering of sufficient data across different climatic and operating conditions.
    - A large-scale trial of hydrogen fuel cell powered vehicles such as forklifts in a range of indoor goods movement applications.
    - A large-scale trial of hydrogen as a cost-effective energy storage mechanism interfaced with intermittent renewable electricity generation.[116]
    - A large-scale trial of a microalgal solar bio-hydrogen production plant coupled to fuel cells that feed electricity into the grid.
  - Ensure, where possible, that such demonstration projects are linked into international trials and that data is shared as a key input into modelling and analysis of energy system options for Australia.
- **World-scale, collaborative R&D projects**
  - Strengthen public-sector and promote private-sector funding support for world-class R&D projects that build on advanced materials, biotechnology, fluids handling and engineering strengths in Australia that already are, or could be, applied to commercially-important technical problems in hydrogen and fuel cells, and their applications. Building on areas of technical strength identified in this roadmap, possible R&D projects could be:
    - Efficient and low-cost production of 'green' hydrogen via direct renewable energy production routes that are scalable, e.g. thermolytic and thermochemical production using concentrating solar radiation; photolytic and bio-photolytic production; high efficiency electrolysis.
    - Efficient and low-cost production of 'clean' hydrogen as part of a power generation (IGCC plus CCS) demonstration with the hydrogen as a 'by-product' (i.e. polygeneration).
    - Low-cost, scalable, storage technologies for hydrogen for on-board and delivery-station applications.
    - Materials and processes for low temperature/low pressure H2 purification.
    - Enabling technologies for transport applications, e.g. electric drive train components (high-efficiency, light-weight motors and advanced batteries) and high-efficiency, hydrogen-fuelled internal combustion engines.
    - Enabling technologies for stationary applications, e.g. balance of plant

116 This could be an existing wind farm or solar-electricity generation facility.

components (high-efficiency, small-scale reformers) and application-specific engineering of integrated stationary fuel cell systems (electricity plus cooling co-generation).

- As a complementary or additional option, a joint initiative among national and international companies, Australian governments and researchers could be established to fund and undertake world-scale, collaborative, focused R&D efforts in Australia in two areas of local technology strength and high, global, commercial opportunity identified in this roadmap where Australia could take a technology leadership position. Possible areas could be:
  – Solid-state storage of hydrogen.
  – Production of low-cost 'green' hydrogen from renewable resources.
  – Production of low-cost 'clean' hydrogen from fossil fuel sources with carbon capture and sequestration.

- **Capacity and capability building**
  - The proposed hydrogen and fuel cell industry association should encourage and work with tertiary and secondary educational institutions to develop relevant technical and business courses incorporating hydrogen and fuel cells as key teaching topics and to foster postgraduate research opportunities in these and allied technical fields.

These activities are summarised in Table 6 together with indicative timeframes and suggested organisations responsible for their implementation.

At the final consultation workshop for this roadmap stakeholders were asked to nominate the five activities that are a first priority for them for commencement of implementation of this roadmap. While acknowledging the importance of building on and extending the R&D capability and capacity for hydrogen and fuel cells in Australia, stakeholders' top five priorities focused on market and supply-chain development activities, as follows:

- Large-scale demonstrations, which stakeholders noted pull and underpin: R&D; technology, industry and policy development; regulations, codes and standards; and overseas interest in Australia as a market.
- Establishment of an advocacy group in Australia (the proposed hydrogen and fuel cell industry association) which is comprehensive and widely supported. An important function for which will be education and outreach to a wide range of parties but particularly to end-users and project/venture financiers.
- Accelerated development of regulations, codes and standards in Australia that facilitate the market uptake of non-industrial hydrogen use and of fuel cell products.
- Systems analysis modelling, including cost modelling and comparative analysis, to guide and prioritise policy and industry development efforts.
- Establishment of public policy that both pulls and pushes progress in Australia in hydrogen and fuel cells, particularly market-support mechanisms such as pricing carbon emissions and establishment of government purchasing policies favourable to hydrogen and fuel cell products.

6.4 Roadmap implementation

Implementation of this roadmap would require a long term commitment from the public, private and research sectors. Learning from the coordination mechanisms for hydrogen and fuel cell roadmaps and RD&D funding in Europe, the USA and Japan, a High-level Coordination Group (HCG) comprising Australian government, industry and research sector representatives should be established to develop implementation options for this roadmap and to provide guidance on public-sector funding commitments to its implementation.

The HCG would then oversight the start-up and progress of the proposed activities under this roadmap with the aim of ensuring that the Roadmap's vision is achieved and that by 2020 well informed and credible decisions about the future of hydrogen and fuel cells in Australia's energy mix can be made, taking into account competing options.

Table 6: Summary of key strategies, options for activities and implementation

Key Strategies	Options for Activities	Indicative Time-Frame for Implementation	Responsibility for Implementation
Policy Framework: Market Support Mechanisms	• Ensure Australia's national emissions trading scheme does not inadvertently create barriers for fuel cells or hydrogen.	2008—2010	• Australian, State and Territory governments
	• Gain a thorough understanding of the GHG benefits of fuel cells and hydrogen in different stationary and transport applications.	2009—2012	• Industry, researchers and emissions-trading operator
	• Devise and implement policy mechanisms that will promote deployment in Australia of high efficiency DG systems, particularly for CHP applications.	2008 onwards	• Ministerial Council on Energy's Renewable and Distributed Generation Working Group
	• Extend, as appropriate, other clean energy market support mechanisms at State, Territory and Australian government levels to include high efficiency DG.	2008 onwards	• Australian, State and Territory governments
Policy Framework: Options Analysis Modelling	• Stay abreast of international modelling efforts; undertake modelling for Australia when appropriate; and compare international and Australian results.	2008 onwards	• Australian governments in conjunction with High-level Coordination Group (HCG)
Knowledge Building: Active in International Forums	• Continue / enhance involvement in multilateral (e.g. IEA, IPHE, APEC, APP) and bilateral forums.	2008 onwards	• Australian governments in conjunction with the HCG
Knowledge Building: Education and Outreach	• Develop education and outreach tools, including an up-to-date database of RD&D activities in hydrogen and fuel cells in Australia, to meet the information and knowledge needs of educators, researchers, government and industry.	2009 onwards	• Hydrogen & Fuel Cell (H&FC) Industry Association
	• As a follow-up to the WHEC 2008 in Brisbane, hold an annual national hydrogen and fuel cells conference with invited international participation.	2009 onwards	• H&FC Industry Association
Market Development: Coordinated Sector Representation	• Establish a hydrogen and fuel cell (H&FC) industry association.	2008—2009	• Hydrogen and fuel cell industry
Market Development: Regulations, Codes and Standards	• Industry demonstrates the need to accelerate the development of regulations, codes and standards in Australia for non-industrial hydrogen use and fuel cell products.	2008 onwards	• Industry suppliers of hydrogen and fuel cells
	• Ensure that Australia's regulations, codes and standards for hydrogen and fuel cells are developed in a timely manner, and in harmony with international best practice.	2008—2012	• Standards Australia; State and Territory governments; industry-sector regulators

Key Strategies	Options for Activities	Indicative Time-Frame for Implementation	Responsibility for Implementation
Supply-Chain Development: Viable Near-Term Applications	• Industry promotes uptake in Australia of economically competitive fuel cell and hydrogen products. • Australian governments promote participation by Australian companies in global supply chains for fuel cell and hydrogen products or services to maximise local industry development and employment growth.	2008 onwards 2008 onwards	• Industry suppliers of hydrogen and fuel cells • Australian, State and Territory governments
Supply-Chain Development: Large Scale Demonstrations	• National and international companies, in collaboration with Australian governments, support large-scale demonstrations in Australia of pre- or early-commercial fuel cell and/or hydrogen products in a small number of near to medium term economic applications. • Ensure, where possible, that such demonstration projects are linked into international trials and that data is shared as a key input into modelling and analysis of energy system options for Australia.	2009—2015 2009—2015	• HCG / H&FC Industry Association • HCG / H&FC Industry Association
Competence Building: World-Scale Collaborative R&D Projects	• Building on areas of technical strength identified in this roadmap, strengthen public-sector and promote private-sector funding support for world-class R&D applied to commercially-important technical problems in hydrogen and fuel cells, and their applications. • As a complementary or additional option, establish a joint initiative among national and international companies, Australian governments and researchers to fund and undertake world-scale, collaborative, focused R&D efforts in Australia in two areas of local technology strength and high, global, commercial opportunity where Australia could take a technology leadership position.	2009 onwards 2010—2012	• Australian, State and Territory governments in conjunction with the HCG • Australian, State and Territory governments in conjunction with the HCG
Competence Building: Capacity and Capability Building	• Encourage and work with tertiary and secondary educational institutions to develop relevant technical and business courses incorporating hydrogen and fuel cells as key teaching topics and foster postgraduate research opportunities in these and allied technical fields.	2009 onwards	• H&FC Industry Association

APPENDIX A – b*wise*IP's AUSTRALIAN MARKET-BASED IP LISTING

The following tables listing the hydrogen and fuel cells intellectual property of Australian market players includes those with activities in Australia. In the case of Eden Energy the IP has been licensed in via acquisition of IP rights from USA companies.

A.1 Australian universities

Juris	Publication or Patent No	Owner/ Holder of the IP rights	Inventor Name	Patent Title	Descriptive Title (for example Derwent Title)
US	5 611 307	University of Melbourne	Watson	Internal combustion engine ignition device	Ignition device for internal combustion engines and hydrogen assisted jet ignitions - has a small outlet orifice in a pre-chamber through which an ignition jet of burning gas is fired
WO	2000-016899	University of Queensland	Millar	Catalysts and process for reforming of hydrocarbons	Catalyst precursor for reforming hydrocarbons to produce synthesis gas comprises a mixture of nickel oxide and an oxide of cubic structural type that is an oxygen ion conductor at elevated temperature
WO	2000-016900	University of Queensland	Millar	Catalysts and process for steam reforming of hydrocarbons	Catalyst precursor for steam reforming of hydrocarbons to produce synthesis gas, includes a mixture of nickel oxide and an oxide of cubic structural type which is an oxygen ion conductor
WO	2000-016901	University of Queensland	Hankamer	Photosynthetic hydrogen production	Producing hydrogen involves culturing photosynthetic microorganism having respiratory electron transfer chain capacity including oxidative phosphorylation pathway, under microoxic and illuminated condition
WO	2005-003024	University of Queensland	Dahle	Magnesium alloys for hydrogen storage	Magnesium nickel alloy useful for producing hydrogen storage material comprises nickel, refining element having specific atomic radius and magnesium
WO	2006-060851	University of Queensland	Diniz	Polymer composite	A polymer composite comprising at least one inorganic proton conducting polymer functionalised with at least one ionisable group and/or at least one hybrid proton conducting polymer functionalised with at least one ionisable group, and at least one organic polymer capable of forming hydrogen bonds.
WO	2006-066345	The Australian National University	Pashley	Increased conductivity and enhanced electrolytic and electrochemical processes	Conducting current through aqueous liquid in electrolysis/ electrochemical processes, involves degassing the aqueous liquid, and applying electric field to the aqueous liquid
WO	2007-082350	University of Queensland	Henville	Process and catalysts for the methanation of oxides of carbon	Production of hydrocarbons e.g. methane comprises contacting carbon oxide(s) with hydrogen in the presence of a catalyst containing nickel and refractory oxide(s)
WO	2008-000045	University of Wollongong	Wallace	Nanostructured composites	Nanotube/ substrate composites for use in the fields of biomedical materials and devices as well as energy conversion and storage, ion transport and liquid and gas separation. The use of such composites as biomaterials are of particular interest

A.2 Australian companies/individuals (except CFCL and Eden Energy)

The table below lists all patents for AU IP Landscape except University IP, Ceramic Fuel Cells Ltd and Eden Energy. It includes those considered not commercially relevant.

Juris	Publication or Patent No	Owner/Holder of the IP rights	Inventor Name	Patent Title	Descriptive Title (for example Derwent Title)
WO	1998-906711	Hydra-Gas Pty Ltd Racz, George	Racz	Fully automated current-controlled electrolytic cell assembly for the production of gases	Electrolytic cell for fuel gas prodn. from water - has coaxial tubular and rod-shaped electrodes with specified ratio in area between anode and cathode and gas collecting chamber
AU	657 841	CSIRO	Nguyen	Production of hydrogen	Hydrogen prodn. from light hydrocarbon(s) and of syn crude from oil shale - by dehydrogenation of light hydrocarbon(s) utilising combusted oil shale with retort off-vapour sepd. to give raw oil and retort gas
WO	1993-023668	Orbital Engine Company Pty Ltd	PALUCH	Fuel/gas delivery system for internal combustion engines	Fuel or gas delivery system for IC engine - delivers hydrogen gas with liq. fuel-air mixtures at selected times into combustion chambers`
WO	1994-412690	Solar Systems Pty Ltd	Lasich	The production of hydrogen from solar radiation at high efficiency	Production of hydrogen fuel gas using solar radiation - comprises splitting radiation into long and short wavelengths to generate thermal and electrical energy for electrolysis of water
WO	1994-21844	Rhyddings Pty Ltd Renjean Pty Ltd Caesar, Marvyn Leonard	Caesar	Electrolytic producer apparatus	Electrolytic gas producer appts. produces mixed hydrogen and oxygen gases - includes housing, electrolyte, electrolyte supply system and gas collection system
US	5 843 292	Hydrogen Technology Ltd	Spiro	Electrolysis systems	Electrolysis cell and system esp for electrolysis of water - comprises an interleaved stack of cathode and anode plates with selective connection between anodes and selective connection between cathodes, esp for oxygen and hydrogen prodn for e.g. gas welders
WO	1995-012066	Nicktown Pty Ltd	SMITH	Engine fuel metering and steam reformer system	Engine fuel metering and steam reformer system for IC engine - uses microprocessor and sensors for control of temp. compensated control valves and liq. level monitors to regulate fuel flow.
WO	1995-031423	CC Energy Pty Ltd	Cummings	Production of methanol	Prodn. of methanol from coal, oxygen and water - using combined thermal and electrolytic process
WO	1998-09001	Green Gas Generator Pte Ltd	Petrovic	Method and advice for generating hydrogen and oxygen	Method to generate hydrogen and oxygen from an aqueous solution - uses apparatus in which electrolytic cells are energized by a pulsating current, and which automatically causes electrolyte circulation
WO	2000-004325	Allan Yeomans	YEOMANS	Heat energy collection and conveying apparatus	Heat transfer and delivery system using dissociation of ammonia by catalyst
WO	2000-14303	Toseski, Dimko	Toseski	Apparatus for electrolytic generation of gas	Electrolytic gas generator has a gas-generating device having an internal chamber partially filled by an electrolytic solution with a space above the solution forming an accumulating zone
WO	2002-042621	H.A.C. Technologies Pty Ltd	CUMMING	Hydrogen assisted combustion	Apparatus, for feeding hydrogen into combustion ignition engine, has device controlling air flow through chamber and having volume control, i.e. butterfly valve, allowing total volume of air passing through mixing chamber to be varied

Juris	Publication / Patent No	Owner/Holder of the IP rights	Inventor Name	Patent Title	Descriptive Title (for example Derwent Title)
WO	2002-044081	RMG Services Pty Ltd	Gomez	Electrolytic commercial production of hydrogen from hydrocarbon compounds	Conversion of hydrocarbon compounds to carbon dioxide and hydrogen comprises using electrolytic cell that operates without diaphragm
US	7 182 851	RMG Services Pty Ltd	Gomez	Electrolytic commercial production of hydrogen from hydrocarbon compounds	Conversion of hydrocarbon compounds to carbon dioxide and hydrogen comprises using electrolytic cell that operates without diaphragm
WO	2003-018468	Technological Resources Pty Ltd	Shaw	Method and apparatus for generating hydrogen gas	Generation of hydrogen gas for fuel cell used in electric-powered motor vehicle, involves bringing heated hydrogen-depleted solution into (in) direct heat exchange relationship with metal hydride
WO	2003-042431	Casey, Alan Patrick Smith, Stewart	Casey	Method and means for hydrogen and oxygen generation	Production of combustible mixture of hydrogen and oxygen by electrolyzing aqueous liquid using pulsed application of water onto electrodes, while applying electrical potential between electrodes not immersed in water
WO	2004-113223	PowerGen International Pty Ltd	Sadikay	Reformate assisted combustion	Hydrogen-containing gas, useful as a fuel or component of fuel in compression engine e.g. diesel engine, contains non-hydrogen components unremoved from blend obtained in a hydrogen generator
WO	2005-005691	PowerGen International Pty Ltd	Shaw	Production and storage of hydrogen	Production and storage of hydrogen used as fuel source of power systems, involves decomposing water in aqueous electrolyte comprised in electrolytic cell, and contacting producing hydrogen with material capable of forming metal hydrides
US	2005-0126924	Technological Resources Pty Ltd	Shaw	Commercial production of hydrogen from water	Production of hydrogen from water, used for fuel cells in transport vehicles, by passing first and second electrolytes through diaphragm-less anode cell and diaphragm-less cathode cell respectively, and applying direct current
WO	2005-103338	RMG Services Pty Ltd	Gomez	Production of iron/ titanium alloys	Production of titanium metal product, e.g. iron/titanium alloy for hydrogen storage, by supplying titanium-containing feed material(s) to ionic liquid compartment, and applying potential across anode and cathode
WO	2005-119015	Albert Bow	Bow	An engine	Mechanical power generating system for use in motor vehicle, has three valves supplying water vapour, hydrogen, and heated air into chamber when chamber has minimum, maximum and minimum volumes, respectively
WO	2006-058369	Poolrite Equipment Pty Ltd	Smith	Reversible polarity electrode systems	Reversing electrode polarity in electrolytic cell, by isolating electrodes of cell, effecting controlled discharge to predetermined value of residual charge, reversing polarity of the electrical charge and reapplying the electrical charge
WO	2007-143776	DUT Pty Ltd	Cummings	Improvements in the utilisation of methane	
US	2007-0269687	RMG Services Pty Ltd	Kongmark	Reactor for simultaneous separation of hydrogen and oxygen from water	A device for the production of hydrogen from water using heat. It is based on the concept of a membrane reactor with two kinds of membranes allowing the separation of hydrogen and oxygen simultaneously in stoichiometric quantities from the reactor volume. The device has a special geometry resulting in a temperature distribution inside the reaction chamber to accommodate the use of hydrogen selective membranes.

A.3 Australian company: Ceramic Fuel Cells Limited

Juris	Publication /Patent No	Inventor Name	Patent Title	Descriptive Title (for example Derwent Title)
US	5 942 349	Badwal	Fuel cell interconnect device	Electrical interconnect device for planar solid oxide fuel cells - comprises chromium content substrate with gas flow channels and metallic oxide surface layer
US	6 280 868	Badwal	Electrical interconnect for a planar fuel cell	Electrical interconnect device for planar fuel cells - has plate-like chromium-containing substrate having fuel gas-flow channels on one side and oxidation resistant coating on sides to contact the anode
US	6 492 053	Donelson	Planar fuel cell assembly	Fuel cell stack with interconnects between each pair of adjacent cells - includes conductive compressible members located in a chamber defined between adjacent interconnects to provide a compressive load on each cell in the stack independent of its position in the stack.
US	6 444 340	Jaffrey	Electrical conductivity in a fuel cell assembly	Electrical conductivity in fuel cell assembly
US	6 294 131	Jaffrey	Heat resistant steel	Steel especially useful for a solid oxide fuel cell component
US	6 797 662	Jaffrey	Electrically conductive ceramics	Metal oxide ceramic material is rendered electrically conductive by the incorporation of silver into the material, e.g. for bipolar plates for solid oxide fuel cells
WO	2000-075389	Jaffrey	Air-side solid oxide fuel cell components	Solid oxide fuel cell component as manifold, base plate, current collector strap, ducting, heat exchanger or heat exchanger plate, is formed of a heat resistant alloy of specific composition
US	7 150 931	Jaffrey	Fuel cell gas separator	Gas separator for fuel cell, has anode and cathode sides and comprises a layer of copper or copper based alloy provided with oxidation resistant material on cathode side
US	6 841 279	Foger	Fuel cell system	Electricity generation using solid oxide fuel cell, by reacting higher carbon hydrocarbon fuel and steam in pre-reformer, and supplying fuel stream to fuel cell
WO	2001-024300	Jaffrey	Fuel cell assembly	Tubular fuel cell assembly includes an anode-side current collector which comprises a tubular metallic structure which permits fuel gas in tubular passage to contact anode layer
US	7 045 239	Donelson	Laminated structure and method of forming same	Sintered laminated structure formation for fuel cells, involves laminating layers containing green sinterable material of differing shrinkage rates, such that one layer is on one face of other layer
US	6 828 052	Zheng	Surface treated electrically conductive metal element and method of forming same	Separator plate for solid oxide fuel cell stack, comprises metal substrate having nickel-tin alloy layer overlying its surface, and silver or silver containing tin layer(s) overlying nickel-tin alloy layer
WO	2002-067351	Ahmed	Fuel cell system	Production of electricity in fuel cells involves pre-reforming higher carbon hydrocarbon fuel, subjecting pre-reformed fuel stream to methanation, and supplying fuel stream and oxidant to fuel cell
WO	2002-076609	Hoang	Liquid phase reactor	Liquid phase continuous reactor for mixing or homogenizing components for powder precipitation, includes screw having spiral groove(s) for adapting relative rotation of screw and barrel
WO	2003-007413	Thomas	Solid oxide fuel cell stack configuration	Solid oxide fuel cell stack includes manifolds that opens with respect to electrodes of fuel cell and gas separator plate to distribute and exhaust fuel and oxygen containing gases, respectively
WO	2003-007403	Rodrigo	A fuel cell gas separator plate	Gas separator used for fuel cell assembly, has electrically conductive path that extends from anode-facing side to cathode-facing side in electrode-contacting zone, contains silver glass composite
WO	2003-007400	Thomas	Seal for a fuel cell stack	Solid oxide fuel cell stack includes fuel cell plate with rigid rib which engages into recess formed between pair of ribs of gas separator plate, and gas sealant being filled in void between rib and recess

Juris	Publication / Patent No	Inventor Name	Patent Title	Descriptive Title (for example Derwent Title)
WO	2003-019707	Barrett	Fuel cell system and method for recycling exhaust	Solid oxide fuel cell system has fuel exhaust recycle line and has jet pump with exhaust outlet from entrainment chamber for discharge of excess fuel exhaust
WO	2003-063282	Bolden	Desulfurisation of fuel	Removal of sulfur from fuel supply stream for fuel cell, by hydrogenating fuel supply stream, removing hydrogen sulfide, and pre-reforming desulfurized fuel stream
WO	2003-065488	Foger	Thermal management of fuel cells	Thermal management of fuel cell comprises processing fuel supply stream in autothermal reformer and reforming methane present in fuel supply stream within fuel cell
US	2005-0153178	Ahmed	Solid oxide fuel cell	Solid oxide fuel cell has hydrocarbon reforming layer having composition different from that of anode layer and including catalyst to promote hydrocarbon steam reforming reaction and component or its precursor to alleviate carbon deposition
US	2005-0158594	Ahmed	Method of operating a fuel cell	Generation of hydrogen for use in fuel cell system comprises processing fuel that is free of organic sulfur-containing compounds to produce hydrogen-containing stream
US	2005-0181247	Foger	Fuel cell system	Thermal management of fuel cell comprises processing fuel supply stream comprising hydrogen, steam, carbon dioxide, and optionally methane using methanator to produce fuel cell supply stream comprising controlled concentration of methane
US	2006-0147765	Barrett	Method of operating a fuel cell	Operation of fuel cell involves relating concentration of the reactive species to maximum current drawn from the fuel cell without redox damage to electrode
WO	2006-010212	Kah	Fuel cell system	Fuel cell system for delivering gaseous fuel to fuel reformer, has jet pump for delivery to steam reformer of gas stream comprising steam and gaseous hydrocarbon fuel, and steam generator for delivery of pressurized steam to steam inlet
WO	2007-009176	Kah	Steam generator	A method of generating steam by heating water in a steam generator comprising a plurality of steam generating channels, wherein water is supplied at a constant rate to each steam generating channel through respective water supply lines, and wherein a sufficient pressure drop is provided across each water supply line in order to prevent flow reversal in the plurality of steam generating channels.

A.4 Australian company: Eden Energy

Eden Energy acquired the IP Rights of US based Brehon Energy PLC and HyRadix (source Eden Energy website)

Juris	Publication / Patent No	Owner/Holder of the IP rights	Inventor Name	Patent Title	Descriptive Title (for example Derwent Title)
US	7 281 531	Brehon Energy PLC acquired by Eden Energy	Fulton	System and method of stoichiometric combustion for hydrogen fueled internal combustion engines	Stoichiometric combustion system for controlling e.g. diesel engine, has fuel system providing flow of fuel and flow of ambient air to engine, and exhaust gas recirculation system providing flow of recirculated gas
WO	2007-044073	Brehon Energy PLC acquired by Eden Energy	Egan	System and method for blending and compressing gases	Gas blending and compressing system used for generating fuel, comprises gas blender to blend two gases at determined blend ratio, and to supply compressor with constant flow of gases at minimum flow rate and maximum pressure of compressor.
WO	2007-061491	Brehon Energy PLC acquired by Eden Energy	Egan	Method and system for producing a supercritical cryogenic fuel (sccf)	System for producing supercritical cryogenic fuel used in internal combustion engine, comprises first tank containing hydrogen gas, second tank containing hydrocarbon fluid, metering valve, compressor, expansion chamber and vortex mixer.
WO	2007-092142	Brehon Energy PLC acquired by Eden Energy	Fulton	System and method for producing, dispensing, using and monitoring a hydrogen enriched fuel	Hydrogen enriched fuel e.g. hythane, producing, dispensing, using and monitoring system for motor vehicle, has control system monitoring emissions produced by vehicle during use of hydrogen enriched fuel.
WO	2007-142728	Brehon Energy PLC acquired by Eden Energy	Lynch	System and method for producing a hydrogen enriched fuel	System for producing hydrogen enriched fuel, has reformer for reacting steam and hydrocarbon and gas blending apparatus in communication with reformer and source of hydrocarbon fuel for blending with generated hydrogen-rich gas
WO	2005-009892	HyRadix Inc acquired by Eden Energy	Doshi	Method for operating a hydrogen generator	Controlling of hydrogen generation process involves changing hydrogen generation rate to second rate insufficient to maintain first amount of hydrogen in the reservoir and changing hydrogen generation rate to a rate within first rate
WO	2005-090230	HyRadix Inc acquired by Eden Energy	Carpenter	Hydrogen generator apparatus and start-up processes	Process to start up hydrogen generator involves passing heated oxygen-containing gas through partial oxidation reformer and downstream unit to achieve first temperature and passing heated steam-containing gas to achieve hotter temperature.
WO	2005-118126	HyRadix Inc acquired by Eden Energy	Doshi	Hydrogen generation process using partial oxidation/steam reforming	Hydrogen is generated by supplying partial oxidation/steam reforming zone hydrocarbon-containing feedstock, cooling the reforming effluent stream, and subjecting cooled reforming effluent stream to purification unit operation.
WO	2007-092139	HyRadix Inc acquired by Eden Energy	Doshi	Integrated reformer and batch annealing processes and apparatus therefor	Batch annealing process for e.g. steel strip, involves providing metal work piece in annealing zone having carbon-containing substance which under annealing conditions cause coke formation, and purging free oxygen from zone
EP	1 525 154	HyRadix Inc acquired by Eden Energy	Russell	Feedforward control processes for variable output hydrogen generators	Operating hydrogen generator for fuel cell used to generate electricity, involves determining conditions of hydrogen generator and hydrocarbon-containing feed, and controlling raw materials feed rates based upon determined conditions

APPENDIX B – MMA'S COST AND MARKET POTENTIAL ANALYSIS

B.1 Introduction

In this appendix, an analysis is undertaken of the market potential for hydrogen in transport and electricity generation. The market potential is explored through the use of a model that determines the long run marginal cost of various hydrogen production and generation options in Australia. A number of case studies are developed for examining the potential, with the case studies being representative of the market opportunities available for hydrogen and fuel cell generation. The cost of hydrogen is compared to petroleum fuel for transport and the cost of fuel cell generation is compared to the cost of alternative generation options. The basis of these analyses is that the least cost alternative will be selected to supply the market. Thus, hydrogen as a transport fuel or hydrogen fuelled fuel cell generation will only have potential if its cost is lower than the alternatives.

The case studies are based on differing options for manufacture and delivery of the hydrogen fuel and the size of the fuel cell generating units. The results presented consider:

- Hydrogen produced in steam reforming units or coal gasifiers at large scale with supply piped to the generating unit or refuelling dispenser
- Hydrogen produced in steam reforming units or electrolysers of medium scale with supply trucked to the generating unit or refuelling dispenser
- Hydrogen produced in steam reforming units or electrolysers of small scale at the site of the generating unit.

The modelling has been undertaken as a high level exercise designed to capture the major trends and sensitivities to inputs on the cost of producing hydrogen and of generating electricity using fuel cells. As such, a number of factors are ignored or treated in a relatively non-detailed manner. In particular the following are important issues that should be considered in using the results of the modelling:

- Hydrogen production for transport fuel is only analysed to the point of vehicle refuelling. It was considered that the variables involved in analysing the transport component of the system were too great to include in the current study. Use of hydrogen for transport applications was therefore compared on a petrol litre equivalent (PLE) basis to unleaded petrol.
    - Clearly, if fuel cell vehicles become commercially available at the fuel efficiencies claimed, which are significantly greater than petrol fuelled vehicles, the costs for hydrogen as a transport fuel on the basis of kilometres travelled will improve relative to petrol.
    - The uncertainties associated with forecasting petrol-fuelled vehicle fuel consumption, which will significantly reduce as hybrid, plug-in hybrid and diesel fuelled vehicles increasingly penetrate the market, are particularly large.
- Costs for hydrogen production and delivery have been developed based on the best available published data for plants capable of producing the required quantities of hydrogen for particular applications. Detailed costs from small scale pilot trials were intentionally not utilised, such as the Perth bus trial as these are unlikely to be representative of the costs incurred when large scale adoption occurs.
    - The Perth bus trial reported a hydrogen cost of \$21/kg H_2. This hydrogen was produced and purified at the Kwinana

refinery, and this production route was not considered. Given that the trial employed three buses and a single fuelling station and the annual hydrogen consumption was about 18,000 kg/year (0.05 tonne/day) we do not believe these costs are representative of the costs for larger plant and delivery system supporting a significant fleet of vehicles.

- The distributed hydrogen production and supply stations for transport use modelled in this work are in the 1 to 3 tonne/day capacity range on the basis that significant numbers of vehicles could be supported.

B.2 Hydrogen production

Hydrogen is currently produced by one of two main methods:

- Reformation of fossil fuels, either coal or natural gas, by steam reformation or partial oxidation; or
- Electrolysis of water, where an electrical potential splits water into its oxygen and hydrogen atoms.

A number of other routes to hydrogen fuel are under development including the use of direct solar energy utilising catalysis, high temperature decomposition, thermal gasification of biomass, and biological production from biomass.

Hydrogen is unlikely to compete with other fuels in any segment until the costs of production and/or the greenhouse emissions associated with production are significantly reduced. Although hydrogen production can result in a zero emission fuel, the technologies associated with this are less developed and the costs currently are prohibitive for widespread uptake. The costs of production of hydrogen have been reported as ranging from $8/GJ, for steam reforming methane, to between $29 and $42 /GJ, for electrolysis. The cost of electrolysed hydrogen is largely dependent on the electricity price used—the higher value in this range is associated with the use of renewable electricity.

Utilising renewable electricity in electrolysis or renewable feedstocks in gasification will produce zero emission hydrogen. However, the costs of renewable electricity will increase the hydrogen cost and most of the waste to hydrogen processes are untried.

With no existing large scale distribution networks for hydrogen, the cost of network development is an additional impediment to large scale adoption.

B.2.1 Methodology

In our analysis of hydrogen production a number of production and supply scenarios have been considered that cover the scale and technologies that would likely be required to supply hydrogen at 99.99 per cent purity to be used in the following applications:

- Large scale fuel cell generation of around 300 kW
- Medium scale fuel cell generation of around 30 – 50 kW
- Small scale fuel cell generation in range 1 – 5 kW
- Supply to a large scale service station for transport fuel
- Supply to a small scale transport fuel dispenser for home use

Within each of these hydrogen demand categories, a number of potential production pathways may be utilised and these are considered in the following section.

Production Pathways

Steam Reformation of Natural Gas

Steam methane reforming (SMR) will only be considered in this analysis, although the same fundamental principles apply to the reforming of methanol, gasoline and other liquid and gaseous fuels.

SMR is an endothermic reaction carried out under high temperature and pressure conditions of around 30 atmospheres and 870°C, over a nickel reforming catalyst. The reaction is reversible and is specified by:

$$CH4 + H_2O \Leftarrow\Rightarrow 3H_2 + CO$$

The nickel catalysts are particularly sensitive to poisoning by sulphur, which must be removed from the gas prior to the reaction.

The high temperature reaction conditions result in significant quantities of heat that may be utilised for feed preheating and generating the steam for the reformer. Sufficient remaining heat is generally available for production of steam for export or preheating combustion air.

The SMR produces a synthesis gas (syngas) with a 3:1 H_2:CO ratio. The hydrogen yield is generally increased through the addition of a shift reactor where CO reacts with water to form additional hydrogen according to:

$$CO + H_2O \Rightarrow H_2 + CO_2$$

The hydrogen product stream is purified utilising pressure swing adsorption (PSA) to produce a high purity hydrogen product of 99.99 per cent purity.

Coal Gasification

Although most often utilised with coal feedstock gasification, it may also be used for a variety of feedstocks including refinery wastes, biomass, and municipal solid waste. The coal feedstock is reacted with oxygen or air under high temperature and pressure (1,150 to 1,425°C and 27 to 80 atmospheres) according to the following reaction.

$$C_aH_b + a/2O2 \Rightarrow b/2H_2 + aCO$$

This is followed by a CO shift reactor to increase the hydrogen yield. Sulphur and CO_2 need to be removed from the product stream prior to purification. Although air may be used directly, the use of pure oxygen provides significant advantages including:

- Avoiding the requirement to remove the nitrogen from the product stream
- Smaller volumes of gas flowing through the reactors
- A higher concentration of CO_2 in the product stream from the shift reactor that would be easier to separate for sequestration

Electrolysis

Electrolysis involves the decomposition of water into hydrogen and oxygen according to the following reaction:

$$H_2O + \text{electricity} \Rightarrow H_2 + 1/2O_2$$

The electrolyser cell contains a concentrated solution of potassium hydroxide (KOH) and a DC voltage is applied across the two electrodes. The charge is transported from cathode to anode by the dissociated OH- ions and producing almost pure hydrogen at the cathode and almost pure oxygen at the anode. The power consumption required for electrolysis at the theoretical efficiency limit is 39.40 kWh/kg hydrogen while commercial electrolysers in sizes up to 5 kg/hr use between 48 and 55 kWh/kg. Electrolysis is generally utilised for smaller hydrogen demands of up to 10 kg/hr. However, Norsk Hydro produces an electrolyser with a capacity of 44 kg/hr.

B.2.2 Economics of hydrogen production

Hydrogen production costs have been estimated using a modified version of MMA's GENCHOICE model. The model calculates the long run marginal cost for new generation plant and has been modified to determine the same outputs for the production of hydrogen in terms of kilograms of product. The long run marginal cost of a new hydrogen plant is equal to the present value of capital, fuel and operating costs divided by the present value of the output over the expected life of the plant.

For each option, the full costs of production are modelled. Costs include:

- Capital cost, which are modelled as a function of capacity (to reflect the economies of scale with unit size).
- Coal, biomass, liquid fuel, natural gas, and hydrogen costs are modelled as delivered cost for the fuel on a $/GJ basis and production efficiencies for each technological option.
    - The natural gas cost is equal to the forecast city gate price for the nearest city gas node as forecast by MMA plus any additional transmission cost (in some locations the additional transmission cost may be

negative if the plant location is closer to the gas field than the city gate node).

- Natural gas wholesale prices are based on MMA modelling of current and future gas supply in all states and forecast increases in gas demand.
- Electricity prices are based on MMA modelling of the electricity markets in each State and Territory, and considers fuel costs, generating units (both existing and new entry and incorporates all current programs to increase renewable generation).

- Non fuel operating and maintenance costs.
- Sequestration costs (if any).

Long run marginal costs are calculated for each year of entry of the plant from 2010 to 2030. In this way, trends in capital costs, conversion efficiency and fuel prices are captured.

Selection of production technologies

In examining the production costs of hydrogen a mixture of natural gas reforming, electrolysis and coal gasification plant were selected that could be used to supply different levels of demand. The plants examined are:

- A 380 tonne/day coal gasification plant
- A 1 tonne/day electrolysis plant
- A 240 kg/day electrolysis plant
- A 1 kg/day electrolysis plant
- A 380 tonne/day natural gas reforming plant
- A 27 tonne/day natural gas reforming plant
- A 3 tonne/day natural gas reforming plant

The sizing of the plants is roughly according to the sizes that would suit a centralised production facility with delivery to users, a service station sized unit, and a small size suitable for home fuelling a vehicle or fuelling a commercial fuel cell.

Levelised costs of production

The underlying assumptions regarding the operating and capital costs and the efficiency of the hydrogen production systems are shown in Table B 1.

The levelised cost of producing hydrogen for the selected plant types is shown in Figure B 1. As expected, the use of electrolysis is the most expensive method to produce hydrogen, while large scale production using natural gas reforming results in the lowest cost, starting at around $2 /kg.

Table B 1

Hydrogen Production System	Hydrogen Output (tonne/day)	Capital Cost 2010 ($/tonne/day capacity)[117]	Fixed Operating Cost 2010 ($/tonne/day capacity)	Variable Non-Fuel Operating Cost 2010 ($/tonne H_2)	Efficiency GJ/kg H_2 Produced)
Large Scale Natural Gas Reforming	380	$483,000	$15,400	$4.64	0.20
Medium Scale Natural Gas Reforming	27	$650,000	$15,400	$4.64	0.21
Small Scale Natural Gas Reforming	3	$880,000	$15,400	$4.64	0.22
Large Scale Electrolysation	1	$5,800,000	$116,000	$0.57	0.18 (0.050 MWh/kg H_2)
Medium Scale Electrolysation	0.24	$7,300,000	$116,000	$0.57	0.18 (0.050 MWh/kg H_2)
Small Scale Electrolysation	0.001	$16,900,000	$116,000	$0.57	0.19 (0.053 MWh/kg H_2)
Large Scale Coal Gasification	380	$445,000	$15,400	$0.11	0.167

117 Capital cost and fixed operating costs are presented as "dollars per unit capacity" so the total plant cost is equal to the value in the table multiplied by the relevant capacity.

Significant reductions in capital cost for the electrolysis plants are assumed[118], particularly for the small scale units that could conceivably achieve greater cost reductions through volume manufacture. The impact on the final production cost of capital cost is relatively small however because of the dominance of electricity cost in the total. This is indicated in Figure B 2 that shows the change in hydrogen cost in response to changes in the capital cost of between ± 20 per cent.

In the analysis an option was included for a small scale natural gas reformer that is produced in large numbers and achieves significant economies of scale in manufacturing, resulting in a cost of 20 per cent lower than the equivalently sized unit. This results in a hydrogen production cost of less than $2/kg by 2020, which approaches that of the large scale NG reforming unit.

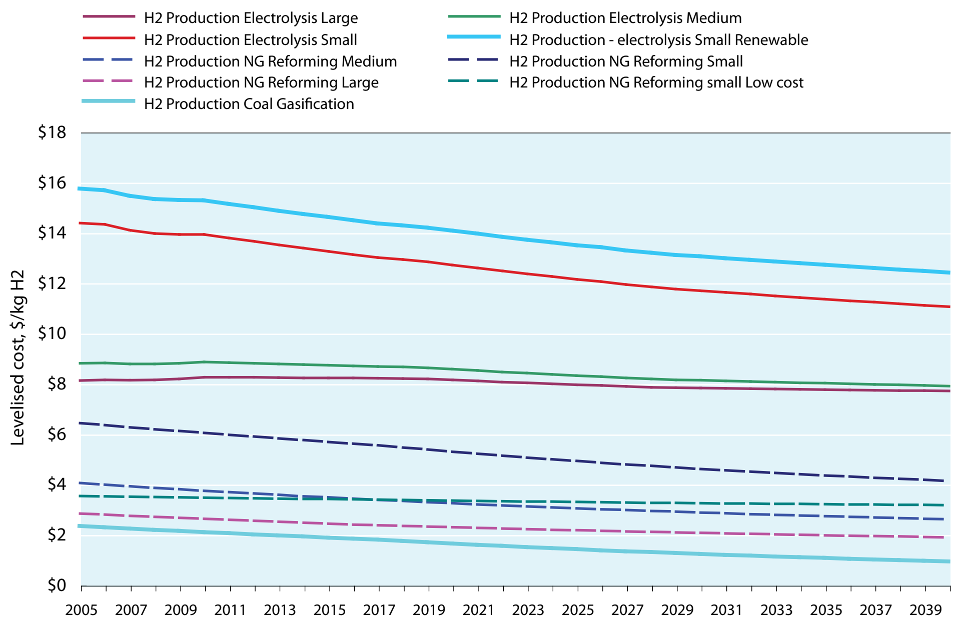


Figure B 1 Production costs of hydrogen ($/kg)

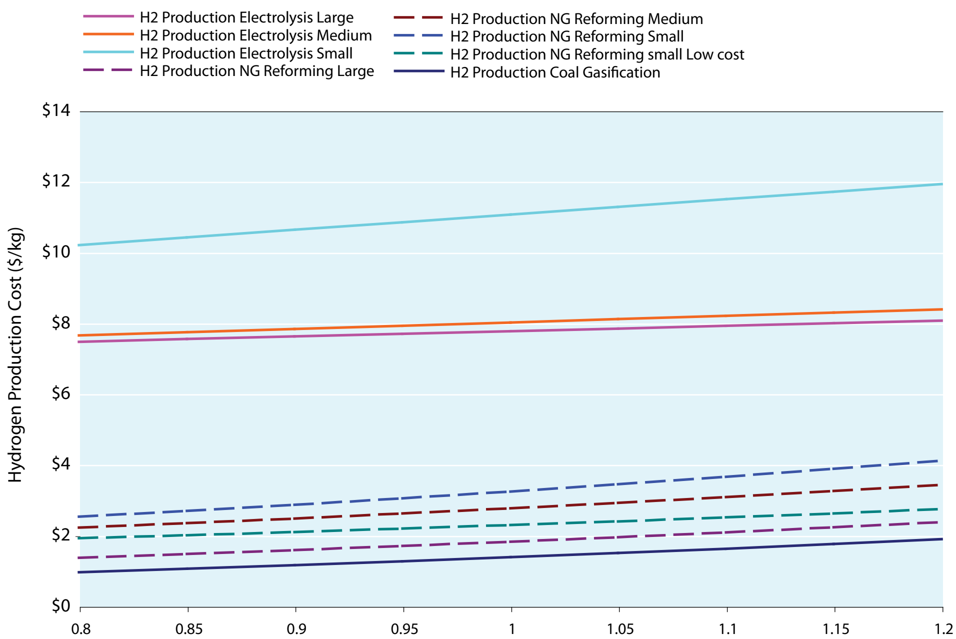


Figure B 2 Hydrogen Production Cost Sensitivity to Capital Cost

118 *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, National Research Council and National Academy of Engineering, 2004.

The impact of utilising renewable electricity for the production of hydrogen by electrolysis is also shown in this figure and adds approximately $2.00/kg to the cost. The additional cost of renewable electricity is added to the electricity consumed by the electrolyser at the current cost of the renewable energy certificate which is $40/MWh.

The effect of changes in fuel price is shown in Figure B 3 for changes from -20 per cent to +30 per cent of the modelled fuel cost. These data show that while reformation of natural gas and gasification of coal are relatively stable with respect to the fuel price, the production cost is much more sensitive to the cost of electricity for electrolysis. High electricity prices push the cost of hydrogen production from small scale electrolysis to about $13/kg.

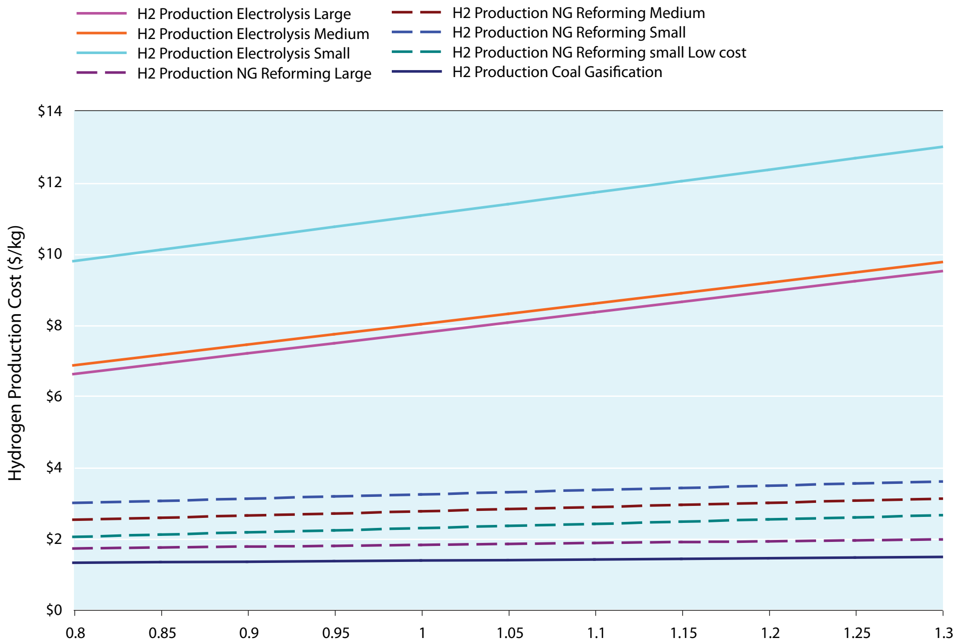


Figure B 3 Hydrogen Production Cost Sensitivity to Fuel Cost

B.3 Market potential for hydrogen as a transport fuel

Transport fuels in Australia are predominantly liquid petroleum products. However, small quantities of gaseous fuels are consumed in buses and taxis. A small but growing proportion of fuel is supplied from renewable sources such as ethanol and biodiesel.

The potential for hydrogen to be utilised as a transport fuel is dependent on a number of factors including:

- The availability and cost of hydrogen fuelled vehicles
- The development and implementation of standards for these vehicles
- The availability of refuelling facilities
- The availability of economic hydrogen production facilities

B.3.1 The economics of hydrogen as a transport fuel

If hydrogen is to be an acceptable fuel for transport applications, it needs to be produced, delivered and dispensed into the vehicle at a cost similar to that of petrol on an energy basis. In conducting this analysis the production costs of hydrogen in $/kg have been converted into delivered costs in terms of dollars per petrol litre equivalent (PLE). That is, the cost of the quantity of hydrogen that will deliver the same energy as a litre of petrol. There are three main scenarios for the delivery of hydrogen to a refuelling station:

- Hydrogen may be produced at a centralised location and piped to the refuelling station
- Hydrogen may be produced at a centralised location and transported by road in high pressure or cryogenic tanks
- Hydrogen may be produced and stored on site

Pipeline delivery has not been considered at the current time because there is unlikely to be sufficient demand to justify the infrastructure costs until a large proportion of the vehicle fleet is using hydrogen. A number of companies are currently developing and trialling hydrogen refuelling systems in the US and Europe, and these are using either onsite generation or road delivery.

B.3.2 Costs of transport and dispensing

The cost of delivering hydrogen in tube tankers to a refuelling facility has been estimated to be $2.10/kg based on US data from the NAS[119], utilising a 2 hour round trip including refilling and unloading. The delivered cost to a refuelling station for each of the supply options is shown in Figure B 4 on a petrol litre equivalent basis. It also has been assumed that the electrolysis units are all co-located with storage and dispensing units, as are the small and medium natural gas reforming units. These units have no delivery charge from production source to the refuelling unit and therefore gain a cost benefit for this component.

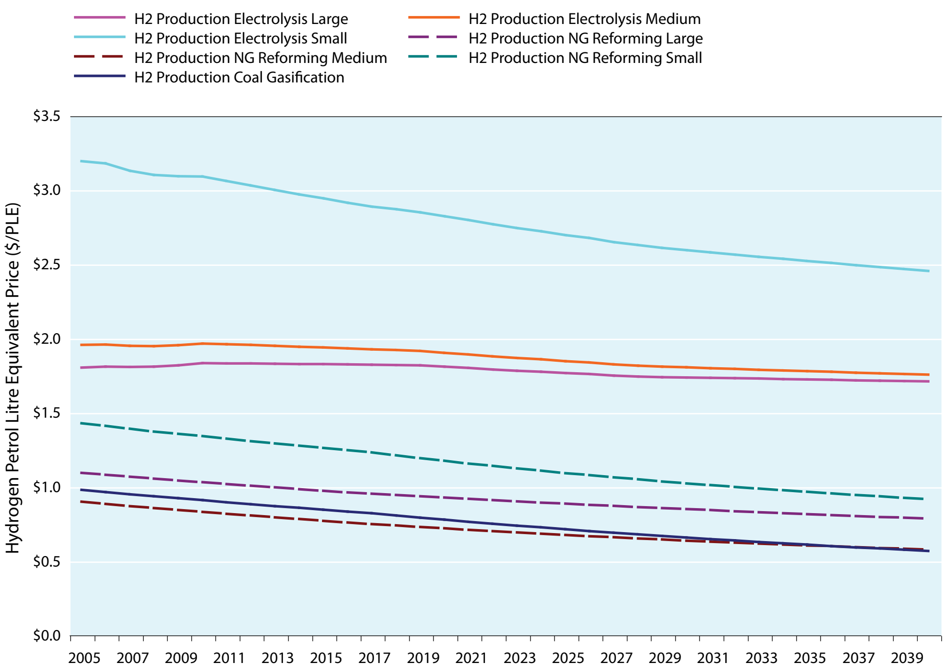


Figure B 4 Hydrogen Cost Delivered to Service Station ($/PLE)

The cost of the hydrogen to vehicle dispensing equipment is highly uncertain because most of this equipment is still under development and not on the open market. However, the information currently assessed indicates that the dispensing equipment would add 10 per cent -20 per cent to the cost of delivered hydrogen. An assumption that 20 per cent of the delivered hydrogen cost is required for dispensing equipment has been made, and the resulting delivered purchase price including a petrol equivalent excise of 38.143 cents per PLE and GST at 10 per cent is shown in Figure B 5.

This clearly shows that electrolyser-produced hydrogen is not competitive with the current petrol prices, with oil at around the $US100 barrel mark. However if petrol prices approach $2.50/L it would approach competitiveness. Natural gas reforming however reduces to around $1.50/PLE in 2020, which is likely to be competitive with petrol at that time. Further development and mass manufacture could significantly reduce the capital cost of production, delivery and dispensing equipment. This would be offset by the likely increase in natural gas costs as the demand for gas increases, as a result of increasing demand for electricity generation and the potential increase in demand for the production of hydrogen.

119 Ibid

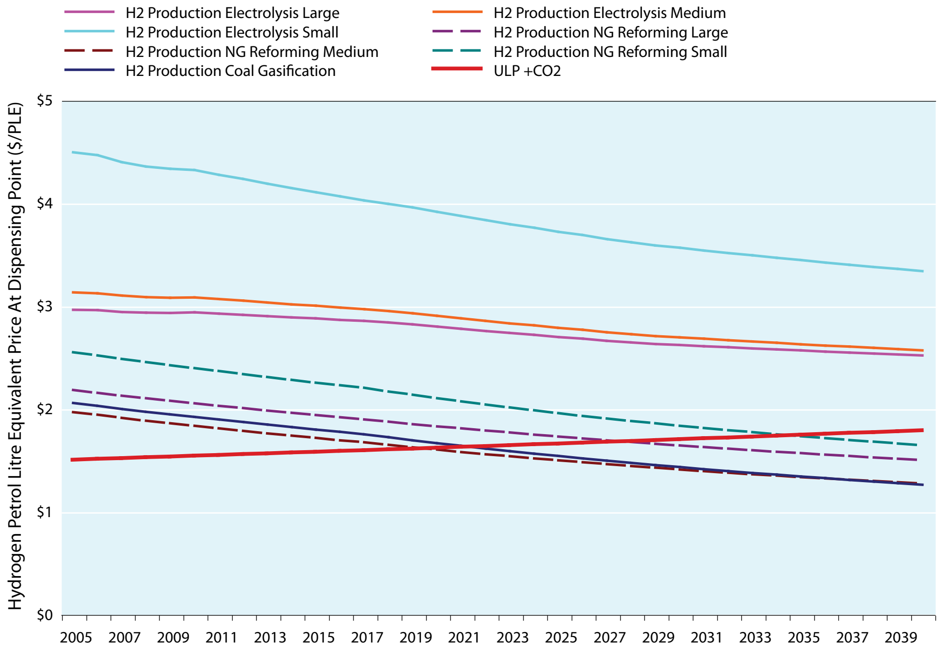


Figure B 5 Hydrogen Cost Dispensed to Vehicle ($/PLE)

Clearly, the dominant determining factor on the economics of hydrogen production is the delivered price of competing fuels. Currently, standard unleaded petrol retails in the vicinity of $1.50/L at a global crude price approaching $US100/barrel. Projecting this price into the future is highly unreliable exercise, given the impacts of OPEC, regional political stability, substantially increasing demand from China and India, and the uncertainty associated with forecasting future supplies and new discoveries.

There appear to be many upward pressures on the oil price and very few downward pressures; even so 12 months ago very few were projecting oil at $US100/barrel. Even in five years time. In fact the US Department of Energy (DOE) projections in 2007 predicted a maximum crude price over the period to 2030 of just below $US30/barrel[120]. An unleaded petrol price of $1.50/L increasing at 0.5 per cent/year has been used as a comparison point for the dispensed hydrogen costs. The dispensed cost of hydrogen does not become lower than this petrol price until 2020 at the earliest.

The impacts of a carbon trading or carbon tax environment is shown in Figure B 6 for a $20/ tonne CO_2-e carbon price that is assigned to all emitting industries and processes. In developing these curves the carbon cost is applied to the CO_2 associated with:

- Natural gas reforming
- Production of the electricity utilised in electrolysis
- Combustion of petrol in vehicles

The impact of a range of carbon prices on the cost of producing hydrogen with natural gas reformation is shown in Figure B 7, with the corresponding prices for unleaded petrol under the same carbon tax regime.

120 Annual Energy Outlook 2007 - With Projections to 2030, Energy Information Administration, Office of Integrated Analysis and Forecasting, U.S. Department of Energy, Washington, DC 20585, Report #: DOE/EIA-0383(2007)

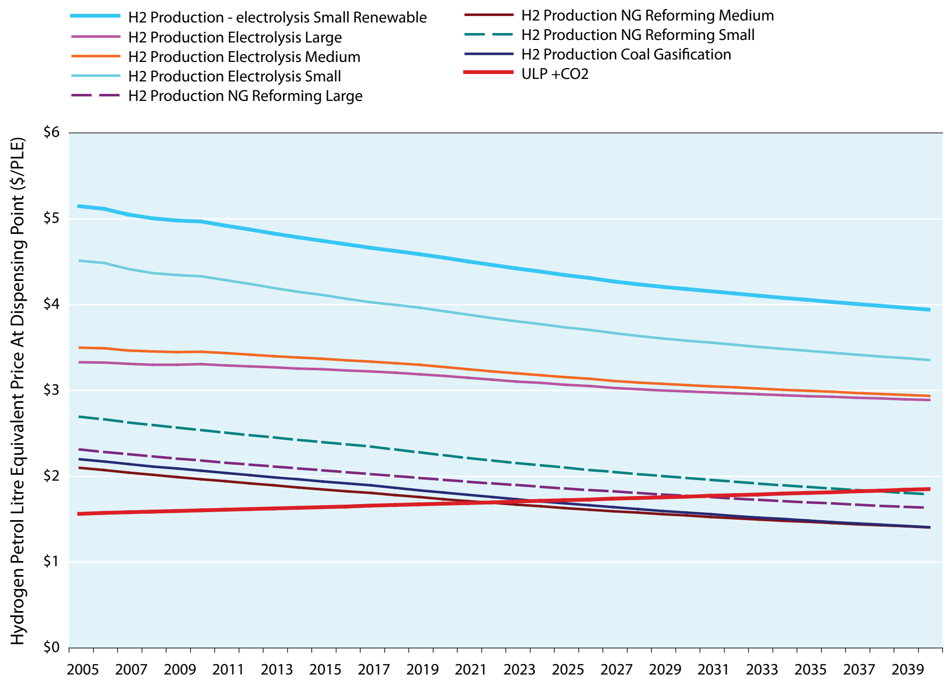


Figure B 6 Hydrogen Cost Dispensed to Vehicle with $20/tonne CO_2 Carbon Tax ($/PLE)

The price equivalence line shown identifies the points at which hydrogen becomes a viable fuel purely on a delivered cost basis. In this example the cost of hydrogen becomes competitive around 2030 and moves to later periods as the carbon cost is increased. This is a result of the relativities in the carbon intensities of the ULP and the hydrogen.

Similar graphs are shown for coal gasification in Figure B 8 and electrolysis in Figure B 9. The much higher cost of producing hydrogen by electrolysis results in the hydrogen never becoming competitive with petrol even where a high carbon price is applied and zero emissions for the electricity to produce the hydrogen is assumed.

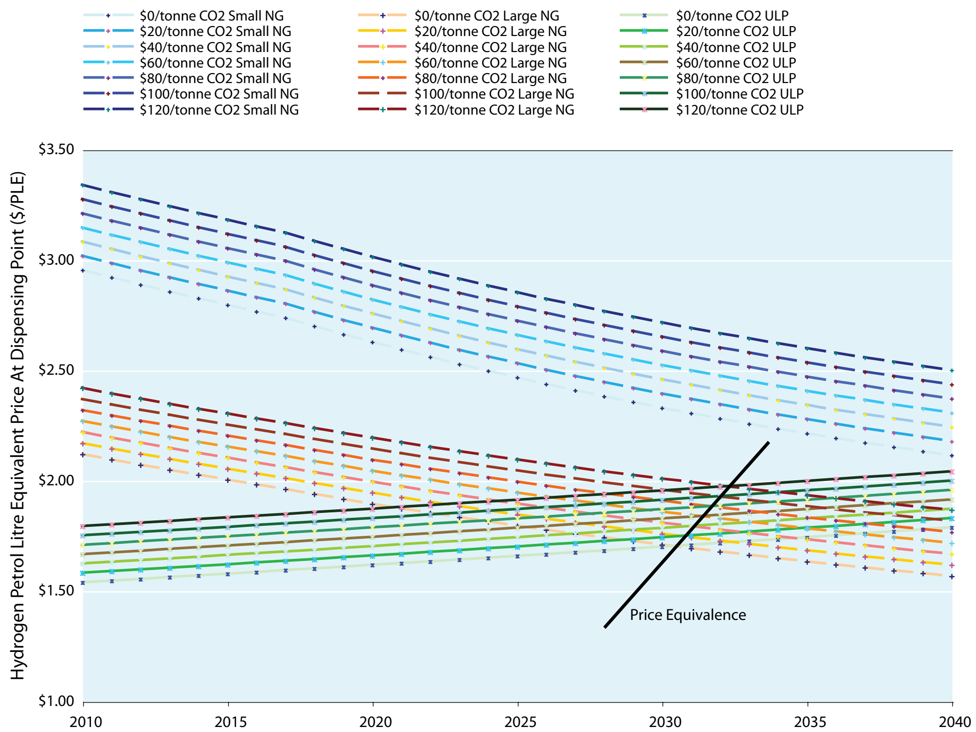


Figure B 7 Impact of Carbon Tax on Natural Gas Reforming ($/PLE)

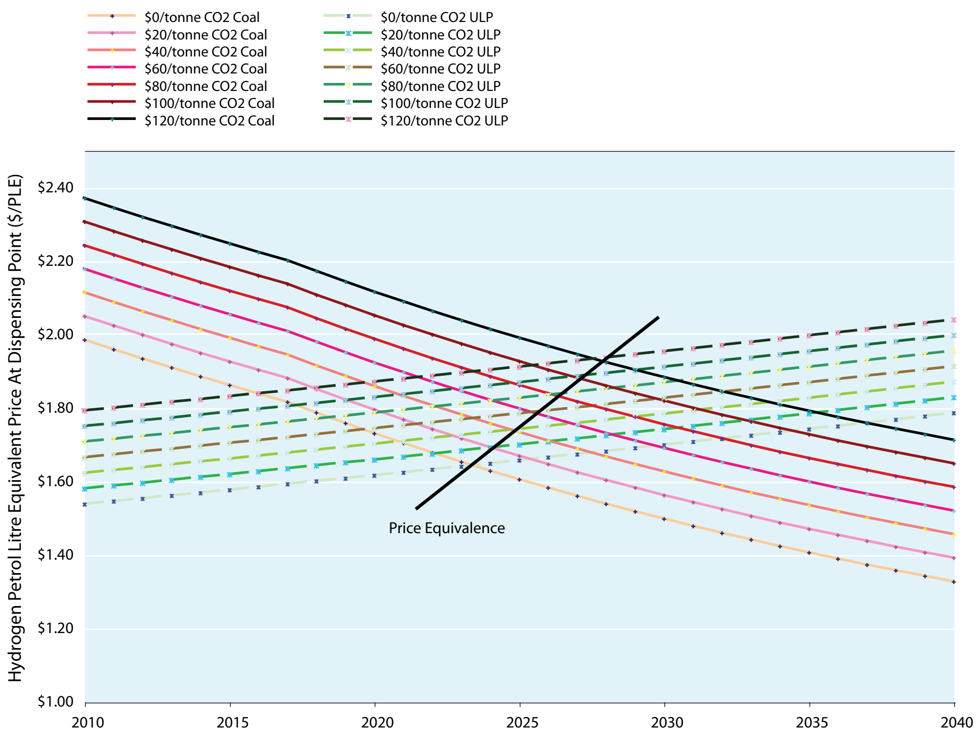


Figure B 8 Impact of Carbon Tax on Coal Gasification ($/PLE)

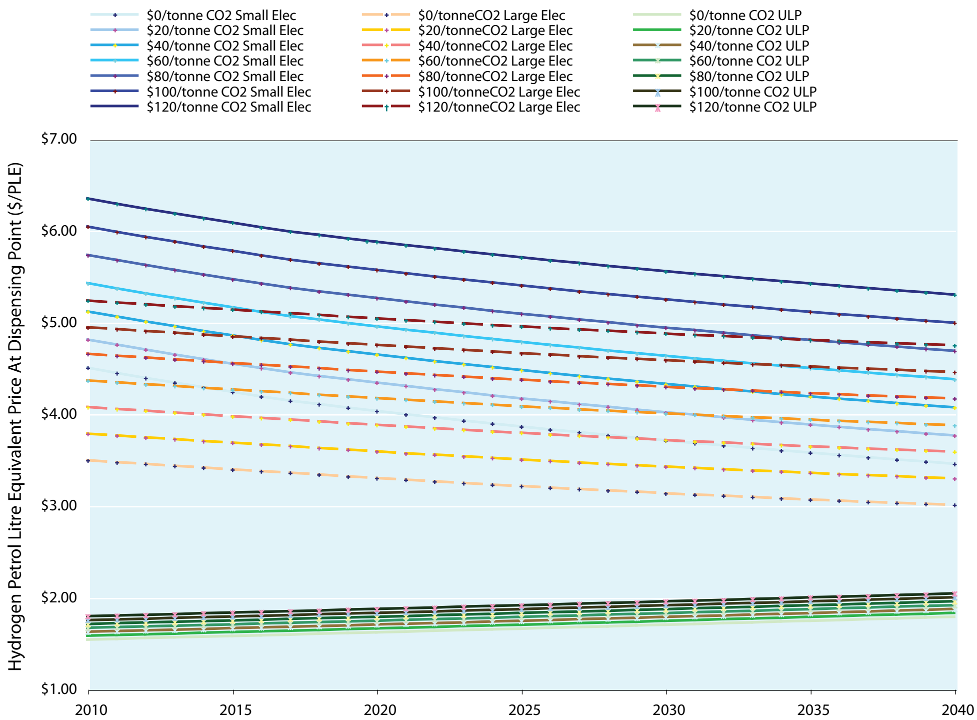


Figure B 9 Impact of Carbon Tax on Electrolysis ($/PLE)

B.3.3 Potential market segments for hydrogen as a transport fuel

The uptake of hydrogen fuel for transport use will not become widespread until a fuelling infrastructure becomes available. There are a few transport sectors where the need for widespread networks of refuelling stations is not a critical requirement. These include:

- Bus networks where operation is centred around a main depot. This would require a single refuelling site to service the dedicated vehicle fleet.
- Other fleet operators including government and council businesses as well as private businesses
- Taxi operators

These operators would, in general, only make a decision to use hydrogen fuel if it were economic to do so, although some government departments may do so for other, more altruistic reasons. Private vehicle owners would not invest in hydrogen fuelled vehicles as their primary transport until the refuelling infrastructure was sufficiently widespread that they were largely unrestricted in their travel. To get to this point, some form of government assistance would likely be required.

B.4 Electricity generation markets

B.4.1 Introduction

The generation of electricity utilising fuel cells will generally be carried out in small scale units of between 1 and 300 kW. Generation requirements greater than 300 kW could be achieved by installing multiple units. These technical features of fuel cell generation mean that they would be installed in the distribution system close to the customer load that they serve. For this reason the following discussion of the Australian electricity generation and supply markets will be focussed on the retail side of the system rather than on the wholesale competitive markets.

The existing electricity generation system consists of the majority of electricity generation plants being large and often located long distances from the major loads. This type of electricity system results in a system comprised of large generators, long transmission distances, and large distribution systems. Although large transmission and distribution losses and costs are incurred, these systems develop because of the economies of scale in generation and the increase in conversion efficiencies that may be achieved by using large scale generating plant located close to the fuel supply.

This incumbent system of electricity generation has not, historically, been designed in order to allow the connection of a large number of small scale generators to the distribution system. This results in a number of difficulties, both technical and regulatory in nature, when it is desired to utilise large numbers of small scale generators. Fuel cell generators will almost exclusively fall into the category of distributed generation resulting in a number of specific considerations in the policy environment that will impact on the uptake of these systems.

B.4.2 Market characteristics

Australia's electricity markets comprise a number of large grid based systems, isolated power supply systems supplying remote towns and mining operations plus stand alone generation systems supplying remote tourist operations, homesteads and small towns. The principal grids are the National Electricity Market (NEM), the South West Interconnected System (SWIS) and the Darwin Katherine Interconnected System (DKIS). Smaller but still important potential markets for high temperature solar thermal include the Alice Springs-Tennant Creek system, the Mount Isa grid and the Pilbara System in Western Australia.

Fossil fuel is the dominant form of electricity generation in Australia (Table B-2). Coal-fired generation contributes 75 per cent of the total generation in Australia and a larger proportion in the Mainland states. Natural gas contributes 14 per cent and renewable energy contributes only 9 per cent, with most of this coming from hydro-electric generation. Wind and other forms of renewable energy currently contribute less than 2 per cent, with solar thermal not supplying to grids at all in Australia.

Table B 2 Generation by Technology and Fuel Type (GWh/year)

	Qld	NSW	Vic	Tas	SA	WA	NT	AUST
Black Coal - Steam Turbine	44,100	63,500	0	0	5,000	8,400	0	121,000
Brown Coal - Steam Turbine	0	0	44,975	0	0	0	0	45,000
Gas - OCGT	3,610	1,270	2,090	2,050	410	6,990	1,580	18,000
Gas - CCGT	629	0	0	0	751	1,770	490	3,600
Gas - Cogeneration	0	513	0	0	1,267	3,553	0	5,330
Gas - Steam Turbine	0	0	567	0	1,512	2,664	0	4,740
Liquid Fuels - OCGT	20	0	0	0	0	1,413	988	2,420
Liquid fuel - Steam	0	0	0	0	1	0	0	1
Hydro	632	5,200	730	10,500	0	0	0	17,100
Wind	42	50	249	479	963	66	0	1,850
Biomass	711	517	94	289	46	143	0	1,800
Geothermal	0	0	0	0	0	0	0	0
Solar Thermal/PV	0	0	0	0	0	0	0	1

Source: MMA analysis from ESAA (2007), WA IMO (2007), Verve Energy (2007) and NEMMCO (2007)

Despite numerous support measures, including mandating the purchase of up to 9,500 GWh of generation, the proportion of renewable generation has fallen from 10.5 per cent in 1996/97 to 9.4 per cent in 2006/07. High electricity-demand growth rates over the past decade have been mainly met by increased natural gas fired generation and higher brown coal generation. Ongoing drought has also limited the contribution from hydro-electric systems.

Fossil fuels dominate generation due to the low cost and maturity of these generation technologies. Nonetheless, there could be an increasing role for renewable energy as long as it can become competitive. Electricity demand is projected to grow by between 1.7 per cent and 2.1 per cent per annum over the period to 2050. The need to curb emissions of carbon dioxide may also favour renewable energy generation.

B.4.3 Distributed generation

Distributed generation is under vigorous development throughout the world. For example, there is now substantial government support for these developments in both the USA and the UK. California has developed a comprehensive strategic plan for the development of distributed generation in the state. In 2001, the UK Department of Trade and Industry also released a substantial report on distributed generation. In some European Countries (such as Germany and the Nordic Countries), many new small scale distributed generators have been commissioned, supported by high energy prices, policies that favour biomass generation, policies favouring DG generally, and the opportunity for cogeneration to supply district heating as well as electricity.

In Australia, there has also been a high level of interest in distributed generation but not much implementation of it. In the mid-1990s, it was felt that a benefit of market reform would be increased adoption of distributed generation. Prior to this reform, public utilities were disinclined to support distributed generation as they had a bias towards large-scale, centrally-dispatched generation.

With market reforms, it was thought that better locational signals and the lower financial risks associated with small scale generation would lead to a higher level of distributed generation. However, the increase in distributed generation has been quite modest. The low level of adoption has been due to:

- Low wholesale prices for electricity due to a surplus of generation
- High capital costs of distributed generation equipment
- High and increasing prices, on a delivered basis, for natural gas (the principal fuel for distributed generation) and the high cost of renewable generation
- Market rules that do not allow for the full financial benefits of distributed generation (such as avoided transmission upgrades, lower losses and grid support) to be captured by the distributed generators as a matter of routine.

In the light of the increasing acknowledgement of greenhouse gas emissions as a serious problem it would appear that meaningful measures for the reduction of GHG emissions are likely to be implemented in Australia. Some DG technologies will benefit from this either because they use renewable forms of energy or, while using a fossil fuel, are highly efficient. Some high-efficiency technologies such as fuel cells, used for DG, are expected to benefit from this to a greater extent than the same technologies applied on a larger scale. The following factors are now, or soon, likely to favourably influence the relative competitiveness of DG:

- Decreasing capital costs of DG technologies, applied on a small scale, particularly those that are inherently modular and, therefore, provide relatively modest economies if large numbers of modules are installed at a given site[121]
- Increased electricity prices due to a carbon tax or equivalent imposing a penalty on transmission and distribution losses as well as on fossil fuel generation.
- High efficiency of (some) DG technologies

Transmission and distribution comprise over half the total delivered cost/price (Table B 3). While it would be difficult for investors in DG to appropriate any of these system benefits, such benefits may result in some decrease in costs and allowable tariffs. This would then result in a lower delivered cost of electricity and make it more difficult for DG to compete than would otherwise be the case. Significant DG penetration/diversity would be required to provide such system benefits and would occur, if at all, in the longer term. No attempt has been made to quantify any decrease in such costs.

Table B 3: Approximate Break-up of the Retail Electricity Price

Component	Approximate Cost/Price/ Charge $/MWh	Comments
Wholesale Electricity Price	40	Yellow shading indicates system costs that may be reduced via DG.
High Voltage Transmission	12	
High Voltage Transmission Losses	2	
High Voltage Distribution	15	
Low Voltage Distribution	35	
Distribution Losses (HV plus LV)	3	
Sub-total	102	
Electricity Retailer Margin	3	Green shading indicates transactional costs - unaffected by DG.
Market Charges	5	
Certificate Schemes	7	
Contract Premium	5	
Retailer Margin	3	
Sub-total	21	
Total (exclusive of GST)	130	

Source: MMA

121 This assumes the same manufacturing costs which are significantly influenced by the rates of production of the modules.

It is quite possible that time-of-use electricity (TOU) pricing will be introduced. The objective would be to load shift from peak to off-peak periods. This would decrease average electricity prices – to the degree that it was successful. The major contributor to the growth in peak demand, however, is not amenable to load shifting: air conditioning. The effect of TOU pricing has not been considered.

B.4.4 Institutional arrangements

Electricity markets comprise a number of components with different institutional arrangements governing each component. A wholesale market has now been established for most of the major grid systems, including the National Electricity Market (NEM), the West Australian Electricity Market (WEM) and the NT market. Transactions occur on spot exchange in most of these markets, but long term contracts and hedges are still the dominant form of transactions between generators and retailers of electricity. Market rules have been established to govern the operation of these spot markets.

Where small scale generators are connected directly to the distribution system the input of electricity into the network is governed by individual agreements between the distribution companies and the generators. A number of specific issues arise in terms of system stability, appropriately valuing the generation and providing a fair price to the supplier.

Direct Benefits of Distributed Generation

The direct benefits of DG, assuming the owner is a party that is independent of the distribution system owner, may include:

- The value of the electricity
- The value of the waste heat, depending upon its utilisation
- The value of any certificates that may be merited.

Benefits due to deferral or avoidance of investment

The installation of DG may make it possible to defer or avoid investment in:

- Additional central generation
- Additional high voltage transmission
- Additional high voltage distribution
- Substation augmentation
- Distribution system augmentation.

The beneficiary of deferral/avoided augmentation in respect of the last three would be the owners of the distribution system to which the DG facility would be connected. Were they also to invest in the DG facility, there would be no issue with regard to payments. If another party owns the DG facility, mutually acceptable payment arrangements may be negotiated. There are arrangements in place that cater for small scale generation net metering. There are no arrangements in place for the investors in DG capturing any of the benefits that may be realised by owners of central generation and network infrastructure facilities. Indeed, the current regulatory regime generally provides a disincentive for distribution system owners, in many instances, to cooperate with investors in DG or to themselves install DG.

Other potential benefits

- Greater system reliability.
- Lower system losses.
- Depending upon the mix of technologies and applications, decreased overall GHG emissions.

B.4.5 The current regulatory regime and DG

Overview

Owners of distribution systems are allowed to earn a regulated return relative to the value of their assets. Growth of their businesses depends, in large part, on growth in the value of their assets. Tariffs are set, and periodically reset, by regulators accordingly. This is done on a broad, regional basis. The current regulatory regime would not cater for DG on a local basis.

- There is an incentive to maximise investment, within the bounds permitted by the regulator
- If other parties install DG within a distribution system, resulting in the deferral or even elimination of the need for additional investment by the distribution system owner, this constrains the growth of the latter's business
- If other parties install DG within a distribution system, this may result in decreased utilisation of the distribution system and lead to a
  - decrease in the deemed value of the assets of the distribution system and, hence,
  - to a decrease in the revenue the regulator permits the owner to derive.

Who, then, could be the beneficiary of what these "additional benefits" and how should they be recognised and arrangements put in place for ensuring that they are real and transferring a portion of them to investors in DG? It would appear that the beneficiaries are the community at large in terms of:

- decreased or deferred investment, but not necessarily resulting in lower tariffs than would otherwise be the case
- greater total system reliability
- possible decreases in GHG emissions
- possible reductions in criteria and toxic emissions.

Established Urban Distribution Systems

In established areas, DG is likely to delay the augmentation requirements of the distribution system by reducing load growth. This will reduce/defer capital requirements but it will also reduce/defer revenue increases allowed by the regulator.

In areas where network augmentation is required to meet load growth, proponents of DG may be able to obtain some benefits by entering into discussions with the distributor. Regulators have allowed the pass-through of network support payments made by distributors to DG owners that have led to improved reliability and deferred/avoided network augmentation, especially where augmentation is difficult e.g. where easements for new assets are difficult to obtain.

New Urban Residential or Industrial/ Commercial Estates

In new estates, DG would reduce the size of the distribution system or its capacity. Again whilst this lowers capital requirements, it also reduces the regulated revenue allowed. DG can, however, capture the entire energy supply business in new areas. Under current legislation, this requires an exemption from the Australian Energy Regulator, considered on a case-by-case basis.

Rural Distribution Systems

The main benefit in rural distribution systems for DG is in the increase in reliability this could bring. In rural distribution systems, supply is mainly achieved by long thin radial lines. A generator at the end of the distribution system would increase reliability significantly. As load growth is generally not significant in rural systems, the distributor would probably not be required to augment the system. While DG will reduce the load to be imported from the network, this reduction in load will be balanced by price increases in the general network. The distributor will thus likely be indifferent.

Regulatory Changes

As discussed, the present regulatory regime does not recognise the system benefits that DG could provide. The uptake and penetration of DG would be greatly assisted if there were such recognition but it would have to be applied in restricted localities to be effective. This would involve considerable changes to regulations and would greatly increase administrative costs.

B.4.6 Role of renewable generation

Renewable generation currently plays a limited role in Australia's electricity markets. Renewable energy generation has grown but its share of total generation has remained steady. Although wind and other new renewable generation have grown, hydroelectric generation has fallen as a result of prolonged drought conditions.

Growth in renewable generation has been mainly through Government support. Measures implemented to support renewable generation includes:

- Federal and State Government imposed mandatory targets for the purchase of renewable generation.
    - The Federal Government's MRET scheme came into operation in 2001 and will mandate the generation of 9,500 GWh of renewable generation from 2010 onwards.
    - Victoria, Queensland, NSW and Western Australia have also imposed their own targets, tallying up to around 27,000 GWh of mandated renewable generation by 2020 (see Table B 2).
    - However, with the recent election of the ALP to the Federal Government means that these schemes are likely to be replaced by a single, expanded, MRET target of 45,000 GWh of new renewable generation by 2020.
    - When added to pre-existing generation, this will give a total level of renewable generation of 60,000 GWh or about 20 per cent of the total electricity demand that is forecast for 2020.
- Green Power Schemes, which grew by 25 per cent over the last year as more people become concerned over climate change and now comprises around 1,500 GWh of generation.
- Renewable Energy Development Initiative (REDI) and Renewable Energy Equity Fund (REEF), which have been used to develop novel renewable energy technologies.
- Renewable Remote Power Generator Generation Program (RRPGP)
- Photovoltaic Rebate Program (PVRP)
- Low Emission Technology Development Fund, which has funded some demonstration projects for low emission technologies, including a 150 MW solar PV concentrator plant.
- The new Federal Government has promised to establish another $500 million fund to demonstrate and develop new renewable energy technologies.

However, despite the support from government programs, renewable energy generation is still more expensive than fossil fuel generation options. Only in remote area power supply systems is renewable generation now competitive with fossil fuel alternatives

B.5 Market potential for fuel cells in electricity generation

B.5.1 Market segments

Potential for Fuel Cells in New Residential Dwellings

Over the past few years there have been approximately 100,000 new houses built in Australia each year. Since about 2000, the increase in new houses has levelled off at this value as can be seen in Figure B 10. Over the same period the number of new dwellings that are not houses – largely apartments – has continued to increase to a value of approximately 45,000 to 50,000 new dwellings each year.

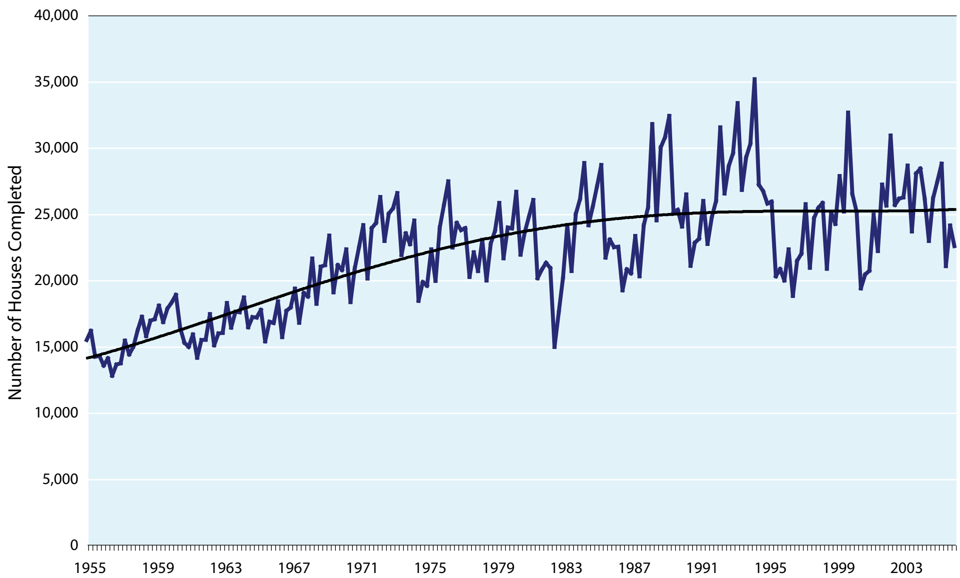


Figure B 10 Historical Housing Completions

If each new house built was required to have 1 to 3 kW of distributed generation installed it would amount to an annual capacity increase of 100 to 300 MW. Incorporating DG into new apartment construction would increase this value to 150 to 450 MW or greater as apartment building could potentially utilise larger generating units. This is a significant increase in capacity when compared to the annual average increase in peak demand over the past five years of 875 MW for the eastern states, where most of the new housing construction is occurring.

These estimates indicate a theoretical maximum and it is considered unlikely that any such requirement would be imposed on the housing construction industry at the moment. However, in the new residential market alone there is significant potential for relatively large quantities of DG to be installed. This potential market would likely be shared between a variety of technologies that would compete on the basis of cost and environmental performance. The technologies likely to be included in this mix are photovoltaics, small wind turbines, combustion engines and fuel cells of various types.

Potential for Fuel Cells in New and Existing Commercial Buildings

There is significant potential for fuel cell generation in commercial buildings; however it is difficult to determine a reliable value of the potential MW that could be installed. Data on the number of high rise buildings in the CBD in the major Australian cities allows the determination of a maximum potential penetration of fuel cells in these applications. These CBD locations are often tightly constrained in terms of electricity distribution and therefore may provide additional benefits to the installer. Supply of natural gas to fuel these CBD based fuel cells could also prove to be difficult as distribution networks for gas have become strained in some areas.

The data on CBD buildings is presented in Table B 4. Based on the data for the four largest cities there is a total of 1,800 high rise buildings and if a 300 kW fuel cell was installed in each of these a maximum of 550 MW of fuel cell generation could potentially be installed. Many of these sites would use more than the 300 kW assumed so the potential capacity could be larger.

Other potential facilities where units of this scale could be installed include hospitals, government buildings and industrial facilities. Including these facilities could easily double the predicted potential indicated in the table.

Table B 4 Potential for Fuel Cells in CBD High Rise

Location	Number Completed	Number Approved	Total	Potential Fuel Cell Capacity (MW)
Sydney	851	34	885	266
Melbourne	511	70	581	174
Brisbane	231	13	244	73
Perth	112	16	128	38
Total	1,705	133	1,838	551

B.5.2 Economics of fuel cell electricity generation

Methodology

Generation costs have been estimated using MMA's GENCHOICE model. The model calculates the long run marginal cost for new generation plant. The long run marginal cost of a new generation option is equal to the present value of capital, fuel and operating costs divided by the present value of the output over the expected life of the plant. For each generation option, the full costs of generation are modelled. Costs include:

- Capital cost, which are modelled as a function of capacity (to reflect the economies of scale with unit size).
- Coal, biomass, liquid fuel, natural gas, and hydrogen costs are modelled as delivered cost for the fuel on a $/GJ basis and a heat rate for each technological option.
  - The natural gas cost is equal to the forecast city gate price for the nearest city gas node as forecast by MMA plus any additional transmission cost (in some locations the additional transmission cost may be negative if the plant location is closer to the gas field than the city gate node).
- Non fuel operating and maintenance costs.
- Transmission connection costs (including deep connection cost if the plant supplies more than the local loads).

- Network fees for backup supply.
- Sequestration costs (if any).

Long run marginal costs are calculated for each year of entry of the plant from 2010 to 2030. In this way, trends in capital costs, conversion efficiency and fuel prices are captured. Costs are also affected by the following:

- Carbon prices. The model adds a variable cost equal to the carbon price multiplied by the emission intensity of the generator. Greenhouse gas emissions from the combustion process result from the conversion of carbon in the fuel to CO_2. The key parameters in determining the CO_2 emissions are therefore the quantities and types of fuel used and the carbon content of the relevant fuels. Carbon contents and combustion emission intensities for each different coal and gas supplying electricity-generating facilities have been identified and incorporated into the model. Emission intensities are based on the emission intensities of fuels supplying power stations as estimated in the National Greenhouse Gas Inventory (NGGI).
- Locational benefits in the form of avoided transmission costs. These benefits, if any, are treated as negative costs. Avoided transmission upgrade costs are treated as negative capital costs. Avoided transmission use of system charges are treated as negative variable costs.

Renewable generation may also provide other benefits. For example, renewable generation provides generators with a hedge against fuel supply risks. Fossil fuel based generators can face significant risks over the future cost of the fuel, even when they enter into a long term contract for fuel (as these often contain price re-openers). Ample supplies of coal and natural gas have meant that the risks of price changes for fuel have been minimal in Australia.

However, in some regions of Australia, recent developments have increased the risk, particularly in remote location. For example, fuel prices have increased sharply in Western Australia and there is considerable uncertainty over future prices for natural gas in particular. Coal prices have increased markedly for new coal contracts across the board due to increased world prices for coal.

Future emission prices are also highly uncertain, with prices depending on the targets on emissions imposed and the cost of abatement. This means that owners of fossil fuel plants also face uncertainties over future cost imposts on emissions.

Selection of generation technologies

In examining the generation costs utilising hydrogen fuelled fuel cells a mixture of unit scales have been selected that could be used to supply different levels of demand. The plants examined are:

- A 300 kW PEM fuel cell for use in commercial or residential buildings and/or clusters of individual homes
- A 300 kW direct fuel cell (e.g. molten carbonate) that internally reforms natural gas or other fossil fuels
- A 2 kW PEM fuel cell used in a single household environment
- A 2 kW direct fuel cell (e.g. solid oxide) that internally reforms natural gas or other fossil fuels

The PEM fuel cells will consume pure hydrogen from either a delivered pressurised tank or from a local hydrogen generation unit. The direct fuel cells will be connected directly to the natural gas supply.

Fuel Cell Costs

Today, the most widely deployed fuel cells[122] cost between approximately $US3,000 and $US4,500 per kilowatt; by contrast, a diesel generator costs $US800 to $US1,500 per kilowatt, and a natural gas turbine can be $US400 per kilowatt or even less.

Proton Exchange Membrane fuel cells are undergoing intense development work in many countries particularly the US as a potential replacement for petrol fuelled internal combustion engines in automobiles. At the current time

122 These are the direct fuel cells in the 300 kW capacity range utilising a direct feed of natural gas.

a number of companies are carrying out on road trials of these vehicles that are fuelled by compressed hydrogen. To achieve comparative cost targets with IC engines these automotive fuel cells need to achieve a complete drive train cost in the vicinity of $US30 to $US50 /kW. Current estimates of this cost for production of 500,000 units using current technology are of the order of $US110/kW.

Japan has committed itself to a major program of introducing fuel-cell cogeneration systems nation-wide. Relatively large numbers of small PEM fuel cells are being deployed in Japan as cogeneration systems in homes.

In 2003, Phase I of the Millennium Project related to automotive and residential fuel cell systems got under way. Phase I was intended to stimulate product development, field testing and set codes, standards and safety regulations for domestic fuel cell applications. The latter were required before large scale field trials could be undertaken.

Phase II of the Millennium Project, from 2005 to 2010, sees a large scale monitoring program of installations being undertaken (2005 to 2007) to demonstrate proof of reliability and energy savings and allow standardisation, followed by the development of markets. By 2010 METI has set a target of 1.2 million fuel cell cogeneration units across Japan. This represents 1.2 GW of distributed generation and some 2 per cent penetration of Japan's residential households.

Phase III will see the wide-spread diffusion of the fuel cells as systems become stable and mass production drives down prices. An indicative market penetration of 10 million cogeneration units is envisaged, meaning some 20 per cent residential market penetration. The 1 kW fuel cell cogeneration systems are installed directly in consumers' homes. They are designed to generate the first kilowatt of electricity and all required hot water.

In 2005 the Ministry of Economy, Trade and Industry (METI) announced that it would subsidise the installation of 500 of the 1 kW fuel cell cogeneration units at a program cost for 2005 of about US$ 26 M or $54,500 per unit. In 2006 the program target was 700 of the 1 kW units at a program cost of about US$28 M or $41,000 per unit.

Ebara Ballard has quoted the results for its 102 systems installed in 2005 as having a 75 per cent overall efficiency, primary energy savings of 21.8 per cent and a 36 per cent reduction in carbon dioxide emissions.

Clearly, at these costs these systems are pre-production and are not economic. However, they do demonstrate that the technology is viable and system costs will decrease significantly as production volumes increase.

Costs for Modelled Options

The capital costs for fully installed fuel cell options and the fuel to be supplied are shown in Table B 5.

Table B 5 Costs of Modelled Options

Option	2010 Capital Cost ($/kW)	Fuel Supply	2010 Fuel Cost ($/GJ)
3 kW PEM Fuel Cell	$5,400	Small Electrolyser	$68
3 kW PEM Fuel Cell Mass Produced[123]	$1,000	Small Electrolyser	$68
3 kW PEM Fuel Cell	$5,700	Small NG Reformer	$24
300 kW PEM Fuel Cell	$3,700	Small NG Reformer	$24
300 kW PEM Fuel Cell	$3,700	Medium Electrolyser	$56
300 kW PEM Fuel Cell	$3,700	Medium Electrolyser Low Cost[124]	$16
300 kW DFC Fuel Cell Low Cost	$3,500	Commercial Natural Gas Supply	$8.60
300 kW DFC Fuel Cell High Cost	$5,200	Commercial Natural Gas Supply	$8.60
3 kW DFC Fuel Cell Low Cost	$3,700	Residential Natural Gas Supply	$13.00
3 kW DFC Fuel Cell High Cost	$5,500	Residential Natural Gas Supply	$13.00

123 Costs for this option meet the DOE target for mass produced automobile power supplies

124 Costs for the low cost electrolyser assume significant improvements in efficiency and manufacturing economies of scale

Assumptions

Initial physical and cost assumptions and key escalators are shown in the following Table B 6.

Costs of Fuel Cell Generation

The modelled cost of electricity generation for each of the fuel cell options examined is shown in Figure B 11, along with the supply costs of grid electricity for residential and commercial customers.

This data in this chart show that the electrolyser hydrogen supply options are clearly not viable options, and as mentioned earlier it is unlikely one would use electricity to generate hydrogen to generate electricity. The only situation where this would be applied is for intermittent renewable electricity generation in remote regions as a method for storing the energy. These options will not be considered further.

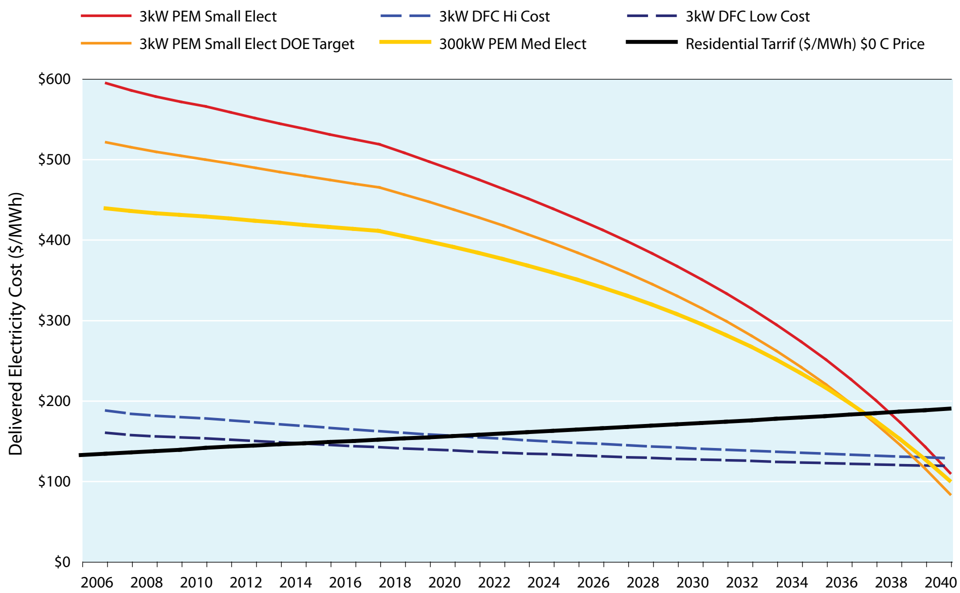


Figure B 11 Levelised Cost of Generation utilising Fuel Cells ($/MWh)

Table B 6 Technology costs and performance assumptions, mid 2007 dollar terms

Option	Life	Auxilliary Load	Sent-out Capacity	Capital Cost, 2010	Capital Cost Deescalater, 2010 to 2020	Capital Cost Deescalater, 2021 to 2030	Heat Rate at Maximum Capacity	Efficiency improvement	Variable Non-Fuel Operating Cost	Fixed Operating Cost
	Years	Per cent	MW	$/kW so	Per cent pa	Per cent pa	GJ/MWh	Per cent pa	$/MWh	$/kW
Fuel Cell Options										
300 kW PEM	25	5	0.3	3,700	3.0	2.0	6.5	0.2	2.6	50
3 kW PEM	20	5	0.003	5,700	3.0	2.0	6.5	0.2	2.6	50
300 kW DFC	25	5	0.3	3,500-5,200	2.0	2.0	6.5	0.2	2.6	50
3 kW DFC	20	5	0.003	3,700-5,500	3.0	2.0	6.5	0.2	2.6	50
Renewables for Comparison										
Hydro Upgrades	40	2	100	2,500	0.5	0.5	na	0.10	1	5
Wind	25	1	99	1,822	2.0	0.5	na	0.20	2	35
Biomass - Steam	30	6	28	2,318	1.0	0.5	11.5	0.10	4	50
Biomass - Gasification	25	10	27	2,484	2.0	1.0	11.0	0.10	5	50
HT Solar thermal plant	40	1	99	2,800	2.0	1.0	na	0.30	2	50
HT Solar thermal with storage	40	5	95	4,760	2.0	1.0	na	0.30	2	50
HT Solar Assist	40	1	99	2,100	2.0	1.0	na	0.30	2	50
Geothermal - Hot Dry Rocks	25	10	45	2,153	2.0	0.5	12.0	0.10	3	70
Concentrating PV	30	3	97	2,700	1.0	1.0		0.10		

Note: Plant capacity, efficiency and cost data based on a sent out basis; na = not applicable

The small-scale natural gas fuelled options, either directly or through a reformer, are shown in Figure B 12. These data show that a few of these options would be competitive with residential electricity supply in the medium term

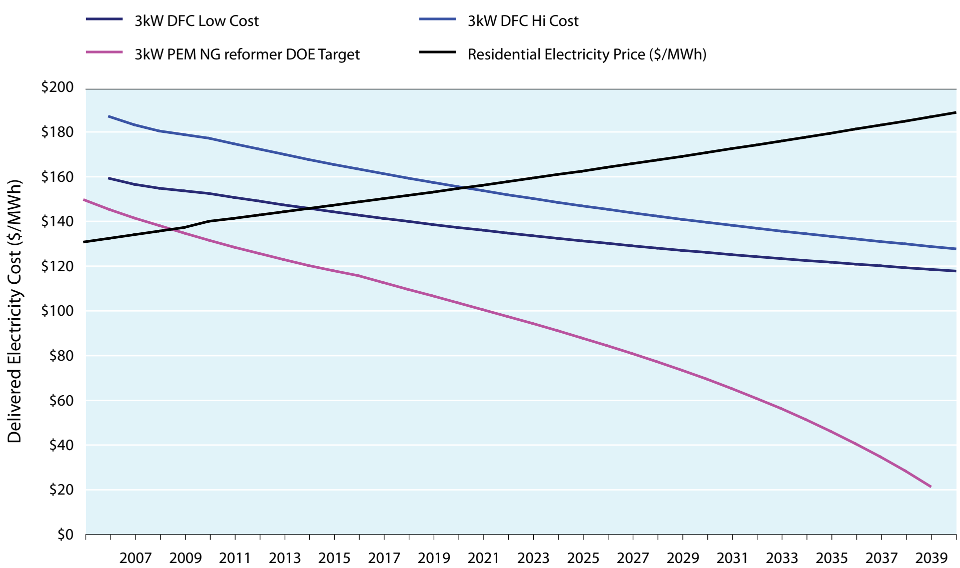


Figure B 12 Cost of Delivered Electricity from Natural Gas Fuelled Fuel Cells

The medium scale natural gas fuelled options, either directly or through a reformer, are shown in Figure B 13. These data show that a few of these options would be competitive with residential electricity supply in the medium term.

In fact the low cost DFC fuel cell appears to be competitive in about 2010; however the assumptions underlying the costs assigned to this option are unlikely to be met in this time frame. In particular the production volumes that would be required to lower the costs to this value would be difficult to achieve by as early as 2010.

The key parameter defining the success of a distributed generation technology is whether the cost of supplied electricity from the fuel cell is less than the grid supply. The fuel cell options that are likely to become economic at a residential level are shown in Figure B 14.

Two of the options shown are low cost scenarios that represent an optimistic ideal outcome on development work being carried out, and should therefore be treated as a possible outcome that is not of high probability. More likely is that a number of these technologies become economic in the period leading up to 2020, as indicated by the generation costs of the higher cost DFC and the 300 kW PEM fuel cell.

In the case of the 300 kW units these would likely be installed in new residential estates to power clusters of new homes or in apartment building in order to compete against a residential tariff. Where waste heat can be harnessed for heating and/or cooling the economics will improve further.

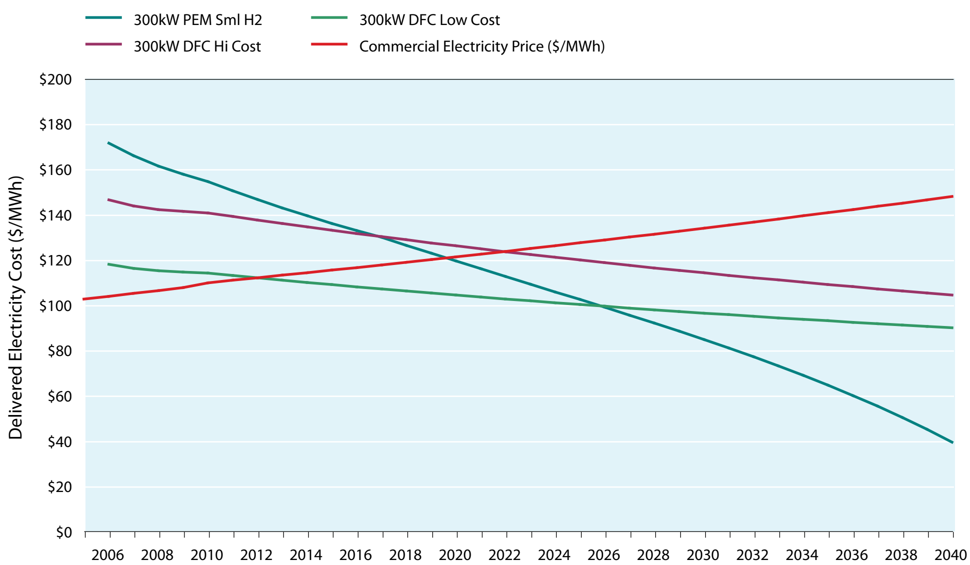


Figure B 13 Cost of Delivered Electricity from Medium Scale Natural Gas Fuelled Fuel Cells

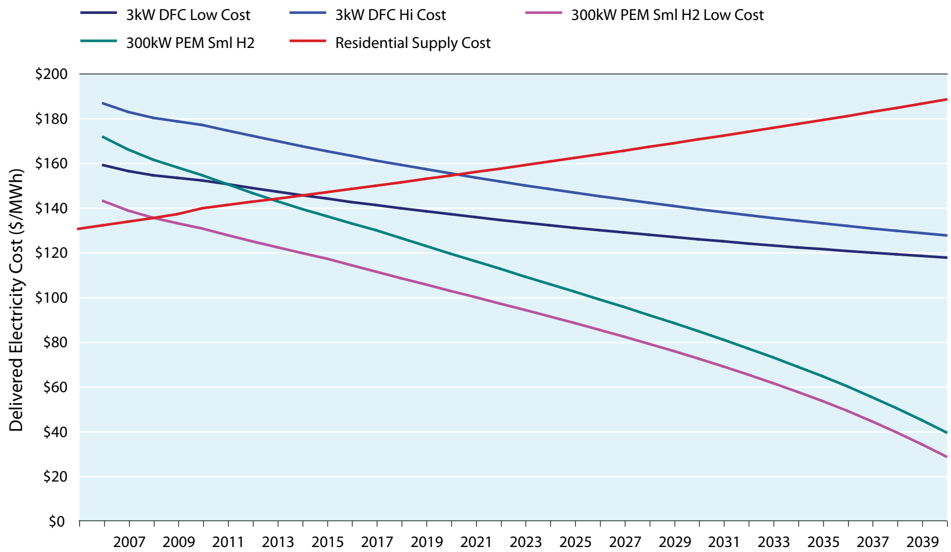


Figure B 14 Fuel Cell Options Competitive with Residential Grid Supply Electricity

The options that are likely to become competitive with the more stringent commercial electricity rates are shown in Figure B 15. Not surprisingly the fuel cell generation options that are competitive in this market are the larger 300 kW systems that do benefit from economies of scale. As was the case with the residential systems the low cost option for the 300 kW DFC unit should not be viewed as a likely outcome but a possible outcome.

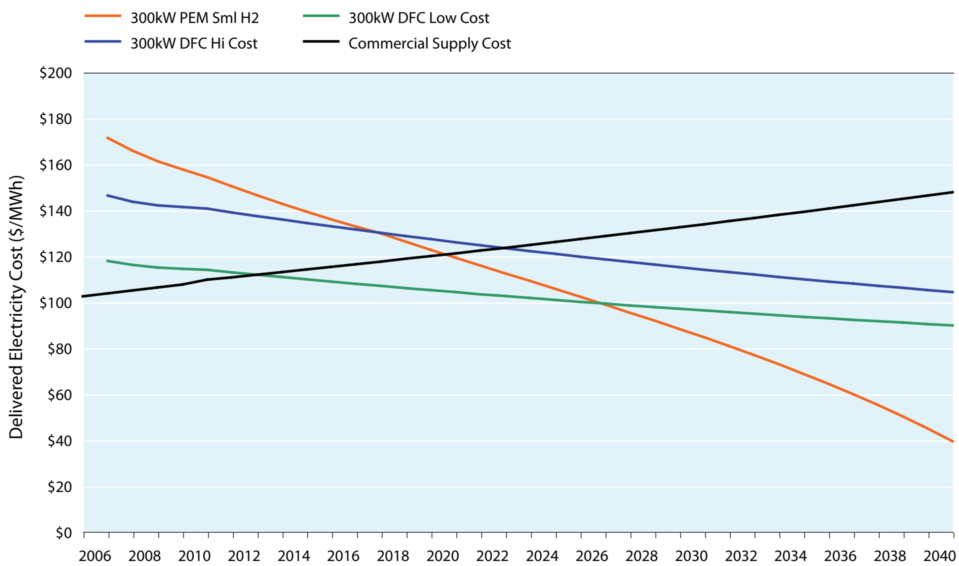


Figure B 15 Fuel Cell Options Competitive with Commercial Grid Supply Electricity

Sensitivity of the Generation Costs to Assumptions

The high level of uncertainty in the costs associated with fuel cell generation means it is important to understand that changes in these parameters will affect the delivered electricity price.

The impacts on the delivered electricity cost for fuel cell generation in response to variations in the capital cost of the system is shown in Figure B 16. This graph shows that most of the generation options exhibit similar trends and in most cases a 10 per cent increase in capital cost results in an increase of between 4 and 6 per cent in the electricity price.

However the case where the DOE target value for capital cost is used the electricity price is largely invariant to changes in the capital cost. This behaviour is attributed to the fact that because at these low capital cost values the electricity price is largely dominated by the cost of fuel. A high sensitivity to the fuel cost is expected for this scenario. This is the case and is shown in Figure B 17 where this scenario shows a much greater dependence on fuel cost than the other options.

The impacts of a carbon trading or carbon tax environment on the economics of 3 kW DFC fuel cells is shown in Figure B 18 for a range of carbon prices that are assigned to all emitting industries and processes. In developing these curves the carbon cost is applied to the CO_2 associated with:

- Emissions generated in the production of hydrogen
- Production of the electricity utilised as an alternative to fuel cell generation

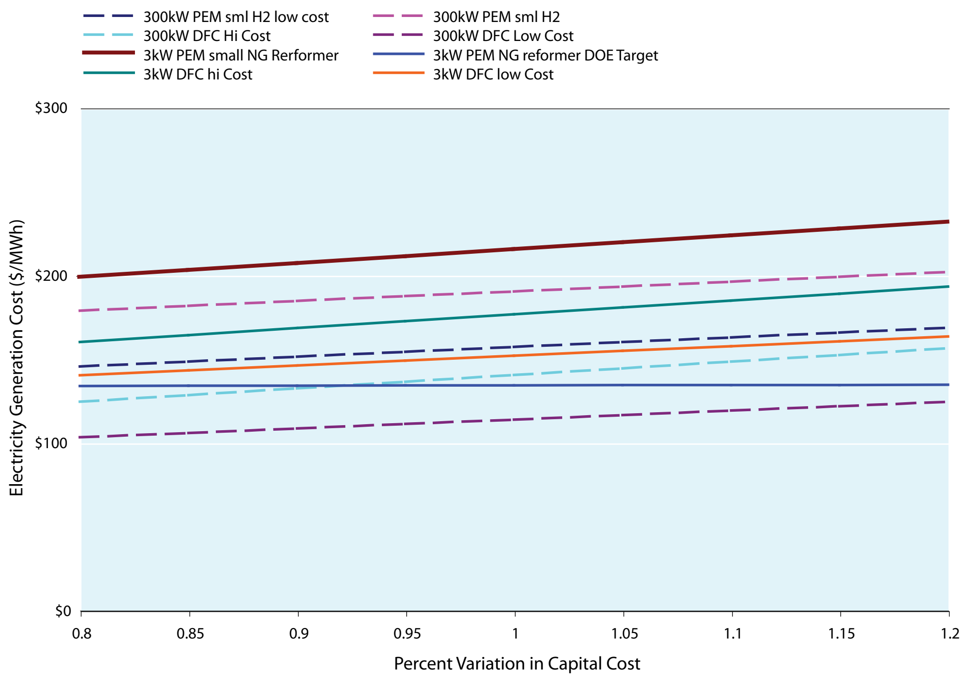


Figure B 16 Sensitivity of Electricity Cost to Capital Cost

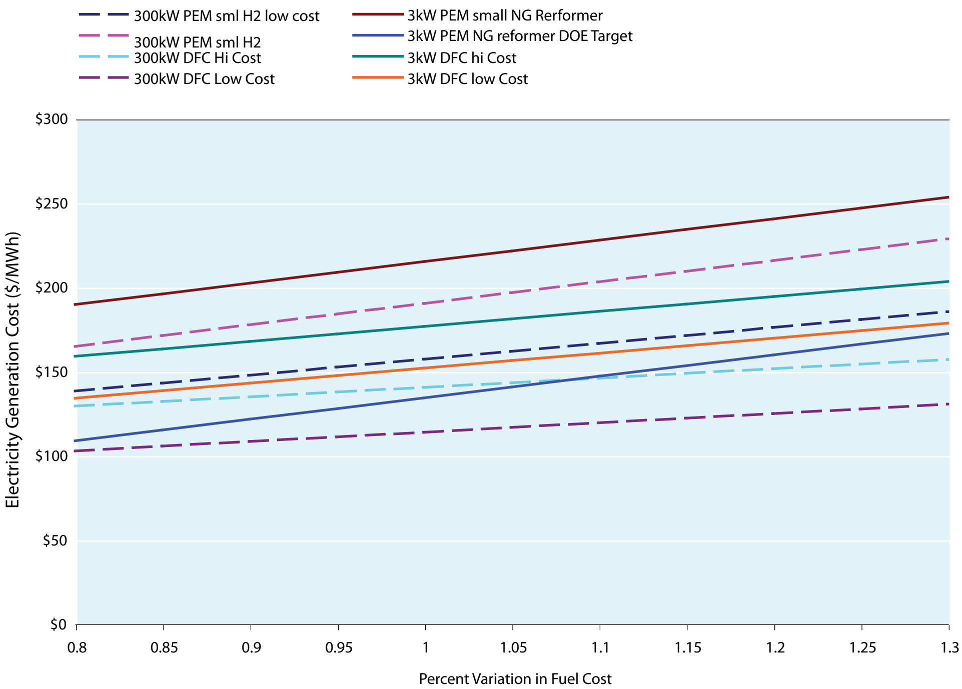


Figure B 17 Sensitivity of Electricity Cost to Fuel Cost

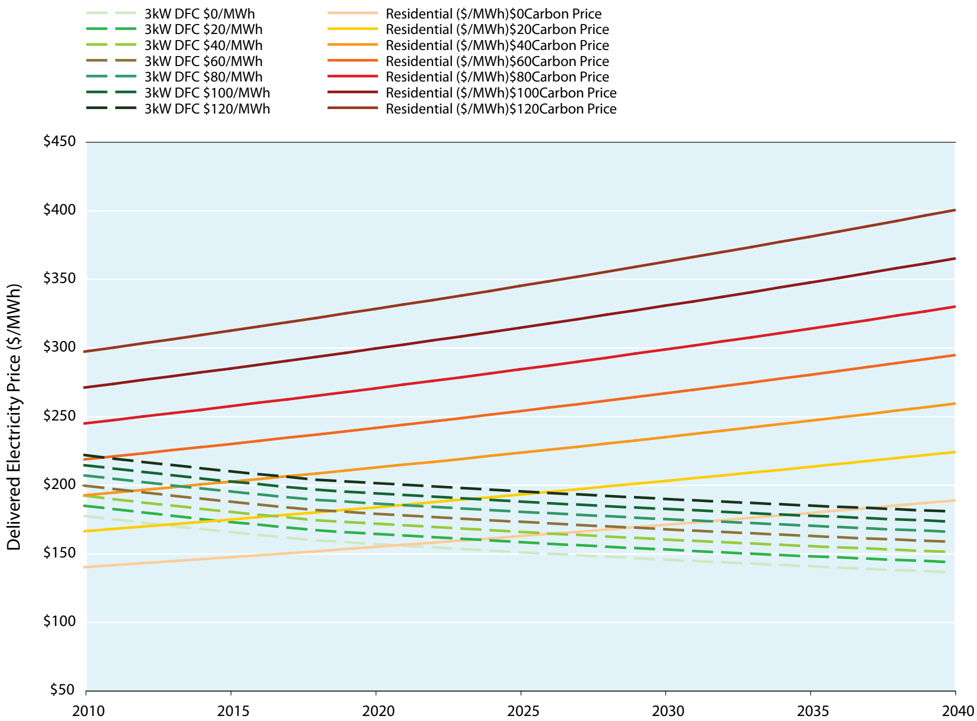


Figure B 18 Impact of Carbon Price on Economics of 3 kW DFC Fuel Cells

The cost of the delivered electricity is compared to grid supplied electricity at the customer's meter over a carbon price range of $0 to $120/tonne CO_2-e. It is clearly seen in this comparison that without a price on carbon these fuel cells would not be competitive with residential supply electricity until around 2020. However, the introduction of even a modest carbon price would result in these systems becoming economically viable much earlier.

The impact on the economics of a 300 kW DFC fuelled by natural gas and a 300 kW PEM fuel cell using hydrogen from a small scale natural gas reformer is shown in Figure B 19. The cost of the delivered electricity is compared to grid supplied electricity at the commercial customer's meter over a carbon price range of $0 to $120/tonne CO_2e.

The direct fuel cells become economically viable at even moderate carbon taxes. However, the PEM cell systems at this scale would require a significant carbon price to meet the pricing of commercial electricity.

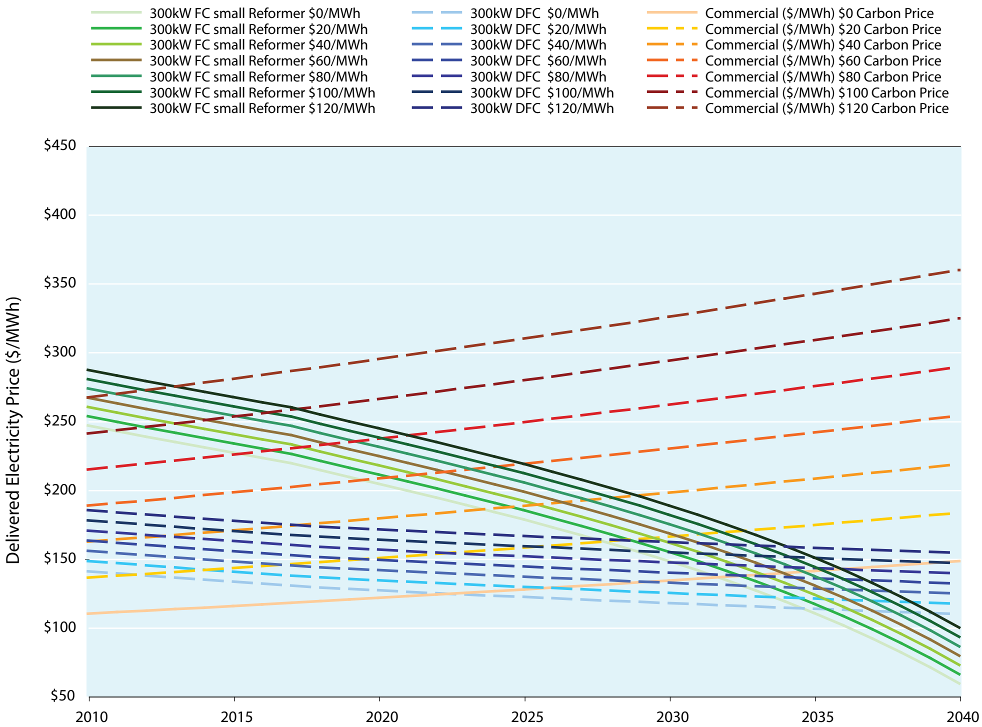


Figure B 19 Impact of Carbon Price on Economics of 300 kW Fuel Cells

B.6 Overall role for hydrogen and fuel cells in the Australian economy

The potential for hydrogen and fuel cells in the Australian transport fuels and electricity markets may be viewed as comprising two distinct time periods.

B.6.1 Hydrogen as a transport fuel

Prior to 2020 there is unlikely to be any significant use of hydrogen as transport fuel except in demonstration projects and small fleet trials.

In the period following 2020 there may begin to be a gradual increase in hydrogen vehicles and consumption for hydrogen. However this is dependent on a number of independent factors being resolved. Firstly, there must be hydrogen vehicles available in the market at a price that is competitive with internal combustion engine vehicles and which provide similar range and comforts. Secondly there must be a hydrogen fuelling network that allows free travel over much of the country. If these occur, hydrogen could become the dominant fuel in new vehicles in the period between 2025 and 2035. Due to the fleet turnover characteristics this could translate to dominance in road vehicles over a period of about 15 years.

Any estimate of timing the uptake of hydrogen as a transport fuel is largely dependent on independent estimates of the price of petrol.If the price and availability of petrol were to rise and fall respectively the introduction of a hydrogen infrastructure could be accelerated significantly.

B.6.2 Fuel cells for distributed generation

Prior to about 2020 there is unlikely to be significant or widespread adoption of either direct or hydrogen fuel cells. However, fuel cells will start to make inroads in specialist applications where high reliability is a necessity. This has already occurred overseas in facilities such as data processing centres and hospitals.

After 2020 the cost of fuel cell electricity becomes comparable with that delivered from the grid and it is at this point that significant uptake could occur. However, this will – to a large degree – be dependent on whether the required policies and standards for connecting distributed generation to the electricity networks is sufficiently streamlined.

The adoption of a carbon trading scheme by the Australian government could accelerate the uptake as the delivered carbon intensity of fuel cell generation will be lower than grid delivered power as a result of its higher efficiency and the avoidance of transmission and distribution losses. The trading scheme would need to recognise and include these forms of generation to achieve these benefits. The carbon offset provided would improve the economics significantly.

To achieve the full greenhouse benefit of a hydrogen-fuelled fuel cell requires the production of greenhouse neutral hydrogen by means of either renewable electricity or through carbon capture at the point of production. Both incur additional costs.

The total potential for fuel cell generation may be up to 450 MW each year in new house construction and there is a potential for about 550 MW of capacity in the high rise building CBD regions. However, this potential capacity will likely be taken up by a variety of distributed generation technologies.

APPENDIX C – STAKEHOLDERS CONSULTED

The following people were interviewed and/or participated in stakeholder workshops during the development of this roadmap. Their contributions are gratefully acknowledged.

National

Joe Hlubucek	Australian Academy of Science
Tom Biegler	Australian Academy of Technological Sciences and Engineering
Vaughan Beck	Australian Academy of Technological Sciences and Engineering
Steve Schuck	Bioenergy Australia
Damian Walsh	BOC Limited
Mike Edwards	BOC Limited
Karl Föger	Ceramic Fuel Cells Limited
Brendan Dow	Ceramic Fuel Cells Limited
Rob Jackson	Clean Energy Council
Abdul Qadar	CO_2CRC
Frank Jan van Schagen	CRC for Coal in Sustainable Development
David Brockway	CSIRO Energy Technology
Paul Graham	CSIRO Energy Technology
Wes Stein	CSIRO Energy Technology
David Rand	CSIRO Energy Technology
John Wright	CSIRO Energy Transformed Flagship
Roy Chamberlain	CSIRO Energy Transformed Flagship
Craig Buckley	Curtin University
Robert Amin	Curtin University
Greg Solomon	Eden Energy Limited
Bashir Gabriel	Ergon Energy
Richard Marshall	General Motors - Holden Innovation
Evan Gray	Griffith University
Jamie Ally	HAC Consulting Pty Ltd / Ballard Power Systems
Glen Head	HAC Consulting Pty Ltd
Alf Ottrey	HRL Limited
Jeffrey Ng	Hydrexia Pty Ltd
John Titchen	Hydro Tasmania
Kane Thornton	Hydro Tasmania
Lewis Jeffery	Hydrogen Energy
Paul Ziegelaar	Hydrogen Energy
Richard Ranshaw	Hydrogen Technology Limited
Dorothy Coubrough	Hydrogen Technology Limited
Nicholas Mylonas	Hydrogen Technology Limited
Adrian Horin	Leslie Consulting Pty Ltd
Luigi Bonadio	Luigi Bonadio and Associates Pty Ltd
Chris Manzie	Melbourne Ventures Limited
Doug MacFarlane	Monash University
Tony Patti	Monash University

Kerry Pratt	Monash University
Chun-Zhu Li	Monash University
Trevor Pryor	Murdoch University
Dr Geoffrey Will	Queensland University of Technology
Chris Goodes	Rio Tinto Limited
Dave Johnson	Shell
Dave Holland	Solar Systems Pty Ltd
Martin Burns	Sustainable Energy Fuel Cells Australia (SEFCA)
Robert Ibrahim	Sustainable Energy Fuel Cells Australia (SEFCA)
Tony Kitchener	SVW Pty Ltd
Jonathan Upfal	SVW Pty Ltd
Michael Brear	University of Melbourne
Ben Hankamer	University of Queensland
Andrew Dicks	University of Queensland
John Zhu	University of Queensland
Max Lu	University of Queensland
Jorge Beltrami	University of Queensland
David Nolan	University of Wollongong
Terry Harders	Victoria University of Technology
Akhtar Kalam	Victoria University of Technology
Agu Kantsler	Woodside Petroleum
Joe McNutt	Woodside Petroleum
Vanessa Guthrie	Woodside Petroleum

International

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Robert Dixon	International Energy Agency	France
Holger Braess	BMW Group	Germany
Gabriel de Scheemaker	Shell Hydrogen	Japan
Tony Clemens	CRL Energy Ltd	New Zealand
Rob Whitney	CRL Energy Ltd	New Zealand
Alister Gardiner	Industrial Research Limited	New Zealand
John Schurink	Industrial Research Limited	New Zealand
Attilio Pigneri	Massey University	New Zealand
Jonathan Leaver	Unitec New Zealand	New Zealand
Steve Szewczuk	South African Council for Scientific and Industrial Research	South Africa
Zwanani (Titus) Mathe	South African National Energy Research Institute	South Africa
Lars Sjunnesson	E.ON Sweden, European Hydrogen Association and IEA Advanced Fuel Cells Implementing Agreement	Sweden
John Loughead	UK Energy Research Centre	United Kingdom
Tim Richards	General Electric	USA
John Nimmons	John Nimmons & Associates Inc.	USA
George Sverdrup	National Renewable Energy Laboratory	USA
Joan Ogden	University of California - Davis	USA
JoAnn Milliken	USA Department of Energy	USA
Jeff Serfass	USA National Hydrogen Association / Technology Transition Corporation	USA

APPENDIX D – HYDROGEN DATA AND EQUIVALENCIES

The following energy content data for hydrogen and other fuels is provided on a lower heating value (LHV) basis.

Factor	Value
Energy content of hydrogen by weight	120.2 MJ/kg or 33.33 kWh/kg
Energy content of unleaded petrol by weight	≈43 MJ/kg or ≈11.9 kWh/kg
Energy content of natural gas by weight	≈47 MJ/kg or ≈13 kWh/kg
Energy content of black coal by weight	≈25 MJ/kg or ≈6.9 kWh/kg

Energy content of hydrogen by volume (compressed H_2 at 35 MPa)	≈2.5 MJ/litre or ≈0.7 kWh/litre
Energy content of hydrogen by volume (liquid H_2)	8.5 MJ/litre or 2.4 kWh/litre
Energy content of unleaded petrol by volume	≈32 MJ/litre or ≈8.9 kWh/litre
Energy content of natural gas by volume (compressed at 20 MPa)	≈9.3 MJ/litre or ≈2.6 kWh/litre

Rules of Thumb

The energy content of 1 kg of hydrogen is equivalent to approximately 3.8 litres (or approximately 1 US gallon) of petrol.

The energy content of 1 cubic metre of hydrogen (at atmospheric pressure) is equivalent to approximately 0.34 litres of petrol; 1 litre of liquid hydrogen is equivalent to 0.27 litres of petrol; and 1 kg hydrogen is equivalent to 2.75 kg of petrol (LHV basis).

ENHANCING AUSTRALIA'S ECONOMIC PROSPERITY