Australian Academy of Science

Towards development of an Australian scientific roadmap for the hydrogen economy

Analysis of Australian hydrogen energy research publications and funding

2040–2050
Hydrogen economy

2030–2040
Hydrogen production and distribution infrastructure

2020–2030
Hydrogen production from fossil fuels with carbon sequestration

2000–2020
Fuel cell and hydrogen systems R&D

Fossil fuel-based economies

Towards development of an Australian scientific roadmap for the hydrogen economy

Analysis of Australian hydrogen energy research publications and funding

Australian Academy of Science

March 2008

Contents

Foreword

The supply of future clean energy supplies to meet ever-increasing requirements is one of the global challenges for the present generation. Worldwide energy needs are estimated by the International Energy Agency to increase by over 50% from 2004 to 2030 as populations increase and economies expand. The reliance on fossil fuels is also not sustainable because of their contribution to increased greenhouse gas emissions and global warming. These scenarios have led to an increased interest in alternative sources of renewable energy such as solar and wind, processes for energy production from coal and other fossil fuels with carbon capture and storage, and research into energy from hydrogen.

Hydrogen is the ultimate clean energy carrier. It is the most plentiful element in the universe, and its efficient oxidation in fuel cells generates power and releases only water. The realisation of a hydrogen economy by mid-century would have hydrogen as the primary energy carrier derived from renewable energy sources, with the advantages of a reduced reliance on dwindling reserves of oil and gas and reduced emissions of carbon dioxide.

This report examines Australia's contribution to research into hydrogen as a future energy carrier and its use in fuel cells through a bibliometric analysis of the published research literature. The study finds that although Australian research is a minor contributor to this fast moving field, Australian researchers can make significant contributions, such as in hydrogen storage materials, carbon capture and storage, and solar-thermal reforming of natural gas. The report also makes a number of recommendations for increased government support for hydrogen energy research and coordination. This report builds on The Academy's symposium on *Science on the way to a hydrogen economy* on 5 May 2006, which brought together international and Australian scientists for a timely discussion about the research and development challenges for widespread and safe hydrogen production, storage, utilisation and distribution. It was convened by Professor Michael Barber FAA, and the symposium program and abstracts are included in this report.

The Academy trusts that this report will make a useful contribution to the directions and support for Australian research into hydrogen energy. It was made possible by a Learned Academies Special Projects grant from the Australian Research Council. The Academy is grateful for the valuable comments on the draft report from Peter Laver AM, FTSE, Vice President of the Australian Academy of Technological Sciences and Engineering, and David Rand ScD, FTSE, Chief Research Scientist, CSIRO Energy Technology. The report has also benefited from comments and advice from a number of individuals, including Professor Sue Serjeantson, Project Director, Australian Academy of Science; and Linda Butler and Dr Kumara Henadeera, Research School of Social Sciences, Australian National University. Dr Joe Hlubucek is also thanked for his research and preparation of the report.

Professor Philip Kuchel FAA
Secretary (Science Policy)
Australian Academy of Science

1. Executive summary

1.1 Introduction

As a contribution towards development of An Australian scientific roadmap for the hydrogen economy, this project provides an assessment of current Australian research into hydrogen as a future energy carrier in comparison with international research efforts. The assessments are also used to identify the most likely areas in which Australian hydrogen research could make significant contributions to hydrogen utilisation as a future fuel for transport and power requirements in Australia and internationally.

The report is based on analyses of hydrogen research publications by Australian and other researchers cited in the Thomson ISI Web of Knowledge Science Citation Index Expanded database; and on the proceedings from *Science on the way to the hydrogen economy*, a symposium organised by the Australian Academy of Science and held in Canberra, on 5 May 2006 (www.science.org.au/sats2006/symposium.htm).

The project, funded by the Australian Research Council in 2006, preceded the decision by the Council of Australian Governments (COAG) in April 2007 for development of four technology road maps for hydrogen, geothermal, solar-thermal and coal gasification.[1] The COAG Roadmap for the Development of Hydrogen Technology in Australia is to be produced by April 2008.[2]

1.2 Background

Hydrogen is attracting considerable research globally as a possible longer term, renewable energy carrier. Its particular appeal is as a clean energy source, when derived from renewable sources, for fuel cell systems. When fuelled by pure hydrogen and oxygen/air, these produce electric power with water as the chemical by-product and no carbon-based greenhouse gas emissions. There are a number of hydrogen fuel cell prototypes in test and field-trial operations for both stationary and vehicle applications, but considerable scientific, technical and economic challenges have to be addressed before hydrogen could become a widespread energy alternative in the next 20 to 50 years.[3,4,5] The challenges include:

- large-scale hydrogen production from coal and natural gas together with sequestration of the CO_2 by-product until hydrogen can be obtained economically from renewable sources; (deleted additional words)
- infrastructure for hydrogen delivery and filling stations;
- improved hydrogen storage technologies;
- fuel cells with improved reliability and lower costs; and
- codes for safe handling of hydrogen and addressing public safety concerns.

The different national priorities for hydrogen energy R&D depend on each country's relative dependence on other energy sources, especially fossil fuels, and strategies to ensure security of supply and to combat climate change by reducing greenhouse gas emissions. Australia enjoys relatively low-cost power for industry and domestic requirements based largely on its vast reserves of coal and natural gas. Not surprisingly, therefore, early federal and state government initiatives have been directed towards more efficient utilisation of coal and gas, but there is also support for the development of alternative renewable energy sources such as wind, solar and geothermal.

This project was based on a bibliometric analysis of hydrogen research in key fields, such as hydrogen production, storage and utilisation in fuel cells, using a comprehensive search list of key words. It used a benchmarking methodology piloted by the Australian Academy of Science for assessing emerging areas of science and technology in Australia, such as nanotechnology.

The bibliometric analysis shows that Australia produced 1.69% of the world's hydrogen publications from 1980 to 2006 (and 1.78% from 1998 to 2006), and the country is the 16th largest producer of hydrogen research papers. This output is lower than for science as a whole, for which Australia produced 2.89% of the world's science publications in 2004. Nevertheless, the number of Australian hydrogen energy publications has been increasing steadily since 1991 and then more rapidly since 2003, and they receive similar citation ratings for other country hydrogen energy research publications.

Australia does not have a specific national hydrogen R&D initiative, but 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 which comprises a consortium of 11 universities, Australian Nuclear Science and Technology Organisation (ANSTO) and CSIRO. The 2005 Department of Innovation, Industry, Science and Research (previously the Department of Industry, Tourism and Resources) Hydrogen Activity Database lists over 120 projects.[6] Australia also has membership of multilateral hydrogen initiatives such as The International Energy Agency Hydrogen Implementing Agreement (IEA HIA) with 21 member countries,[7] The IEA Advanced Fuel Cells Implementing Agreement, and The International Partnership for the Hydrogen Economy which was established in 2003 with 16 other countries to accelerate the development of hydrogen and fuel cell technologies.[8]

1.3 Summary of key findings

The key findings from this project are:

1. Australia will continue to use the fossil fuels coal, oil and gas to provide base power generation for industry and domestic electricity requirements for the next 15 to 20 years, with research into clean coal technologies to continue in Australia, and internationally.
2. Australia is well-placed to contribute significantly to research into clean coal technologies, including CO_2 capture and storage, as a result of significant government funding and industry participation. Australian research success in this area and collaboration with key export market countries, will contribute to:
    a. continuing exports of these economically-important commodities and their use for power generation with low greenhouse gas emissions;
    b. the transition to fossil fuel energy alternatives, including hydrogen; and
    c. national and international initiatives for lowering greenhouse gas emissions.
3. Australian research into hydrogen energy applications will be in niche areas, since there is very limited research-based or technology-based industry being established for market-driven opportunities.
4. Australian hydrogen energy research in a number of sectors is high-quality, but it is spread over a range of basic and applied research areas. It is also lacking in critical mass in most sectors other than clean coal technologies, and research into hydrogen storage materials.

5. Australian hydrogen research will make important contributions in research-intensive areas such as CO_2 separation and sequestration, hydrogen storage materials, solar-thermal reforming of fossil fuels and biomass for hydrogen production, and distributed energy supply for remote areas.

6. There has been significant research funding for hydrogen energy technologies by the Australian Research Council, but there is a need for federal and state government initiatives to support early-stage startup companies and industry participation for commercialisation of the promising research to ensure that Australia can participate in the development of this important emerging energy sector.

7. There is a need for continuing Australian R&D into hydrogen energy technologies and applications to ensure that Australia can both contribute to this sector in areas of niche strengths, and also develop the necessary expertise to incorporate international hydrogen energy developments into Australia's energy strategies in a timely manner.

8. The Australian Government should consider a revised energy technology assessment for hydrogen from the 'reserve' to 'fast follower' category based on the present speed of global developments for hydrogen energy R&D and applications.

9. The COAG Roadmap for the Development of Hydrogen Technology in Australia, due in April 2008, will provide more detailed guidance for government and industry on hydrogen energy R&D capabilities in Australia and priority areas for research and applications development. In addition, the roadmap could identify mechanisms to foster Australian R&D in energy alternatives to fossil fuels, including hydrogen, which is likely to be the next major global research-based technology and industry development sector to follow the ITC and biotechnology sectors.

10. The coordinated development of Australian hydrogen energy R&D and applications as part of Australia's future energy strategies would benefit from the development of an 'Australian Hydrogen Energy Initiative' which could incorporate support for:

    a. continuing hydrogen energy R&D with particular attention to building critical mass in areas of Australian expertise through a CRC or other consortia;

    b. early-stage startups for proof-of-concept of promising hydrogen energy research discoveries;

    c. commercialisation through existing AusIndustry and other government programs;

    d. demonstration projects; and

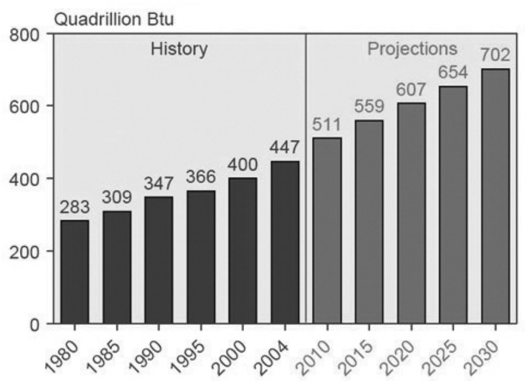
    e. the establishment of an effective Hydrogen Energy Industry Group or Association to foster sector collaboration and community awareness about the transition to a hydrogen economy.

2. Introduction

2.1 The significance of hydrogen

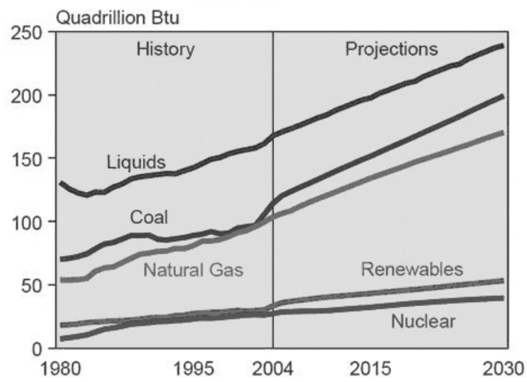
Reliable and affordable energy supplies have been the basis worldwide for industry development and higher standards of living. To date access to oil and gas from fossil fuels has been the most readily available energy source. It has shaped the industries for power supply, resource development, manufacturing, and the design of vehicles, buildings and private homes.

The US International Energy Outlook Report for 2007 indicates a strong growth in world-wide energy demand, namely, 57% from 2004 to 2030, if present laws and policies remain unchanged (Figure 1).[9] The largest projected increase is for the non-OECD regions, in particular China and India (2.6% per annum for 2004 to 2030 compared with 0.8% for the OECD region). During this period, it is also forecast that the major energy sources will be coal, oil and gas, although economically-accessible resources of oil and gas are expected to peak between 2020 and 2030 (Figure 2).



Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2004* (May-July 2006), web site www.eia.doe.gov/iea. **Projections:** EIA, System for the Analysis of Global Energy Markets (2007).

Figure 1. World marketed energy consumption, 1980-2030



Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2004* (May-July 2006), web site www.eia.doe.gov/iea. **Projections:** EIA, System for the Analysis of Global Energy Markets (2007).

Figure 2. World marketed energy use by fuel type, 1980-2030

As the demand for energy has increased through population growth and economic expansion, other energy sources have come on line, such as hydroelectric, nuclear, geothermal, solar and wind. Some of these alternatives to fossil fuels have made significant contributions to energy requirements for particular countries and regions, but the overall contributions to global energy demands have been small. For example, according to the US Energy Information Administration, renewable energy sources (solar, wind, biomass and hydroelectric power) accounted for 9.4% of the total electricity generated in the US in 2003. Biomass power is the second largest source of renewable electricity (after hydroelectric power), making up 19% of the total renewable electricity, or 76% of the non-hydro renewable electricity.[10]

Interest in alternative energies has increased significantly in recent years with the realisation that world supplies of oil and gas from fossil fuels are finite and will decrease steadily from about 2025. In addition, industry and vehicle emissions of greenhouse gases have been identified as major contributors to decreased air quality and global warming as the cost of oil and gas increase at the same time. These developments, and growing concerns about the continuity of secure energy supplies, have led to different government actions to explore significant contributions by fossil fuel alternatives for national and regional energy requirements. These government actions have been shaped by:

- existing fossil fuel energy supplies and costs, and future requirements for industry and communities;
- access to alternative natural resources such as hydroelectric and geothermal;
- targets to reduce vehicle and greenhouse emissions;
- natural advantages for alternative energy generation from wind and solar;
- future vehicle zero-emission targets utilising hydrogen as an energy carrier and source; and
- new technology industry development opportunities.

Amongst the renewable energy alternatives, hydrogen is seen by some as the ultimate energy carrier and source for a modern economy because it can be generated from different primary sources such as fossil fuels, nuclear and eventually from renewables such as biomass, wind and solar, and ultimately from water. It can then be used in fuel cells to generate power efficiently for centralised, distributed and transportation requirements with zero greenhouse gas emissions.

A hydrogen economy will be realised when hydrogen produced from renewable resources becomes the primary energy carrier and source for stationary, distributed and transportation power generation. Under this scenario, the use of fossil fuels will be phased out, and greenhouse gas emissions minimised. In the past, hydrogen has been used as a fuel for internal combustion engines as a component of syngas in wartime during shortages of petroleum, and hydrogen is a very efficient engine fuel.[11]

However, significant challenges need to be addressed before there is widespread utilisation of hydrogen, but the many prototypes in test and operation demonstrate the potential. These include the international multi-city fuel cell bus trial which has been running for three years, including in Perth, and several car manufacturers are also trialling hydrogen fuel cars with internal combustion engines and fuel cell engines.

General Motors, Honda and BMW are amongst the car manufacturers which have announced plans to supply light duty hydrogen vehicles from 2010 for government authorities and regions with hydrogen refuelling facilities. Canada, China, Japan, Korea and Germany could be amongst the earliest countries to adopt such technologies in vehicles.[12] For example Kia, in collaboration with Hyundai, has developed a Sportage prototype with an 80 kilowatt hydrogen-powered fuel cell engine, with a driving range of about 380 kilometres.[13] At present the car is limited by the 1500 hours life of the fuel cell stack, but it has models operating in Korean and US government test fleets. It is reported that Kia is on track for production of a Sportage by 2012 for an estimated Aus$40,000, with the aim that a fuel cell vehicle will cost the same as a car with an internal combustion engine by 2020 to 2025.

Widespread introduction of hydrogen-fuelled vehicles will also require the necessary infrastructure for hydrogen distribution and fuel stations. For example, in North America at the end of 2007 there are more than 170,000 petrol stations and only about 20 hydrogen filling stations, none of which are accessible to the general public. General Motors' estimates that the installation of hydrogen pumps at 12,000 filling stations would provide 70 percent of US motorists with access to the fuel, and that would cost US$10-15 billion. This would locate hydrogen pumps within 3 kilometres of each other in the 100 most populated metropolitan areas in the US, and would also allow for at least one pump every 40 kilometres along the 210,000 kilometres of major highways in the US.[14]

2.2 Hydrogen safety

There is considerable industrial experience with respect to the safe handling of hydrogen gas in refineries and for transport in accordance with regulations, but public perceptions and concerns about the safety of hydrogen need to be addressed.[15] Organisations such as the US National Fire Protection Agency and the Society for Automotive Engineers are working with authorities such as the International Standards Organisation to address safety needs and standards. Fuel cell manufacturers, hydrogen tank manufacturers and automakers are also developing best practices for hydrogen use and safety.

While hydrogen has many safety issues that need to be addressed, images of the Hindenburg and the hydrogen bomb often cloud meaningful discussion of hydrogen's safety as a fuel. The Hindenburg is perhaps the most spectacular disaster where hydrogen was erroneously reported as the cause. While hydrogen did indeed burn in the disaster, a new coating used on the zeppelin cover was highly flammable and was the primary cause for the major fire that engulfed the frame.

A number of studies have examined aspects of hydrogen safety and concluded that, while hydrogen raises a different set of safety concerns to gasoline, hydrogen is no more dangerous than gasoline. BMW undertook a number of crash tests and found the safety of the fuel to be sufficient. The University of Miami, in its test, set fire to two cars, one with hydrogen and the other gasoline. While both created fires when ignited, the gasoline fire engulfed the entire car causing total damage, whereas the hydrogen flame vented vertically and failed to spread to the rest of the vehicle.

3. Hydrogen energy

3.1 Priority research areas

The symposium on *Science on the way to the hydrogen economy* organised by the Australian Academy of Science in May 2006 (Appendix A)[16] provided an overview of the prospects and challenges for developing a hydrogen economy, with presentations by Dr George Crabtree, Director of the Materials Science Division at the Argonne National Laboratory in Illinois, USA, and Dr John Wright, Director of the CSIRO Energy Transformed Flagship in Newcastle, Australia. These and the other presentations outlined current international and Australian research directed at the many aspects of hydrogen production, storage, distribution and utilisation. The papers describe new materials, technology developments and different approaches aimed at improving efficiencies and reducing costs by several orders of magnitude.

The realisation of a hydrogen economy based on generation from renewable resources and its widespread use in fuel cells, by mid-century, will involve a transition from co-generation of hydrogen and its use in hybrid systems with a variety of processes. These directions will be guided by country and regional access to:

- fossil and renewable energy supplies;
- environmental priorities for greenhouse gas reduction; and
- government and industry policies for hydrogen technology development.

3.2 Hydrogen production

Hydrogen is currently produced for use in petroleum refineries, fertiliser, chemical and food industries. The US produces about 11 million metric tons annually and global production is about 50 million metric tons per year, with 48% from natural gas, 30% from oil, 18% from coal, and 4% from water electrolysis.[17]

The widespread availability of fossil fuels suggests that they will continue to be the source of hydrogen for the next twenty years and the cheapest and most efficient process at present is steam reforming of natural gas.[3] Gasification of coal to produce hydrogen is also used widely and it is particularly important for countries with large reserves such as Australia, the US and China. The major challenges for these processes include:

- optimisation of the hydrogen yield;
- purification to a practical blend for use in fuel cells with the removal of impurities (which could poison catalysts in the fuel cells); and
- separation and isolation of the carbon dioxide by-product (which can be as high as 30%).

Thermocatalytic decomposition of natural gas is another process being investigated since the by-product is solid carbon which is easier to store than carbon dioxide, because it occupies a smaller volume and has less mass than the equivalent amount of carbon dioxide.

Biomass, in the form of crops and cellulosic crop wastes, are proven sources for ethanol and biodiesel fuels in countries where they can benefit from incentives. However, their more widespread use could be limited by competition for land and food crops. The benefit of biomass is that it is a renewable resource which can undergo thermochemical conversion to produce hydrogen, with carbon dioxide and nitrogen as by-products. Although the use of such biomass evolves CO_2, the cycle can be considered to be greenhouse gas emission neutral when the whole lifecycle of the product is considered. Another attraction is that biomass could be suitable for distributed energy supply. An estimate of the potential is available from a 2005 study in Minnesota which calculated that there was enough residual biomass and energy crops in the state, which if collected and fed to the most efficient conversion technologies available, the hydrogen produced could replace up to 89% of the total gasoline currently used in Minnesota. Exclusive use of agriculture residue could replace 65% of the gasoline currently used. However, this potential can not be realised unless economically-viable collection, transport, energy conversion and energy distribution systems are in place.[18]

Since one of the driving forces for a hydrogen economy is reduction and eventual elimination of greenhouse gas emissions, primarily carbon dioxide from vehicles and base power generators, the separation and sequestration of carbon dioxide by cost-effective processes are major objectives. For example, since 1998 one million tons of CO_2 have been sequestered each year in the North Sea Sleipner gas field to assess the viability of geological carbon storage. The US, UK and Australia are amongst the countries with other major CO_2 sequestration projects underway, with plans to determine the feasibility and cost. In a paper to the annual Coal 21 conference in September 2007, CSIRO estimated that carbon capture and storage (CCS) could double the cost of generating electricity, and that an alternative process for utilising coal and avoiding CCS is offered by direct carbon fuel cells.[19] Instead of burning coal, the latter uses an electrochemical process to generate electricity from carbon. The potential efficiency of a direct carbon cell can be over 90%, and the small stream of pure CO_2 cuts the cost of the normal CCS process by about 60%, if needed at all. However, direct carbon fuel cells have received almost no funding.

Electrolysis of water to produce hydrogen without carbon dioxide also attracts considerable research, but it is an energy intensive process and the hydrogen and oxygen released need to be separated. A particular attraction is that a fully sustainable hydrogen energy power system is possible if the energy for electrolysis can be supplied efficiently by a renewable energy source such as solar or wind. Alternatively, the large current and heat requirements for such large-scale electrolysis could also be provided by a nuclear reactor.

Solar radiation for heat and photovoltaic energy supplies will make increasing contributions towards greenhouse gas free power generation, but solar energy can also be coupled to hydrogen production through thermal reforming of natural gas and electricity generation for water electrolysis. These routes to hydrogen may not be cost-effective in isolation, but the hydrogen could be a valuable energy storage mechanism for solar and other renewable energy sources such as wind which generate power periodically, particularly for remote area applications.

3.3 Hydrogen storage and distribution

Oil-based petroleum fuels can be stored conveniently, and transported by established road, sea and pipeline systems. The storage and distribution of hydrogen by comparison is recognised as one of the major infrastructure challenges for widespread utilisation of hydrogen.[20] The technologies are well-established for storage and transport of hydrogen as a liquid in cryogenic containers, or as a gas in pressurised containers, but these options are too costly and bulky for transport over long distances or for on-board storage in vehicles. Research for base-load generation of power from hydrogen therefore tends to be directed towards smaller distributed facilities near point of use such as filling stations, business or residential communities. Research into hydrogen storage for use in fuel cells and hybrid fuel cell vehicles as well as other portable applications is aimed at metal hydrides, complex hydrides and, more recently, carbon nanomaterials. The progress with research into hydrogen storage materials is covered in several sessions of the symposium[16] organised by the Australian Academy of Science on *Science on the way to the hydrogen economy*, in May 2006, and the abstracts are at Appendix A.

A measure of the challenges to be overcome for effective solid state hydrogen storage and regeneration is provided by the targets established by the US Department of Energy (DOE) for vehicle on-board hydrogen storage systems for 2007, 2010 and 2015. They cover a range of technical requirements for hydrogen fuel cell vehicles to achieve comparable performance to current petrol driven vehicles.[21] The current status in terms of weight, volume and cost of various hydrogen storage technologies is shown below (Figure 3).

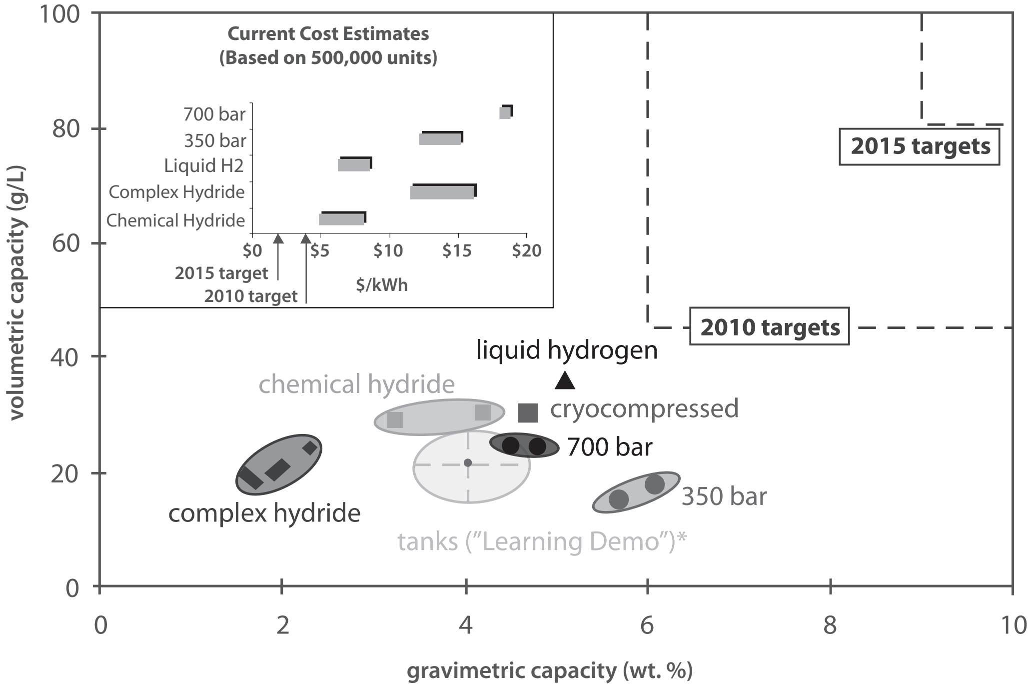


Figure 3. Status of hydrogen storage technologies

Costs exclude regeneration and processing. Data based on R&D projections and independent analysis (FY 2005–06). To be periodically updated.

*** Learning demo data shows range across 63 vehicles.**

Several research groups have achieved the 2010 DOE density target for gravimetric capacities of about 7% in laboratory experiments for hydrogen storage using chemical and complex hydrides. However, volumetric capacity densities are still too low, and would require excessively large hydrogen fuel tanks.

As mentioned above, efficient hydrogen storage technologies could also be used in conjunction with solar and wind energy systems which generate power periodically.

3.4 Hydrogen fuel cells

The increase in the level of hydrogen energy technology developments is demonstrated by the sharp increase in triadic patent applications from about 6,000 in the late 1990s to over 120,000 as of March 2006.[22] The relative fields of interest, and priority for fuel cells research and development, is shown in Table 1.

Table 1. Total number of triadic patent applications for hydrogen energy technologies, at March 2006

Fields of interest	Number of patents
Fuel cells	80,000
Hydrogen storage	4,500
Electrolytic hydrogen production	6,000
Fuel cells for electricity and heat cogeneration	700

Fuel cells can offer the highest energy efficiencies compared with other power generation technologies and are the key enabling technology for a hydrogen economy. For example, fuel cells can be as efficient as internal combustion engines, and for co-generation applications fuel cells can achieve energy efficiencies of over 80%.[23] Hydrogen fuel cell technologies are developing rapidly with many systems having been trialled for several years in applications ranging from stationary power generation for heat and electricity to power for cars and buses. The developments are driven by strategies to become market leaders in this emerging technology sector, as well as by strategies to reduce greenhouse gas emissions. However, considerable research is still required to increase reliability and reduce costs for component electrodes, membranes and catalysts.

The major types of fuel cells include:

- proton exchange membrane fuel cell (PEMFC);
- direct methanol fuel cell (DMFC);
- solid oxide fuel cell (SOFC);
- alkaline fuel cell (AFC);
- phosphoric acid fuel cell (PAFC); and
- molten carbonate fuel cell (MCFC).

These different technologies are likely to be utilised in different applications, although PEMFCs and SOFCs are emerging as the leading fuel cell technologies with the broadest commercial applications. PEMFC technology is preferred for mobile and portable applications with lower operating temperatures. SOFCs by comparison operate at considerably higher temperatures and present the best prospects for distributed base-load power and for heat co-generation.

4. Country strategies for hydrogen energy implementation

4.1 Introduction

The rates of introduction of alternative energy sources, including those utilising hydrogen, depend on a number of inter-related factors which are part of the different country strategies and hydrogen technology roadmaps. Key market-pull factors are the rising cost of petroleum supplies and the predicted decline in global fossil fuel resources from about 2025. The market-push factors on the other hand include priorities for energy security and to reduce greenhouse gas emissions. In addition, a number of countries and regions have introduced targets for increasing contributions to their energy supplies by renewable energy sources, as well as the introduction of carbon taxes to promote R&D into alternative energy supplies and their uptake. There are also industry development priorities for hydrogen energy technologies and fuel cell technology leadership, as in Japan and Canada.

It is now estimated that over 100 countries, primarily in Europe, south east Asia and North America, have launched or envision the launch of national hydrogen and fuel cell research, development, deployment and demonstration programs.[24] It is estimated that national governments invest over US$1 billion in hydrogen and fuel cell research and development programs each year. In addition, private sector investments in hydrogen and fuel cell technologies are generally three to seven times larger than government programs. These trends have led to the increased level of research activity into hydrogen energy technologies as is apparent from the sharp increase in research publications that has occurred in the last five years (see below).

4.2 Hydrogen economy development programs from selected countries

National initiatives for transition to a hydrogen economy are presented below.

4.2.1 Brazil

Brazil launched a program of hydrogen and fuel sector cooperation with the US in 2003. Brazil has several centres of excellence in hydrogen and fuel cell technologies, with Petrobras and LACTEC (Instituto de Tecnologia para o Desenvolvimento) being two of the leader organisations. Brazil is one of the world leaders in the production of biofuels and is committed to accelerating hydrogen production from biomass (www.mme.gov.br or www.mre.gov.br).

4.2.2 Canada

Natural Resources Canada and Industry Canada have been early leaders in hydrogen and fuel cell research and development activities. While the Canadian government and private sector have placed emphasis on stationary fuel cell systems, one of the most widely recognised hydrogen economy infrastructure development activities is the British Columbia Hydrogen Highway. Complementary hydrogen infrastructure investments include a hydrogen airport and a hydrogen village (www.nrcan-nrcan.gc.ca or www.h2.ca or www.hydrogeneconomy.gc.ca). More recently, a five-year Canada Research Chair in the Development of Nanomaterials for Fuel Cell Applications at the University of Western Ontario was announced in November 2007 (http://communications.uwo.ca/com/western_news/stories/sun_shines_as_new_canada_research_chair_20071203440747/).

The federal and British Columbia provincial governments are investing over C$100 million in these projects, including C$89 million in North America's first fleet of 20 hydrogen fuel cell buses and refuelling infrastructure. There are over 300 Canadian-built fuel cell forklifts in operation this year and another 1200 are expected to be in operation by the end of 2008. More than 500 Canadian-built fuel cell back-up power units were ordered in 2007, and over 900 Canadian fuel cell stationary units are expected to be in operation this year.

4.2.3 China

China has launched an ambitious hydrogen and fuel cell research and development program to help meet the energy service needs of over one billion people and a rapidly expanding economy. Although fossil fuels are abundant in China, renewable and nuclear energy pathways for hydrogen production are being tested. Based in part on joint ventures, prototype hydrogen powered vehicles are being produced and tested in major cities. Beijing will host the 2008 Summer Olympics and the Chinese will be demonstrating clean energy technologies including hydrogen and fuel cell technologies at this global event (www.most.gov.cn or www.chinahydrogen.org).

4.2.4 European Commission

In 2003 the European Commission planned to invest over €2 billion over the following ten years for hydrogen and fuel cell technology development. Complementary national programs have also been established in France, Germany, Italy, Spain, the UK and other member countries. Renewable energy pathways for hydrogen production will be emphasised in this European program. The Commission is also active in technology validation, and the Clean Urban Transport for Europe program is testing fuel cell powered buses in various European, Asian and Australian cities (http://europa.eu.int/comm/research or http://europa.eu.int/comm/research/energy or www.h2euro.org).

In March 2007, the European Commission released a Status Report on its Implementation Plan for the European Hydrogen and Fuel Cell Technology Platform. The plan focuses on four main actions needed by 2020 to create a hydrogen energy system by 2050, namely:

- hydrogen vehicles and refuelling stations;
- fuel cells for heat and power generation;
- sustainable hydrogen supply; and
- fuel cells for early markets.

The plan outlines a roadmap with public and private investment of €7.4 billion in 2007 to 2015 (www.hfpeurope.org/uploads/2097/HFP_IP06_FINAL_20APR2007.pdf).

The European Union 7th Research Framework Program for energy research also includes eight themes for hydrogen and fuel cell research, including a collaborative program in 2008 with industry on fuel cells and hydrogen.

4.2.5 Iceland

This island state has a long history of hydrogen and fuel cell investments and has targeted a hydrogen economy for over a decade.[25] Abundant and relatively inexpensive geothermal and hydroelectric power resources make it feasible to produce hydrogen for distributed energy and transport sectors. Public-private partnerships have spurred infrastructure development, and technology validation programs with bus and automobile trials (www.mfa.is).

4.2.6 India

In 2006, India announced its hydrogen roadmap with a proposed investment of US$5.6 billion over 15 years for a broad-based program of R&D and industry-led public-private partnerships. Over the last ten years, the Indian cities of New Delhi, Kolkata, Mumbai and Chennai have switched from conventional petroleum fuels to relatively clean compressed natural gas (CNG) for buses, trucks and automobiles. This transition has inspired Indian technology leaders to envision a hydrogen economy with cars running on-board electrolysers using CNG and using CNG-hydrogen for vehicle testing and validation programs to advance the hydrogen economy (http://mnes.nic.in/press-releases/press-release-04062007.pdf).

4.2.7 Italy

Italian government and private sector investments in hydrogen and fuel cell research, development and technology validation activities have grown steadily in recent years. Fiat, Nuvera Fuel Cells and others have been important private sector investors. Italy has an ambitious goal of developing hydrogen technology parks in Venice, Milan and Turin. The parks will be developed via public-private partnerships, and the Lombardy region of Italy has been a leader in hydrogen and fuel cell technologies (www.minambiente.it).

4.2.8 Japan

Federally-funded fuel cell and hydrogen technology activities have tripled since 1995, reaching over US$200 million in 2002. Public-private partnerships have sustained the planning and construction of 10 hydrogen-fuelling stations in the corridor between Tokyo and Yokohama. Toyota and Honda have been private sector leaders in hybrid vehicle development and marketing and these companies are well-positioned to be leaders in hydrogen-powered vehicles. The central government has set aggressive near- and long-term goals for development of hydrogen fuelling infrastructure and fleets of cars, trucks and buses (www.meti.go.jp or www.jhfc.jp).

4.2.9 New Zealand

CRL Energy was awarded a government contract in April 2007 for NZ$533,334 for 16 months from the Foundation for Research, Science and Technology to develop a pathway showing how New Zealand could make the transition to a hydrogen energy economy if hydrogen becomes part of the country's future.[26]

4.2.10 South Africa

South Africa proposes to establish a Hydrogen Centre of Competence focusing on hydrogen production, storage, delivery and distribution. The country considers that it is in a good position to participate in the emerging hydrogen economy as it has more than 75% of the world's known reserves and platinum, which is as a key catalytic material used in hydrogen fuel cells.

Hydrogen and fuel cell technologies have been identified as a 'frontier science and technology' initiative that could, potentially, position the country to compete within the dynamic knowledge economy, with South Africa also regarded as a leader in the technology to produce liquid fuels from coal through gasification (www.gasworld.com/news.php?a=2278).

4.2.11 United States of America

In January 2002, the US Department of Energy (DOE) and the US Cooperative Automobile Research (CAR) announced the FreedomCAR partnership to conduct pre-competitive, high-risk research into advanced automotive technologies.[27] In January 2003 President Bush announced the US$1.2 billion Hydrogen Fuel Initiative research and development program.[28]

US federal hydrogen programs are matched by large and aggressive state programs; for example in California and Connecticut.[29] In addition, Chrysler, Ford and General Motors (GM) all have broad commitments to developing hydrogen-powered vehicles. GM plans to have 100 fuel-cell vehicles on the road later this year, and Honda Motor Company plans to produce a small number of fuel-cell cars next year for sale in the US and Japan. The US DOE is also sponsoring the US$1 billion FutureGen initiative[30] run by a consortium of international companies (including three Australian participants) to build the first clean coal powered power station with carbon dioxide sequestration for zero greenhouse gas emissions (www.eere.energy.gov/hydrogenandfuelcells or www.hydrogenus.com or www.iaha.org). However, the future of the project is uncertain with the recent announcement from the US DOE to review its funding for this project and to examine alternative carbon capture and storage projects.[31]

4.2.12 United Kingdom

In May 2007, the Department of Trade and Industry released *Meeting the energy challenge: A white paper on energy*. This report outlines broad strategies for cutting CO_2 emissions. These include energy savings by industry and private homes, increasing energy from renewables, and energy microgeneration from alternative low carbon sources, including hydrogen technologies.[32]

5. Australian government programs in support of hydrogen energy and other renewable energy and clean coal technologies

5.1 Australian Government programs

Hydrogen energy R&D projects receive a minor part of federal (and state) government energy R&D funding. The Department of Resources, Energy and Tourism (DRET) and the Department of Innovation, Industry, Science and Research (DIISR) (formerly the Department of Industry, Tourism and Resources) manage a number of renewable energy programs. The Office of the Renewable Energy Regulator has policy responsibility for the Mandatory Renewable Energy Target for an additional 9,500 gigawatt hour of electricity to be produced from renewable sources by 2010, although no hydrogen energy projects have been supported by this program. The energy projects supported under these programs (www.greenhouse.gov.au/renewable/government.html) include:

1. Low Emissions Technology Demonstration Fund (with DRET), an A$500 million initiative for 2005 to 2019, part of the Government's *Energy White Paper: Securing Australia's Energy Future*, which includes:
    a. Chevron's Gorgon CO_2 injection project ($60m);
    b. CS Energy's Callide A Oxy-Fuel Demonstration Project ($50m);
    c. Fairview Power's Project Zero Carbon from Coal Seams ($75m);
    d. Solar Systems Australia's Large Scale Solar PV Concentrator ($75m);
    e. International Power-Hazelwood 2030 Clean Coal Future ($50m); and
    f. HRL Limited's 400MW Integrated Drying and Gasification Combined Cycle power plant ($100m) in collaboration with a Chinese firm as an Asia Pacific Partnership initiative.
2. Advanced Electricity Storage Technologies program with DRET, which includes:
    a. Wizard Power and ANU ($7.4m) for solar energy storage system based on ammonia dissociation into hydrogen and nitrogen; and
    b. Four other projects for solar energy storage using graphite blocks, consisting of a CSIRO collaboration with developer ZZB to demonstrate its Zn-Br 500kw hours battery, and two projects for V-redox batteries with photovoltaic solar panels and wind turbine.

DRET and CSIRO participate in the International Partnership for the Hydrogen Economy hydrogen infrastructure project. CSIRO is a member of the International Energy Agency Hydrogen Implementing Agreement.

The Australian Antarctic Division will also be exploring renewable energy options, including hydrogen demonstration projects including energy storage as hydrogen generated by water electrolysis using wind power, and use in fuel cells for stationary and transportation power.

5.2 State government renewable energy and hydrogen energy programs

The state governments have various programs for reducing greenhouse gas emissions including renewable energy targets, support for solar and wind energy projects, and clean coal technologies. There is limited state government support for hydrogen energy projects, but these include hydrogen storage projects in Queensland and Tasmania, the recently completed hydrogen fuel bus trials in Western Australia, and the development of a hydrogen-fuel motor vehicle engine in Victoria.

5.2.1 Tasmania

Hydro Tasmania (www.hydro.com.au) has established a partnership with the University of Tasmania's Hydrogen and Allied Renewable Technologies program, and an involvement with the US DOE's Hydrogen Industry Review Program. Hydro Tasmania's Technology and Commercialisation program has three areas of focus:

1. New renewables, including solar, geothermal, marine and other emerging technologies, as well as maintaining a capacity in wind energy technology.
2. Remote Area Power Supply (RAPS) and Energy Storage, which includes:
    a. King Island Wind Power's Carbon Block Energy Storage Project, in partnership with Lloyd Energy Systems;
    b. Cape Barren Island Wind-Hydrogen Project;
    c. Flinders Island Remote Area Power Supply Project; and
    d. considering a role in the wider RAPS market.
3. Renewable transport, including initiatives with hydrogen, biodiesel and electric hybrids.

Tasmania has also been the subject of a multi-level energy analysis for four hydrogen demand scenarios and five alternative infrastructure pathways, since its population distribution within a state infrastructure could be a useful Australian model for the development of an integrated system for hydrogen energy production, distribution and use.[33] It could incorporate remote area hydrogen generation and use, as well as hydrogen re-fuelling centres for public transport and private sector vehicles, based on the population densities in the two major cities of Hobart and Launceston.

5.2.2 New South Wales

The state has a number of initiatives to reduce greenhouse gas emissions, including a target as part of its Greenhouse Gas Reduction Scheme to reduce these emissions to 2000 levels by 2025, and by 60% by 2050. There is support for renewable energy programs with nearly 3,000 megawatts of renewable energy generation proposals at various stages of consideration for additional electricity generation through wind, solar, biomass and other zero emission technologies.

Through the state's Sustainable Energy Research and Development program, funding of A$877,188 has been provided in 2007 for five solar thermal projects by the CSIRO, the University of Wollongong, and industry, although hydrogen production or storage are not priorities. The projects are:

- study and implementation of solar thermal solid state electron power generators, University of Wollongong;

- solar thermal absorption cooling, New Energy Partners Pty Ltd;
- solar thermal organic Rankine cycle for distributed energy applications, CSIRO Energy Technology;
- high concentration solar research facility and pre-commercial solar gas prototype, CSIRO Energy Technology; and
- direct solar steam generation at Liddell Power Station, Solar Heat and Power Pty Ltd.

5.2.3 Victoria

This state accounts for 22% of Australia's greenhouse gas emissions, and 52% of these arise from the use of brown coal for electricity generation in Victoria. It has established an Energy Technology Innovation Strategy to develop new, low-emission energy technologies and to establish least-cost solutions for stationary energy supply and use in a carbon-constrained world.[34] The Victorian government has committed over A$187 million in funding to a range of low emissions energy technology initiatives. Funding for two Victorian large scale pre-commercial brown coal demonstration projects include:

- $50 million towards a 400 megawatt $750 million power generation plant that will demonstrate a Victorian-owned and developed integrated drying and gasification combined cycle technology. The Australian Government has also committed up to $100 million to this project;
- $30 million towards a $369 million coal drying and carbon capture project at Hazelwood Power Station. The Australian Government has also committed up to $50 million to this project;
- Up to $50 million has been committed for a 154 megawatt $420 million solar power electricity generation plant to be built by Solar Systems Generation in north west Victoria. The Commonwealth Government has also committed up to $79.5 million to this project;
- Around $29 million has been committed by the Australian Government to support the Centre for Energy and Greenhouse Technologies to continue its work assisting emerging technologies to reach commercialisation;
- A $12 million grants round for high quality brown coal R&D proposals that can leverage input from industry and the Commonwealth;
- $10 million to support sustainable energy R&D, including renewable energy, energy efficiency and clean distributed generation;
- $4 million for a trial of carbon dioxide capture and storage in the Otway Basin; and
- $2.2 million to support construction of a pre-commercial plant demonstrating coal drying technology known as mechanical thermal expression.

The Victorian Department of Primary Industries – through its $10 million Energy Technology Innovation Strategy: Sustainable Energy Technology R&D Grants program – has provided $1.2 million for research into efficient hydrogen-fuelled car engines. The hydrogen project will be led by the University of Melbourne in partnership with the Ford Motor Company of Australia, Haskel Australia Pty Ltd and the Universities of North Florida, California (Berkeley) and Delaware. The research project, at a total cost of $2.92 million, will look at designing a more efficient hydrogen-fuelled car engine and also investigate new approaches to hydrogen storage.[35]

5.2.4 Queensland

This state accounts for 28% of the nation's greenhouse gas emissions. ClimateSmart 2050 was announced in June 2007 to provide additional support for:

- clean coal technologies;

- increased natural gas for electricity generation;
- renewable energy technologies such as geothermal and solar thermal;
- CO_2 sequestration;
- energy saving strategies; and
- research into hydrogen fuel cell technologies for general use (www.thepremier.qld.gov.au/library/pdf/climate/ClimateSmart_2050.pdf).

The Queensland Government's hydrogen initiatives include an agreement with the University of South Carolina, which was signed in May 2007, to collaborate on developing and commercialising hydrogen energy technologies. South Carolina passed legislation in June 2007 to establish the Hydrogen Infrastructure Development Act, and in August 2007 created a US$15 million fund for the development of hydrogen and fuel cell research in the state.[36]

The Queensland Government has also provided funding support for Hydrexia Pty Ltd, a spin-off company from The University of Queensland, to develop its hydrogen storage technology using an innovative magnesium alloy developed at the university.

5.2.5 South Australia

The goal for the state's energy sector is to significantly reduce greenhouse emissions while continuing to support productivity and prosperity as outlined in *Tackling Climate Change: South Australia's Greenhouse Strategy 2007–20* (www.climatechange.sa.gov.au). To achieve this, strategies and actions have been developed to: improve the efficiency of energy use; increase take-up of renewable and low emission technologies; and ensure that energy investment and markets follow a transition pathway to low greenhouse emissions.

Recent renewable energy projects in the state, funded under the Australian Government's Renewable Energy Development Initiative program, include:

- Innamincka hot fractured rock power plant being developed by Geodynamics Ltd. $5 Million for a project that integrates sustainable heat mining from a hot fractured rock (HFR) geothermal reservoir to produce zero-emission electricity. The project will be Australia's first HFR geothermal plant.
- $3.98 million for a proof-of-concept project by Scopenergy Limited located on the Limestone Coast, which will lead to a 50 megawatt geothermal power plant. The project will better define prospects for more than 1000 megawatt of geothermal power in the region. The project will lead to an estimated greenhouse gas abatement of almost 40 million tonnes of carbon dioxide.
- $5 million for the development of world-leading reduced-silicon solar photovoltaic technology by Origin Energy Solar Pty Ltd. The solar photovoltaic SLIVER technology is significantly more efficient, and will assist with fostering the uptake of solar power and building Australia's market share of the global photovoltaic sector.

5.2.6 Western Australia

Three fuel cell buses were supplied by DaimlerChrysler as part of a three year international demonstration project in Perth until October 2007. The state government had joined forces with several cities in Europe and Canada to promote the use of hydrogen as a sustainable transport fuel. About $10 million has been invested by the state government to increase public awareness about transport energy issues in this project which has prevented the emission of 300 tonnes of carbon since the trial started in 2004.[37]

6. Australian R&D in hydrogen energy technologies

The symposium on *Science on the way to the hydrogen economy* organised by the Australian Academy of Science in May 2006 highlighted both international and Australian R&D into hydrogen energy technologies.[16] The symposium abstracts are presented in Appendix A and outline Australian and international R&D into development of new materials for hydrogen storage, fuel cell design, hydrogen production from fossil fuels by gasification as well as by solar thermal reaction, and photobiolysis to produce hydrogen from water using green algae.

The DRET Australian Hydrogen Activity Database[5] and the DRET Australian Hydrogen Activity report also provide good overviews of hydrogen research projects in Australia.[38] The report covers more than 120 projects at 36 different organisations in 2005. These include many early stage research projects as well as market assessment studies. The 120 projects listed in the Australian Hydrogen Activity report are categorised into five groups as shown below in Table 2, to provide an indication of the different research areas, although the scales of the different projects vary considerably.

Table 2. Classification of the 120 hydrogen research projects listed in the DRET Australian Hydrogen Activity report, 2005

Categories of research	Number and type of research project	Number of projects in category
Hydrogen production from fossil fuels	coal gasification, 13 biomass gasification, 8 solar-thermal reforming, 3 hydrogen separation, 2 carbon sequestration, 3	29
Hydrogen production from water	electrolysis, 10 photoelectrolysis, 8 microbiological, 7 thermolysis, 1	26
Hydrogen storage and distributed generation	storage, 10 distributed generation, 7	17
Hydrogen use	fuel cells, 13 transportation applications, 5 portable microfuel applications, 1 engines and turbines, 5 batteries and capacitors, 2	26
Standards and implementation	implementation, 8 education, 4 public acceptance and market studies, 10	22

The Australian Hydrogen Activity report shows that the majority of the research has been carried out by the universities and CSIRO; an example of hydrogen production and storage research at an Australian university appears in Box 1. The larger hydrogen research groups in Australia include CSIRO, the National Hydrogen Materials Alliance, the ARC Centre for Functional Nanomaterials, and carbon sequestration research by the CRC for Greenhouse Gas Technologies (CO2CRC). An application in 2004 to establish a Hydrogen Energy CRC in 2005 was not successful.

Box 1. Hydrogen production and storage research at the University of Sydney

Dr Andrew Harris of the **School of Chemical and Biomolecular Engineering** leads a multidisciplinary team working on thermochemical conversion of biomass with steam to produce a hydrogen-rich gas output. Related projects include the development of tailored calcium oxide nanoporous sorbents for CO_2 capture during biomass gasification, nanoporous silicon carbide membrane development, large scale synthesis of carbon nanotubes, as well as improved process technologies such as process intensification of fluidised bed reactors and porous burner reactors [Florin NH and Harris AT (2008) *Mechanistic study of enhanced hydrogen synthesis in biomass gasifiers with in situ CO_2 removal using CaO,* AIChE Journal, in press].

Professor Cameron Kepert of the **School of Chemistry** and his team are investigating nanoporous metal-organic frameworks (MOFs) for their ability to sorb large volumes of hydrogen gas at non-extreme temperatures and pressures. This includes synthesis of a copper benzenetricarboxylate MOF and neutron powder diffraction to study deuterium adsorption. The data revealed six distinct D_2 adsorption sites in the framework, with sites at Cu^{2+} atoms occupied first, followed by nonmetal sites in smaller pores and then in larger pores, to provide a very detailed structural understanding of the way in which D2 loading occurs [Peterson VK, Yun Liu, Brown CM and Kepert CJ (2006) *Neutron powder diffraction study of D_2 sorption in Cu_3 (1, 3, 5-benzenetricarboxylate)2*. Journal of American Chemical Society, vol 128, p 15578].

Professor Thomas Maschmeyer of the **School of Chemistry** and his team are developing novel processes with improved sustainability using catalysis as the key technology. The projects include novel single-site heterogeneous oxidation catalysts; preparation, characterisation and testing of nanoparticles stabilised and supported in mesoporous hosts as catalysts and functional materials; functional coatings on microstructured reactors; and hydrogen generation from water with sunlight. Recently, they have made a nanostructured photocatalyst that uses 4.7% of incident visible light photons to generate hydrogen from water – a photoefficiency more than twice that of any other reported catalyst (paper in preparation). The team is currently working on the stabilisation of the catalyst and its incorporation into a purpose-designed flat plate photoreactor.

Hydrogen research is undertaken by the CSIRO Energy Transformed Flagship and a number of CSIRO Divisions, in particular CSIRO Energy Technology. The CSIRO Hydrogen Technologies program includes fabrication, testing and evaluation of polymer electrolyte membrane fuel cells up to several kilowatts in size; gas cleaning and separation technologies which may be used with a coal gasifier or integrated with a natural gas or a liquid fuel reformer; and solar energy in the reforming of natural gas.[39]

The National Hydrogen Materials Alliance (NHMA) is a research cluster of 11 universities and ANSTO, which aims to develop new materials that improve the efficiency and economics of hydrogen generation, storage and use. The NHMA cluster will receive $9.6 million over three years.[40]

In the industry sector, participation has been dominated by the large petroleum and gas exploration and supply companies, with projects to evaluate hydrogen production with capture of carbon dioxide emissions from coal and gas energy sources, projects in Australia,[41] and as part of international projects such as the planned, but now under review, FutureGen initiative.[30,31] BP and Rio Tinto announced in May 2007 that they would investigate the possibility of building a $2 billion 500 megawatt coal-fired power station with carbon capture technology at Kwinana in Western Australia in 2011, following a $60 million feasibility study.[42] The facility could capture up to 90% of its carbon emissions, or four million tonnes of carbon dioxide. The carbon would be transported offshore by a pipeline and stored in a geological formation two kilometres beneath the seabed of the Perth Basin. Alcoa also launched its new carbon capture technology at its Kwinana alumina refinery in a process which traps the carbon dioxide with bauxite residue.[43] The Kwinana plant will trap 70,000 tonnes of CO_2 a year (the equivalent of taking 17,500 cars off the road), which will increase to 300,000 tonnes of CO_2 per year when the technology is implemented across all three of its refineries. BHP Billiton and Xstrata Coal, are participating in the international FutureGen initiative to build the world's first integrated sequestration and hydrogen production research power plant. The US$1 billion, 10-year demonstration project announced in 2003 and sponsored by the USA is intended to create the world's first zero-emissions fossil fuel plant. A site in the US state of Illinois was selected in December 2007, but in February 2008 the US DOE announced a review of its funding for this project and possible new directions for its funding support for carbon capture and storage projects.[31]

These gasification projects are intended to provide a transition for Australia from hydrogen produced from low emission coal and gas to future hydrogen production from renewable sources. The successful development of these technologies would also support Australian export of coal and gas.

Ceramic Fuel Cells Limited (CFCL) is the leading research-based fuel cell development company in Australia with more than 75 patents granted in international markets for 29 inventions. CFCL also launched its SOFC module in 2007 at the Hanover Fair in Germany. The 1kw unit uses natural gas as the fuel for distributed power and heat generation and is designed for incorporation by utility companies into co-generation units.[44] The company is targeting Europe and Japan first since the regulatory systems in these markets already encourage investment, deployment and use of micro-combined heat and power systems. It is one of a handful of small Australian energy startup companies, and the early state of this industry sector is apparent from a comparison with the emerging nanotechnology sector in Australia which has about fifty nanotechnology companies.

Other Australian companies with an interest in hydrogen technology include Eden Energy Ltd[45], Oreion Australia Energy Pty Ltd[46], Wind Hydrogen Ltd[47], Hydrogen Technology Limited[48] and Hydrexia Pty Ltd.[49]

Eden Energy Ltd[50] was listed on the Australian Stock Exchange in May 2006, with interests in hydrogen production, storage and transport fuel systems, including production and motor vehicle applications for Hythane (a hydrogen-natural gas mixture) through subsidiaries in the US and projects in China and India. Eden Energy announced in January 2008 that it has been awarded a contract by Indian Oil Corporation to build a US$1.0 million hydrogen/Hythane retail fuel outlet in Delhi. The company also collaborates with the University of Queensland on research into low temperature pyrolysis of fossil fuels for hydrogen production.

Oreion Australia Energy Pty Ltd[51] is using technology licensed from the CSIRO to develop Oreion Hytest, a modular user-friendly fuel cell test station for researchers and fuel cell developers. The company is also developing Oreion Hymicro, a direct hydrogen micro fuel cell as a replacement for batteries to power small scale electronic devices, such as mobile phones and laptop computers, needing power sources of up to 500 watt.

Wind Hydrogen Ltd[52] launched a $12 million public offer in June 2007 with plans for 19 wind farms in the UK, and one in Australia at Woolsthorpe in Victoria. It proposes to use its patented technologies under development in the US and UK for hydrogen production by electrolysis, and for energy storage.

Hydrogen Technology Limited[53] has developed an electrolysis system for production of hydrogen and oxygen as an alternative to acetylene and hydrocarbon gases for metal cutting and joining processes which eliminates emissions of greenhouse gases, carbon monoxide and nitrogen oxides in the workplace.

Hydrexia Pty Ltd[54] a spin-off company from the University of Queensland has received funding from the Queensland Government and AusIndustry for development of its hydrogen storage technology using an innovative magnesium alloy developed at the university.

7. Hydrogen energy research funded by AusIndustry and the Australian Research Council

7.1 AusIndustry

AusIndustry has funded the following two projects. Hydrexia Pty Ltd received $300,579 in June 2007 as a Commercial Ready Grant for development of hydrogen storage systems; and Hydrogen Technologies received $52,000 as a COMET Grant to help commercialise its project involving the cutting, brazing and welding of metals using hydroxy gas (hydrogen and oxygen).

7.2 Australian Research Council (ARC)

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 as summarised in Table 3. The projects were identified from titles and project summaries which indicated that the major objectives of the research were experimental or theoretical work on aspects of hydrogen generation, storage, purification or related developments. Other projects, such as some nanomaterial research projects, that have broad aims and could also contribute to hydrogen research applications are not included. For example, funding for the ARC Centre for Functional Nanomaterials is not included here, although some of its projects would make significant contributions to hydrogen research.

Table 3. ARC funding for hydrogen projects and fellowships announced in 2001–07

	Projects (48)	**Fellowships (4)**	**Total**
2002	125,000	67,000	192,000
2003	536,000	650,334	1,186,334
2004	1,211,950	650,148	1,862,098
2005	2,736,578	735,311	3,471,889
2006	3,511,880	890,473	4,402,353
2007	4,189,206	890,473	5,079,679
2008	4,302,916	310,325	4,613,241
2009	3,336,709	310,325	3,647,034
2010	1,446,148	155,163	1,601,311
2011	250,000		250,000
Total	**18,373,161**	**4,659,551**	**23,032,712**

Figure 4 provides a summary of the types of projects that have been funded, noting that this includes some duplication. For example, a project on hydrogen production from biomass would register for both hydrogen production and biomass. The chart of hydrogen research project priorities in Figure 4 shows that hydrogen production is the major objective, with nanomaterials research being prominent for improving hydrogen generation and storage, and also for improving the efficiency of fuel cells and component membranes. Other leading applications include hydrogen storage, fuel cells and membranes.

The 48 projects and four fellowships are listed in Appendix B and to provide an overview of the range of projects, and institutions receiving grants. Note that in some cases there are collaborating institutions but the table lists only the grant awardee.

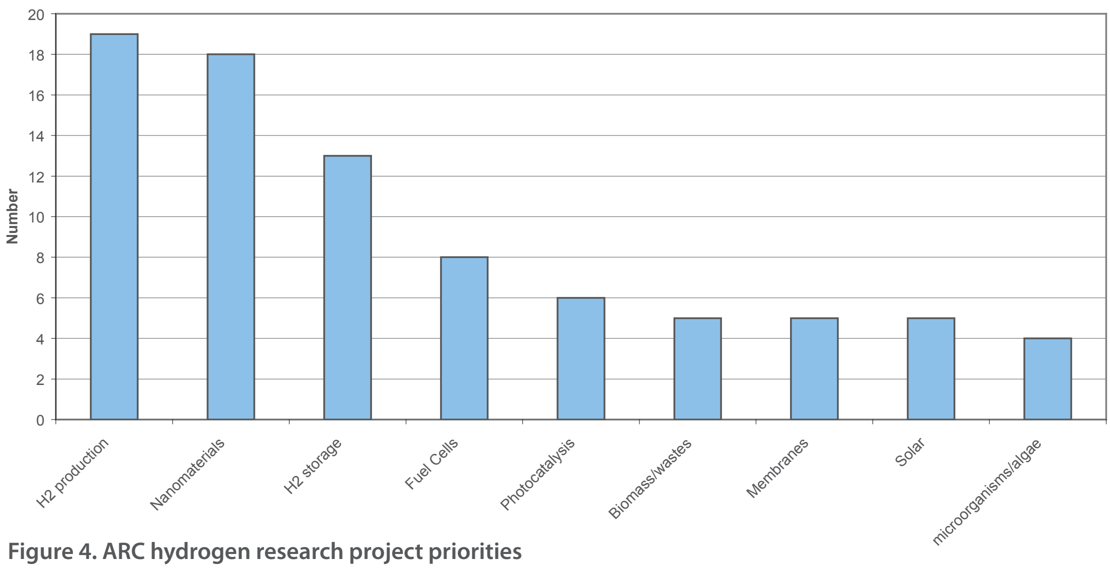


Figure 4. ARC hydrogen research project priorities

8. Australian contribution to global hydrogen energy research – bibliometric comparisons

8.1 Methods

The quantitative study in this project is based on a comprehensive bibliometric analysis of hydrogen research in key fields. It applies a benchmarking methodology piloted by the Australian Academy of Science for assessing emerging areas of science and technology in Australia, such as Australia's capability in nanotechnology.[55] The analyses compared hydrogen energy publications by Australian and other researchers cited in the Thomson ISI Web of Knowledge Science Citation Index Expanded database. The methodology includes:

- developing a comprehensive list of keywords related to the field (Appendix C); and
- performing a comprehensive bibliometric analysis of the field (Appendix D).

The fields analysed are:

- hydrogen production;
- hydrogen separation;
- hydrogen distribution and storage;
- hydrogen engines;
- hydrogen fuel cells; and
- facilitating technologies.

8.2 Results

A global search for hydrogen energy research publications using the Thomson ISI Web of Knowledge shows that the number of world science publications relating to hydrogen energy has been increasing linearly since 1990, indicating that hydrogen energy is rapidly becoming an important area of research throughout the world, particularly for countries and regions which have established hydrogen research initiatives. Figure 5 shows that Australia is the 16th largest producer of hydrogen energy research publications.

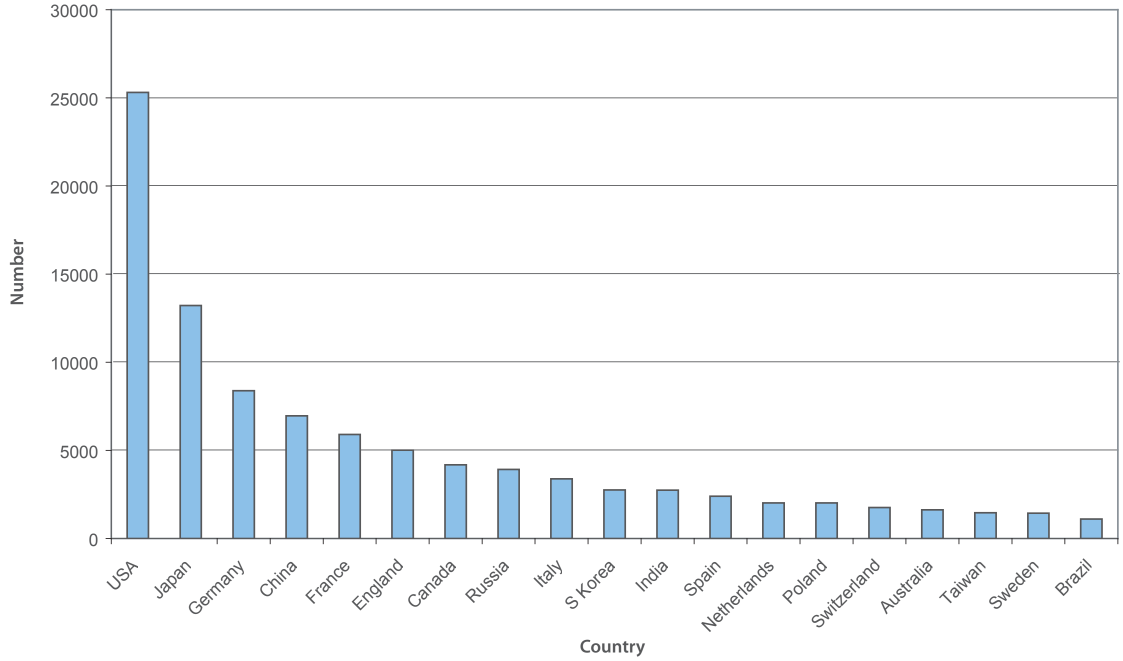


Figure 5. Australia's share of global hydrogen research publications

The bibliometric analysis showed that Australia produced 1.69% of the world's hydrogen publications in the above fields from 1980 to 2006, which increased slightly to 1.78% more recently for 1998 to 2006. This is lower than for science as a whole, for which Australia produced 2.89% of the world's science publications in 2004. However, the number of Australian hydrogen energy publications has grown steadily since 1991 and then more rapidly since 2003, as shown in Figure 6.

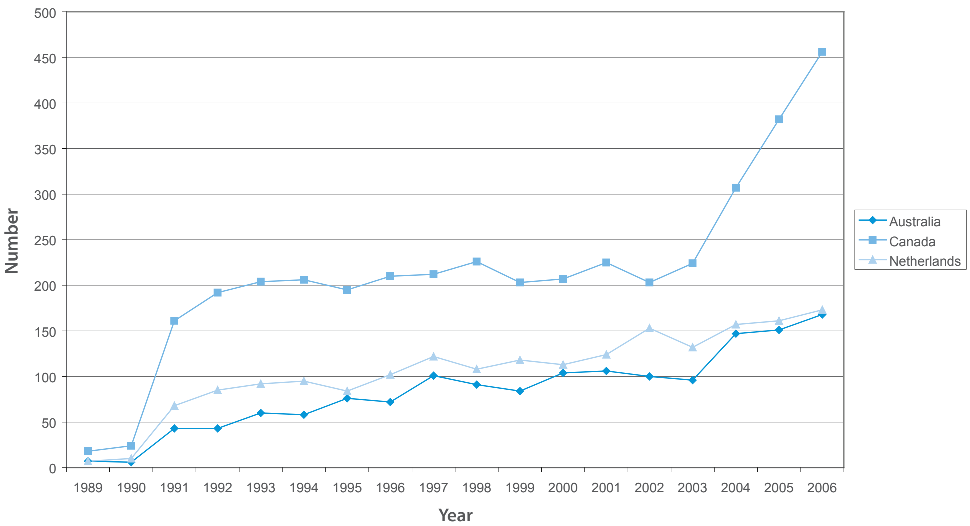


Figure 6. Trends in hydrogen research publications for three countries

The percentage of Australian research publications on hydrogen energy is also increasing, indicating that hydrogen is a growing area of research in Australia, but this increase is less rapid than for the world as a whole. Figure 6 also provides a comparison of hydrogen energy publication rates for three countries which shows Australia to have a similar rate of publications to the Netherlands, but falling behind the steep increase in Canadian hydrogen energy publications since 2003.

So far Australia, as the 16th largest producer of hydrogen research papers, has been a minor contributor to the overall field. However, the citation analysis of Australian hydrogen publications indicates that Australian papers are being published in relatively high impact journals, and are receiving similar but slightly lower than average citation ratings compared with other hydrogen research publications in those journals (Table 4).

Table 4. Citations per paper (1945–2007)

Hydrogen research area	World papers	Australian papers
Fuel cells	11.2	11.1
Solar hydrogen production	9.7	8.9

Australian hydrogen energy publications for 1980 to 2006 show a significant level of international collaboration, with 39% of publications including an international collaborator, and the five leading collaboration countries being the USA, England, Germany, China and Japan (Figure 7).

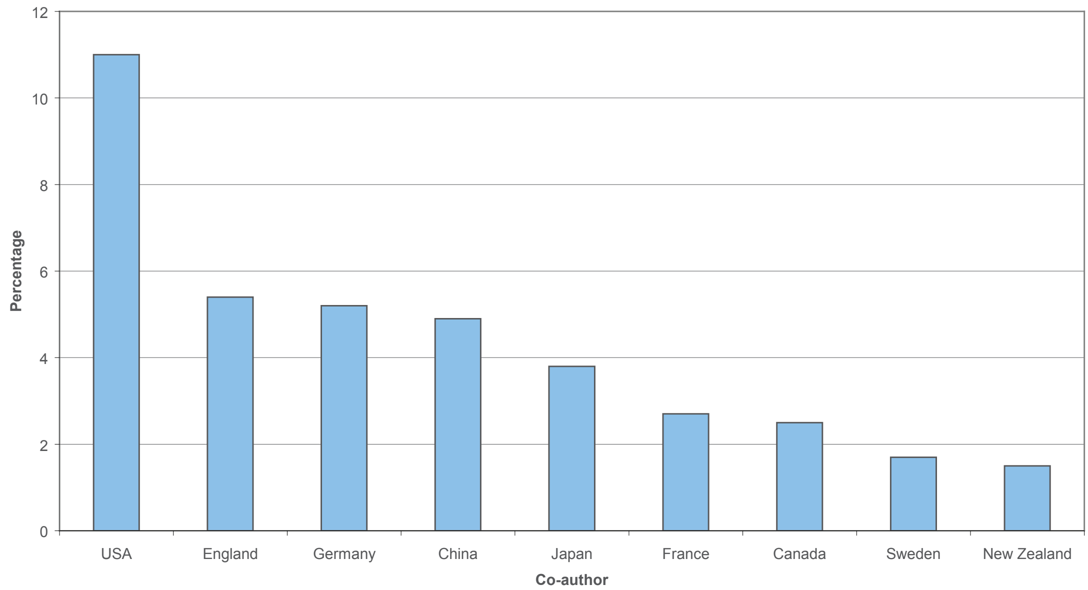


Figure 7. Australia's leading international country collaborators in hydrogen research

The leading Australian institutions in hydrogen energy research by the percentage share of publications for 1980 to 2006 are shown in Figure 8.

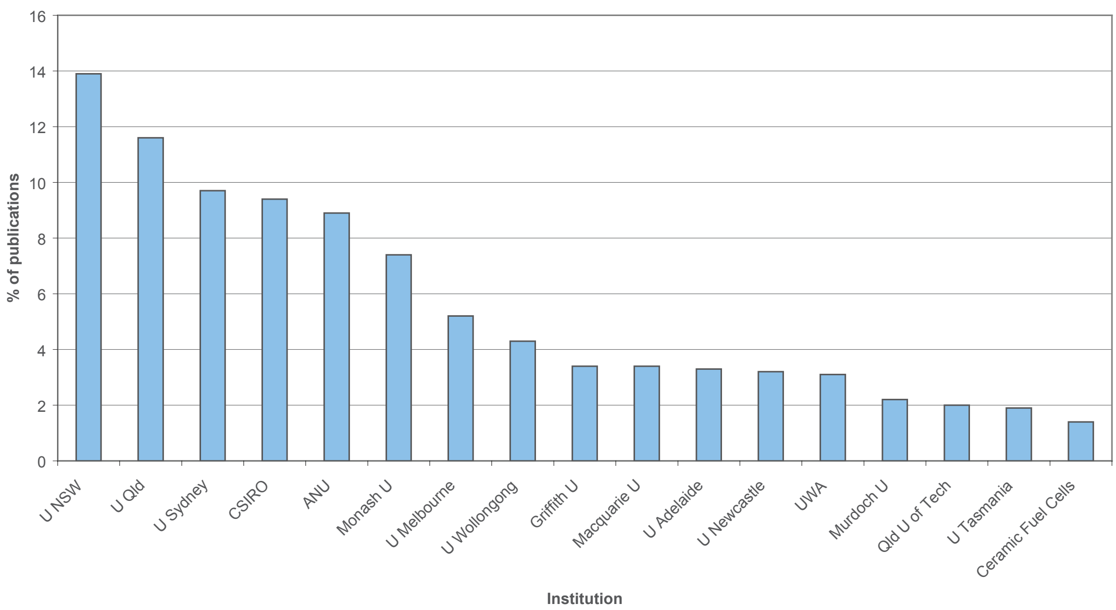


Figure 8. Hydrogen research publications by Australian research organisations

9. Development of an Australian scientific roadmap for the hydrogen economy

The above overview and analyses of Australian R&D in hydrogen energy technologies, and assessment of the Australian contribution to the fields internationally, has been undertaken to provide a measure of Australian R&D and capabilities in these fields. The findings and recommendations from this work can be taken into consideration in the development of an Australian Scientific Roadmap for the Hydrogen Economy.

Internationally, research into hydrogen as a renewable energy resource is increasing and has been led by countries with a large reliance on imported oil and gas, with concerns about energy supply security, or with targets for reducing greenhouse gas emissions. Other countries have also established programs to develop and commercialise hydrogen fuel cell and related technologies to become leaders in this emerging technology area.

Australia is fortunate to have extensive reserves of coal and gas which have contributed to relatively low energy costs for industry and the broader community. However, Australian scientists also have a strong record of research and development into renewable energies, and solar energy in particular. The Australian Government and broader community have also accepted the need to reduce the country's greenhouse gas emissions with a range of projects including research into clean coal technologies and renewable energy sources as described in this report. Federal and several state governments have also introduced targets for increased supply of energy from renewable energy sources, and there are plans to introduce emissions trading schemes.

As a result of Australia's extensive fossil fuel reserves, the R&D by the coal and gas industries is directed towards coal and gas for base load energy generation by gasification to produce hydrogen with carbon sequestration, until renewable energies are able to make significant contributions to energy requirements. This can be considered in relation to the Australian Government's report on Securing Australia's Energy Future which provides a strategic assessment of priorities for energy technology development in Australia with identification of three broad categories, defined as: [56]

- market leaders – technologies with strategic importance for Australia that international efforts will not adequately address, or in which Australia has a clear technology advantage;
- fast followers – technologies where Australia has a strategic interest but where domestic efforts should focus on supplementing international developments, adapting technologies to suit Australian needs and, adopting these technologies quickly when available; and
- reserve – technologies in which Australia has a lesser strategic interest at this stage, but which may become more important in the future.

In the matrix of energy technology assessments and priorities for Australia, as shown in Table 5 from the report on Securing Australia's Energy Future[43], hydrogen is listed as a reserve energy technology for Australia. Hydrogen is seen as a potential long-term energy carrier and source, particularly for transportation and portable applications.

Table 5. Energy technology development priorities for Australia

Market leader	Fast follower	Reserve
Play a leading role in international R&D efforts	Strongly position Australia to follow international developments quickly	Position Australia to monitor international developments and follow as needed
Energy supply technologies		
Advanced brown coal	Advanced black coal	Hydrogen
Geosequestration	Natural gas	Tidal
Hot dry rocks	Wind	Large-scale hydro
Photovoltaics	Biomass	Nuclear
Remote area power systems	Wave	
Coal mining and extraction	Solar thermal	
Energy demand technologies		
Solid oxide fuel cells	Intelligent transport systems	Other fuel cells
	Energy efficiency	
	Advanced conventional vehicles	
	Hybrid electric vehicles	

As outlined in this report, Australia is a minor contributor to R&D into hydrogen energy technologies. Industry R&D priorities are directed towards utilisation of coal and natural gas reserves and reduction of greenhouse gas emissions, through gasification of coal and natural gas for hydrogen production with separation and trapping of the carbon dioxide.

The most significant Australian industry R&D-based companies in the field of fuel cells are Ceramic Fuel Cells Limited (CFCL) and Oreion Australia Energy Pty Ltd. CFCL is testing its SOFC technology for power and heat applications for initial target markets in Europe and Asia; Oreion is developing its fuel cell test station and a direct hydrogen micro fuel cell as a replacement for batteries to power small scale electronic devices, such as mobile phones and laptop computers.

CSIRO R&D into energy technologies covers a range of projects, including hydrogen production from fossil fuels such as coal, gas and biomass. The CSIRO research into hydrogen production by solar thermal conversion in particular, could be considered to be world-leading and also highly relevant to Australian conditions (www.det.csiro.au/science/r_h/nsec.htm). Research into hydrogen energy technologies by the Australian universities covers a broad range of projects as would be expected. However, a focus on materials development can be discerned for a range of applications such as hydrogen storage, new and improved materials for catalysts, fuel cell electrodes and membranes. This research could make important niche contributions to hydrogen technology developments internationally, but there may not be a critical mass in many sectors except for research into hydrogen storage materials.

Australia also has traditional strengths in solar and biological research and this is reflected in a number of innovative research projects. These are at a relatively early stage, and there would be challenges for scale-up, but they could make significant contributions to understanding these fundamental processes. The projects include photoelectrolysis research at the University of NSW and at the University of Queensland.[32] Projects for hydrogen production from biomass wastes using algae and bacteria are being undertaken at a number of universities and CSIRO.[32]

In relation to the challenges that need to be addressed for hydrogen to become a practical energy carrier and source, it is in Australia's favour that the progress still depends on significant research breakthroughs which are where Australian researchers can still make important contributions through innovative approaches and discoveries. This could include increased international collaboration through programs such as the European Commission's Fuel Cells and Hydrogen Joint Technology Initiative. This European industry-led integrated program of research, technology development and demonstration activities will receive €470 million from the EU with matching industry funding to accelerate the development of hydrogen technologies to the point of commercial take-off between 2010 and 2020.

The development of an Australian Scientific Roadmap for the Hydrogen Economy needs to take into consideration a number of factors to assess the opportunities, costs, barriers, R&D needs and priorities for Australia to transition to a hydrogen based economy. These include:

1. Fossil fuels
    a. Australia's extensive fossil fuel energy reserves of coal and gas
    b. How greenhouse gas (and other) emissions from these fuels used for stationary electricity power generation can be reduced in the short term through clean coal technologies; and in the longer term by gasification to produce hydrogen, or enriched hydrogen blend fuels, with practical carbon sequestration technologies.
2. Renewable energy sources
    a. Assess the relative energy supply contributions, and the potential in each of these for using hydrogen as the means for energy storage, distribution and consumption, which could be made by solar, wind, geothermal, hydro, biomass, and uranium for the different energy requirements for stationary and distributed electric power, industry (manufacturing and resources sectors), domestic users, and for road and air transport.
3. Energy policies
    a. Federal and state government initiatives to encourage market-driven R&D into development of clean fossil fuel and alternative energy resources, such as emissions trading schemes and greenhouse gas reduction targets
    b. Federal and state government support for basic research into alternative energy solutions which build on Australian research strengths
    c. Support for demonstration and other projects to develop capabilities for adapting overseas developments to Australian requirements, and to increase community awareness.
4. Role of hydrogen as an energy carrier and fuel for Australia
    a. Assessment of Australian and international R&D into hydrogen as an alternative energy carrier and fuel, derived from fossil fuels and renewable energy resources
    b. Realistic time frame for staged introduction of hydrogen derived from fossil fuels, including demonstration projects, selected trials for stationary power generation and transport applications
    c. Time frame for infrastructure development for hydrogen generation from fossil fuels, including distribution, storage, delivery to end users in accordance with regulatory requirements
    d. Time frame for large scale production of hydrogen from renewable energy sources
    e. Priorities for hydrogen energy research in Australia based on niche strengths in Australia, and for development of capabilities for incorporation of foreign technologies and products.

10. Conclusions

The following conclusions arise from a consideration of the factors outlined above for development of an Australian Scientific Roadmap for the Hydrogen Economy, with the findings from this project review and bibliometric analysis of the strengths of Australian R&D in hydrogen energy technologies. The key findings from this project are:

1. Australia will continue to use the fossil fuels coal, oil and gas to provide base power generation for industry and domestic electricity requirements for the next 15 to 20 years, with research into clean coal technologies to continue in Australia, and internationally.
2. Australia is well-placed to contribute significantly to research into clean coal technologies, including CO_2 capture and storage, as a result of significant government funding and industry participation. Australian research success in this area and collaboration with key export market countries, will contribute to:
    a. continuing exports of these economically-important commodities and their use for power generation with low greenhouse gas emissions;
    b. the transition to fossil fuel energy alternatives, including hydrogen; and
    c. national and international initiatives for lowering greenhouse gas emissions.
3. Australian research into hydrogen energy applications will be in niche areas, since there is very limited research-based or technology-based industry being established for market-driven opportunities.
4. Australian hydrogen energy research in a number of sectors is high-quality, but it is spread over a range of basic and applied research areas. It is also lacking in critical mass in most sectors other than clean coal technologies, and research into hydrogen storage materials.
5. Australian hydrogen research will make important contributions in research-intensive areas such as CO_2 separation and sequestration, hydrogen storage materials, solar-thermal reforming of fossil fuels and biomass for hydrogen production, and distributed energy supply for remote areas.
6. There has been significant research funding for hydrogen energy technologies by the Australian Research Council, but there is a need for federal and state government initiatives to support early-stage startup companies and industry participation for commercialisation of the promising research to ensure that Australia can participate in the development of this important emerging energy sector.
7. There is a need for continuing Australian R&D into hydrogen energy technologies and applications to ensure that Australia can both contribute to this sector in areas of niche strengths, and also develop the necessary expertise to incorporate international hydrogen energy developments into Australia's energy strategies in a timely manner.
8. The Australian Government should consider a revised energy technology assessment for hydrogen from the 'reserve' to 'fast follower' category based on the present speed of global developments for hydrogen energy R&D and applications.

9. The COAG Roadmap for the Development of Hydrogen Technology in Australia, due in April 2008, will provide more detailed guidance for government and industry on hydrogen energy R&D capabilities in Australia and priority areas for research and applications development. In addition, the roadmap could identify mechanisms to foster Australian R&D in energy alternatives to fossil fuels, including hydrogen, which is likely to be the next major global research-based technology and industry development sector to follow the ITC and biotechnology sectors.

10. The coordinated development of Australian hydrogen energy R&D and applications as part of Australia's future energy strategies would benefit from the development of an 'Australian Hydrogen Energy Initiative' which could incorporate support for:

    a. continuing hydrogen energy R&D with particular attention to building critical mass in areas of Australian expertise through a CRC or other consortia;

    b. early-stage startups for proof-of-concept of promising hydrogen energy research discoveries;

    c. commercialisation through existing AusIndustry and other government programs;

    d. demonstration projects; and

    e. the establishment of an effective Hydrogen Energy Industry Group or Association to foster sector collaboration and community awareness about the transition to a hydrogen economy.

11. References

[1] COAG (2007), Communique on Climate Change, Meeting of 13 April 2007. Retrieved from www.coag.gov.au/meetings/130407/index.htm

[2] Wyld Group Pty Ltd for the Australian Government, Department of Industry, Tourism and Resources, October 2007, Discussion paper: Hydrogen Technology Roadmap – Market Potential and Challenges, Innovation Opportunities and Policy Issues, 19 pages.

[3] Mulder, G et al (2007), Towards a Sustainable Hydrogen Economy: Hydrogen Pathways and Infrastructure, International Journal of Hydrogen Energy, v32, pages1324-1331.

[4] Ogden, Joan (2004), Hydrogen as an Energy Carrier: Outlook for 2010, 2030 & 2050, Workshop Proceedings: The 10-50 Solution: Technologies and Policies for a Low-Carbon Future, The Pew Center on Global Climate Change and the National Commission on Energy Policy, March 2004.

[5] Rand, D.A.J. and Dell, R.M. (2008), Why Hydrogen Energy? In Hydrogen Energy: Challenges and Prospects, RSC Energy Series. ISBN 978-0-85404-597-6. View contents at www.rsc.org/Shop/books/2007/9780854045976.asp

[6] Australian Hydrogen Activity Database (2005), Department of Resources, Energy and Tourism, www.ret.gov.au

[7] IEA Hydrogen Implementing Agreement, www.ieahia.org/

[8] International Partnership for the Hydrogen Economy, www.iphe.net/

[9] International Energy Outlook 2007, Energy Information Administration, US Dept of Energy, May 2007. Retrieved from www.eia.doe.gov/oiaf/ieo/index.html

[10] Energy Information Administration (July 2004). Renewable Energy Trends 2003 with Preliminary Data for 2003. Table C-3, page 24, www.eia.doe.gov/cneaf/solar.renewables/page/rea_data/rea.pdf

[11] Doucet, J and Laverty, B (2007), The Push to Coal Gasification in Alberta, University of Alberta School of Business. Retrieved from www.business.ualberta.ca/cabree/pdf/2007%20Winter/Laverty_Coal_Gasification_560.pdf

[12] GM: Hydrogen cars will re-establish company, Associated Press, 15 September 2006. Retrieved from www.msnbc.msn.com/id/14848423/

[13] Kia develops green vehicles that don't cost the earth, Herald Sun, 14 December 2007, page 45. Retrieved from www.news.com.au/heraldsun/story/0,21985,22912872-5012441,00.html

[14] Back to the future: electric vehicle at the core of GM's vision, Globe and Mail, 13 December 2007. Retrieved from www.theglobeandmail.com/servlet/story/RTGAM.20071212.wh-GMmain-1213/BNStory/specialGlobeAuto/?pageRequested=3

[15] The New Jersey Hydrogen Learning Center, retrieved from www.policy.rutgers.edu/ceeep/newhome/njh2lc_about.html

[16] Australian Academy of Science (2006), Proceedings from symposium on *Science on the Way to the Hydrogen Economy*, 3-5 May 2006, www.science.org.au/sats2006/symposium.htm

[17] Hydrogen Energy Frequently Asked Questions, www.airproducts.com/Products/LiquidBulkGases/HydrogenEnergyFuelCells/FrequentlyAskedQuestions.htm

[18] Minnesota Department of Commerce and Minnesota Office of environmental Assistance (2005), Minnesota Biomass – Hydrogen and Electricity Potential. Retrieved from www.pca.state.mn.us/oea/p2/forum/MNbiomass-NREL.pdf

[19] Wibberley, L (2007), Alternative Pathways to Low Emission Electricity, Coal 21 Conference, Hunter Valley, NSW, Australia. Retrieved from www.coal21.com.au/Media/Conference%2007/day%202%201100%20Wibberley.pdf

[20] Stanley, D (2007), Shell takes Flexible Approach to Fueling the Future. Retrieved from www.hydrogenforecast.com/ArticleDetails.php?articleID=250

[21] U.S. Department of Energy - Energy Efficiency and Renewable Energy Hydrogen, Fuel Cells and Infrastructure Technologies Program – Hydrogen Storage, retrieved from www1.eere.energy.gov/hydrogenandfuelcells/storage/printable_versions/tech_status.html

[22] Hydrogen 06 Report Switzerland (2006), page 20. Retrieved from www.hydropole.ch/Hydropole/HYDROPOLE.htm

[23] European Hydrogen and Fuel Cell Technology Platform Strategic Research Agenda (2005), Transportation Applications, pages 55-65. Retrieved from https://www.hfpeurope.org/uploads/677/686/HFP-SRA004_V9-2004_SRA-report-final_22JUL2005.pdf

[24] Dixon, R.K (2007), Advancing towards a Hydrogen Energy Economy: Status, Opportunities and Barriers, in Mitigation and Adaption Strategies for Global Change, v12 (3), pages 325-341.

[25] Vogel, G (2004) Will the Future Dawn in the North? Science, v305 (5686), pages 966–967.

[26] CRL Energy Ltd (2007), Pathway to Hydrogen Economy. Retrieved from www.crl.co.nz/latest_news/April07.asp

[27] The FreedomCAR and Fuel Partnership Plan (2006). Retrieved from www1.eere.energy.gov/vehiclesandfuels/about/partnerships/freedomcar/index.html

[28] President's Hydrogen Fuel Initiative. Retrieved from www1.eere.energy.gov/hydrogenandfuelcells/presidents_initiative.html

[29] Breakthrough Technologies Institute, Inc (2006), State Activities that Promote Fuel Cells and Hydrogen Infrastructure Development. Retrieved from www.fuelcells.org/info/StateActivity.pdf

[30] FutureGen Initiative, www.fossil.energy.gov/programs/powersystems/futuregen/

[31] Clean Coal Power Plant Canceled-Hydrogen Economy, Too. Retrieved from www.sciam.com/article.cfm?id=clean-coal-power-plant-canceled-hydrogen-economy-too&page=1

[32] Department of Trade and Industry (2007), Meeting the Energy Challenge: A White Paper on Energy, 343 pages. Retrieved from www.berr.gov.uk/files/file39387.pdf

[33] Pigneri, A and Spazzafumo, G (2005), Drafting a Hydrogen vision for Tasmania, Proceeding of the Hypothesis VI International Symposium, La Havana, Cuba, May 2005. Retrieved from http://hydrogen.its.ucdavis.edu/publications/pubpres/pubs2005/pigneri05

[34] Department of Primary Industries, Victorian Government 1996 – 2007, Energy Technology Innovation Strategy (ETIS). Retrieved from www.dpi.vic.gov.au/dpi/dpinenergy.nsf/linkview/916fb089198cc145ca2572bb000985b4afe5d9442e22210aca2572bb00096717

[35] Victorian Minister for Energy and Resources Media Release, 28 March 2007, Research Grant to Focus on Hydrogen Fuelled Cars. Retrieved from www.dpc.vic.gov.au/domino/Web_Notes/newmedia.nsf/b0222c68d27626e2ca256c8c001a3d2d/63f02a2f1612d9adca2572ac007a0d2f!OpenDocument

[36] South Carolina Hydrogen and Fuel Cell Alliance (2007), State Pledges $15 Million to Back Hydrogen Energy Research Projects. Retrieved from www.schydrogen.org/aug_07_news.html

[37] Cockerill, R (2007), Hydrogen Bus Trial Draws to a Close. Retrieved from www.gasworld.com/news.php?a=1996

[38] Rand, D.A.J and Badwal, S.P.S (2005). Australian Hydrogen Activity, Department of Industry, Tourism and Resources, Canberra, Australia, ISBN 0 642 723 729, see www.ret.gov.au

[39] CSIRO, New Technologies to Advance the Hydrogen Economy, 13 December 2005. Retrieved from www.csiro.au/science/psuj.html

[40] CSIRO, Research Cluster aims for breakthroughs in hydrogen Materials Science. Retrieved from www.csiro.au/partnerships/ps2lq.html

[41] Australian Government (2006), Australian Government Submission into the House of Representatives Inquiry on Geosequestration. Retrieved from www.aph.gov.au/house/committee/scin/geosequestration/subs/sub41.pdf, 35 pages.

[42] Wilson, N (2007), BP, Rio in Clean Coal Push, The Australian, 22 May, 2007, retrieved from www.theaustralian.news.com.au/story/0,20867,21772580-601,00.html

[43] 'Carbon Capture' system set to revolutionise greenhouse emissions in aluminium industry, 29 April 2007, retrieved from www.alcoa.com/australia/en/news/releases/20070429_carboncapture.asp

[44] Dow, B (2007). Ceramic Fuel Cells Limited FY07 Results – Investor Presentation, October 2007. Retrieved from www.cfcl.com.au/Assets/Files/20071002_Roadshow_Statutory_accounts[1].pdf

[45] Eden Energy Ltd, www.edenenergy.com.au

[46] Oreion Australia Energy Pty Ltd, www.oreion.net

[47] Hydrogen Technology Limited, www.hydrogentechnology.com.au

[48] The Sydney Morning Herald (20 June, 2007), Wind Hydrogen Ltd launches $12M IPO. Retrieved from www.smh.com.au/news/Business/Wind-Hydrogen-Ltd-launches-12m-IPO/2007/06/20/1182019190727.html

[49] Hydrexia Pty Ltd, www.hydrexia.com.au

[50] Australian Academy of Science (2004). Nanotechnology Benchmarking Project. Retrieved from www.science.org.au/policy/nanotech.htm

[51] Australian Government (2004), Securing Australia's Energy Future, pages 31-32. Retrieved from www.pmc.gov.au/publications/energy_future/index.htm#fuel_reform

12. Appendices

Appendix A

Program, abstracts and presentations from the following symposium can be viewed at:
www.science.org.au/sats2006/symposium.htm

Science on the way to the hydrogen economy

Science at the Shine Dome **Annual Symposium**

Opening address
Dr Jim Peacock
President, Australian Academy of Science

Opening comment
Chair: Dr Michael Barber
Executive Director, Scientific Planning, CSIRO

Dr John Wright
Director, CSIRO Energy Transformed Flagship
Setting the scene: What is the hydrogen economy?

Plenary Lecture
Dr George Crabtree
Senior Scientist, Argonne National Laboratory, USA
The two hydrogen economies

Professor Cameron Kepert
Federation Fellow, University of Sydney
Hydrogen storage in nanoporous materials

Chair: Professor Leslie Field
Deputy Vice-Chancellor (Research), University of New South Wales

Dr Sukhvinder Badwal
CSIRO Manufacturing and Infrastructure Technology
Fuel cells

Professor Andrew Dicks
ARC Centre for Functional Nanomaterials, University of Queensland
Advanced nanomaterials for fuel cells

Dr Evan Gray
Physics, Nanoscale Science and Technology Centre, Griffith University
Hydrogen storage: status and prospects

Dr Ben Hankamer
Institute of Molecular Bioscience, University of Queensland
Solar powered H_2 production from H_2O using engineered green algal cells

Chair: Dr Bob Watts
Councillor, Australian Academy of Science

Dr Catherine Grégoire Padró
Los Alamos National Laboratory, USA
Production of hydrogen

Professor David Trimm
Federation Fellow, CSIRO Petroleum Research
Catalysis and syngas for the production of hydrogen

Dr Jim Hinkley for Dr Wes Stein
CSIRO Energy Technology
Making hydrogen from the Sun

Professor Harry Watson
Faculty of Engineering, University of Melbourne
Hydrogen car prospects

Dr John Wright

Director, CSIRO Energy Transformed Flagship

Setting the scene: What is the hydrogen economy?

Hydrogen: number one in the Periodic Table and the simplest and most abundant element in the universe. It is a very 'social' element on Earth and does not exist alone but combines readily with other elements, particularly oxygen, to form water. It is also the fuel that powers stars, including our sun, giving us other components of life such as light and heat.

However, like most useful substances, hydrogen is not without its problems. It needs to be coaxed from its combination with other elements to exploit its properties. In specific combinations with oxygen it forms an explosive mix and, being so light, it is a fugitive gas, which challenges us to contain and store it appropriately.

The phrase 'The Hydrogen Economy' has entered the lexicon of energy-speak. What is so special about hydrogen in this respect? It has the potential for offering solutions to the major energy challenges of global GHG emissions, affordable energy for all people and a clean and green future.

Could the hydrogen economy be this panacea for all our energy problems? Only time will tell. A catchy phrase is one thing, but the will and the process required to capture such benefits and overcome the drawbacks associated with the use of hydrogen as a future fuel are very different constructs. These issues will be explored as a 'scene-setting exercise' for this Symposium.

Dr George Crabtree

Senior Scientist, Argonne National Laboratory, USA

The two hydrogen economies

Hydrogen offers a compelling solution to the energy challenges of supply, security, pollution and climate change. Although today's technology enables several routes for producing, storing and using hydrogen, none of them are yet competitive with fossil fuels for cost, performance or reliability. Dramatic advances in the basic understanding of hydrogen and its interactions with materials are needed to bring a hydrogen economy to practical realisation. The current state of hydrogen technology and the research challenges for creating a mature hydrogen economy will be discussed.

Professor Cameron Kepert

Federation Fellow, University of Sydney

Hydrogen storage in nanoporous materials

The hydrogen molecule, H_2, represents one of the most fundamental of chemical species. As scientists, we have deep understandings of its structure and its numerous interesting chemical and physical properties. The recent focus on hydrogen as an alternative energy carrier and the associated need for safe and efficient methods for production and storage has led to a whole new set of intriguing questions, and, in turn, to exciting new science.

In considering methods to store hydrogen gas, we are faced with an interesting choice: to convert it into another chemical compound from which the gas can be released, or to store the molecule 'as is' as H_2. In the latter approach, the very low mass of H_2, whilst responsible for its excellent energy density, leads to considerable challenges in achieving a 'chemical handle' on this molecule. This talk will broadly address what these challenges are, the emergence of new families of nanoporous material designed to overcome these challenges, and the prospect for real technological solutions to the hydrogen storage problem.

Dr Sukhvinder Badwal

CSIRO Manufacturing and Infrastructure Technology

Fuel cells

A number of different fuel cells are under development for a range of applications including distributed generation of heat and electricity at load centres (remote areas, residential and commercial dwellings), transport (cars, buses, locomotives, scooters, auto-rickshaws, small transporters) and portable power (electronic appliances, portable power packs, emergency power, etc.).

Fuel cells offer numerous advantages over conventional power generation systems such as high energy density, high efficiency, low noise, low pollution and particulate matter emissions, ability to co-generate heat and electricity at load centres, high-quality power (no spikes or electrical noise), minimum transmission/distribution infrastructure and losses, modularity and fuel flexibility.

A number of companies are conducting trials of fuel cells in buses, cars and for stationary power generation. Semi-commercial fuel cell units with limited warranties are available, however, the cost is high and the lifetime short.

Major hurdles for the commercialisation of the fuel cell technology are their short lifetime, high cost, lack of hydrogen refuelling infrastructure and availability of robust and cost-effective hydrogen storage technologies.

Substantial materials research and development effort is still required to increase the reliability of the technology and to reduce overall fuel cell stack cost.

In this presentation, fuel cell technology, operational issues and challenges will be discussed and commercial progress reviewed. In addition, CSIRO's work on micro, portable and small fuel cells and the related technologies will be described.

Professor Andrew Dicks

ARC Centre for Functional Nanomaterials, University of Queensland

Advanced nanomaterials for fuel cells

Nanomaterials feature strongly in fuel cell systems. All fuel cells consist of layers of anode, electrolyte and cathode. The performance of fuel cells depends critically on the structure of these material layers, at the macro-scale and nano-scale. In addition, nanomaterials feature as catalysts for the processing of fuel. For example, natural gas can be converted directly into hydrogen for fuel cells by reaction with steam over a supported nickel catalyst at high temperatures. The design of such a catalyst is critical to the long-term performance of a natural gas-fed fuel cell system. The study of nanomaterials is therefore an essential part of understanding how to improve performance and reduce costs of fuel cells.

Work at the University of Queensland focuses on the study of nanomaterials for solid oxide fuel cells (SOFC) and proton exchange membrane (PEM) fuel cells, as well as fuel processing solutions. Application of electron microscopy and micro-analysis is helping to advance the understanding of how SOFC operate. The preparation of new materials, using techniques such as sol-gel synthesis, is assisting with the improvement of PEM fuel cell performance. Collaboration with the Australian National University could lead to the provision of a low-cost method of preparing the electrodes and electrolytes for small fuel cells suitable for consumer electronic devices such as mobile phones.

Dr Evan Gray

Physics, Nanoscale Science and Technology Centre, Griffith University

Hydrogen storage: Status and prospects

The essence of the hydrogen storage problem is that gasoline has 17 wt% hydrogen, a higher calorific value per hydrogen atom than pure hydrogen, and a high energy density by volume. Consequently, hydrogen mass energy densities acceptable to the automobile industry in the short term are presently achieved reversibly only with highly pressurised gas, but this approach can never meet volume density targets.

The approach taken by many researchers looking for solid-state hydrogen storage materials is now to start with host materials with the lowest possible average atomic number, so that the mass fraction of hydrogen is maximised for a given hydrogen uptake. Li-based materials have the potential to meet the US Department of Energy's mass density criteria (6 wt% H by 2010, 9 wt% by 2015) and be technologically viable, given sufficient improvement in other characteristics including thermodynamic stability (or ease of desorption/decomposition), absorption rate and insensitivity to poisoning by impurities in the gas stream. Australia's excellent light-metal resources could be the basis of a new materials-based industry if these problems can be solved.

Recent progress will be surveyed, with an emphasis on lithium-based materials, including $LiBH_4$, $LiAlH_4$ Li_3NH_4 and nitrides of Li-Mg alloys. The Hydrogen Storage stream of the National Hydrogen Materials Alliance will be described.

Dr Ben Hankamer

Institute of Molecular Bioscience, University of Queensland

Solar-powered H_2 production from H_2O using engineered green algal cells

At the International Energy Congress in Sydney 2004, world energy producers concluded that within the next 15 to 20 years, world energy production would have to double (from 13 TW-yr), in order to provide even basic electrical energy needs for the populations of China, India and other emerging developing nations. However, extensive scientific evidence points to the fact that it is of utmost importance to maintain atmospheric CO_2

levels below 450ppm to prevent major environmental damage. Taken together, these factors indicate the need for rapid implementation of clean energy technologies (7-11 TW-yr) by 2025.

Through the Solar Bio-H_2 Project, we are working towards the development of efficient algae and photo-bioreactors capable of using the process of photosynthesis to capture solar energy and use it to extract H_2 from H_2O. Combustion of H_2 yields only H_2O, completing the clean energy cycle. Developments at the level of genetic engineering, culture optimisation and bioreactor development will be presented. The ultimate aim will be to use marine organisms for this purpose, as this will allow H_2 fuel production to be coupled with desalination. In this process, H_2 and O_2 are released from sea water. Subsequent combustion of these gases results in the production of freshwater from seawater. Such systems theoretically have the advantage that they do not compete with agriculture for either scarce water resources or arable land.

Dr Catherine Grégoire Padró

Los Alamos National Laboratory, USA

Production of hydrogen

The world relies on energy to power industry, move people and products, and keep us safe and comfortable. Fossil fuels provide much of the energy we use today, but their supply is inherently and geographically limited, and there are significant environmental impacts to their use. To address issues of social equity, global climate change, urban air pollution, energy security and economic growth, new energy solutions are needed.

Hydrogen has the potential to provide all energy services with little or no impact on the environment, both locally and globally. It can be made from domestic resources, offering opportunities for energy independence. Hydrogen is an energy carrier, as is electricity, and can be produced from many resources. Unlike electricity, hydrogen can be produced at one point in time and used at a later time. This is an important characteristic, especially when we consider storing large amounts of intermittent renewable energy, or distributing large quantities of energy from one region to another.

Molecular hydrogen is not found in substantial quantities in nature – hydrogen atoms (H) are almost always associated with other elements, principally oxygen (i.e., H_2O) and carbon (ie, CH_4, coal and organic matter). Energy must be used to produce hydrogen. This energy can be thermal, photonic, or electrical energy, and can be provided by renewable, fossil, or nuclear resources. It is important to consider the process by which hydrogen is produced, as well as the feedstock from which it is produced, when evaluating the environmental, security, efficiency and economic impacts.

Professor David Trimm

Federation Fellow, CSIRO Petroleum Research

Catalysis and syngas for the production of hydrogen

Analysis of the prospective size of the market for hydrogen, coupled with the economics of production and delivery, shows that hydrogen obtained from natural gas or coal will predominate in the short to medium time span. Conversion involves the reforming of natural gas or the gasification of coal to form syngas, a mixture of carbon monoxide and hydrogen that can be further processed to produce pure hydrogen.

Equations:

$CH_4 + H_2O = CO + 3H_2$

$CH_4 + CO_2 = 2CO + 2H_2$

In this research, the role of catalysis in promoting natural gas reforming reactions is developed and compared with high temperature short contact time catalysed partial oxidation of methane to produce syngas. Novel methods of co-generation of electricity and syngas are shown to enhance the profitability of partial oxidation. Advances in the catalytic processing of products for reforming, that are designed to produce pure hydrogen suitable for fuel cell operations, are discussed. Novel catalysts for high temperature and low temperature water gas shift reactions and selective oxidation of residual traces of carbon monoxide are described.

The particular needs of Australia also offer interesting opportunities through solar-powered catalytic decomposition of methane. The newly developed process might allow distributed generation of hydrogen fuel.

Dr Wes Stein (presented by Dr Jim Hinkley)

CSIRO Energy Technology

Making hydrogen from the sun

The abundance of high quality solar radiation in Australia has long fuelled activity in solar energy. The unreliable nature of solar radiation can be overcome by combining the solar energy with natural gas – the benefits of solar energy embodied in the form and convenience of gas. Australian solar energy could be transported across the country and ultimately overseas. The outcome, solar hydrogen, is available for various hydrogen applications. The process from sun to hydrogen – which has been demonstrated – requires the application of many scientific disciplines and provides for a transition to a sustainable energy future. Areas for continued advances, such as membranes, have been identified.

Professor Harry Watson

Faculty of Engineering, University of Melbourne

Hydrogen car prospects

Two potential applications of hydrogen as a fuel for road transport are compared that include; use of hydrogen as a fuel for combustion in spark-ignited internal combustion engines and; the application of hydrogen to fuel cells. In the fuel cell, chemical energy is converted directly to electrical energy. This avoids some of the difficulties associated with converting hydrogen energy to useful work through combustion, because the high temperatures needed in a heat engine are not required. Fuel cell performance is examined and followed by a review of hydrogen-fuelled cars and engines. Comparisons of energy efficiency and cost are presented. It is concluded that current combustion engine performance is marginally worse than prototype fuel cells. It therefore seems likely that wide scale implementation of hydrogen fuel cells in cars will be delayed beyond 2020, unless there is a rapid development in technology of both vehicles and infrastructure.

Appendix B

Hydrogen research projects and fellowships with ARC funding announced 2001–07

Project funding announced	ARC project number	Institution	Project title
2001	DP0211213	University of New South Wales	Novel Fe-Cr oxide and skeletal (Raney) catalysts for water gas shift reaction
2001	LP0211975	Swinburne University of Technology	Reforming of liquid hydrocarbon fuels for application in solid oxide fuel cells technology
2002	DP0343926	Griffith University	Hydrogen absorption by nanostructured carbons
2002	DP0346105	University of Queensland	Theoretical and experimental studies of catalyst doping and defects in carbon nanotubes for hydrogen storage
2002	DP0344931	University of Queensland	Nanocomposite proton-conducting membranes for fuel cell applications
2002	FF0348378	University of Queensland	Molecular engineered nanomaterials for advanced fuel cells
2002	FF0348382	University of Sydney	From nanostructured functional materials to sustainable processes
2003	SR0354872	Curtin University of Technology	The ARC Cleaner Energy and Hydrogen Research Network
2004	LX0560210	University of South Australia	Feasibility of biological hydrogen production from biomass wastes using activate sludge microorganisms
2004	FF0561456	University of Sydney	Advanced molecular nanomaterials
2003	DP0449660	University of Wollongong	Hydrogen storage materials for energy conversion applications
2003	DP0451589	University of NSW	Titania-based materials with enhanced photo-sensitivity for solar-hydrogen
2003	DP0451907	University of Wollongong	Synthesis and processing of fine powders and nanomaterials by electric discharge assisted milling under hot and cold plasmas
2004	DP0556821	Australian National University	Development of new membrane-electrode assemblies for low temperature fuel cells
2004	DP0557654	Australian National University	Catalytic electron transfer in photosystem II of plants and bacteria
2004	DP0556439	RMIT University	Accurate quantum modelling of the van der Waals interaction and its application to molecular physisorption onto surfaces
2004	DP0557805	University of Melbourne	Contributions to the foundations upon which true crystal engineering of functional solids will be based
2004	DP0557945	University of Sydney	Reactions of nanoparticles of metal oxides and hydrous oxides and their applications in photocatalysts and electrode materials

2004	DP0558700	Curtin University of Technology	Lowering the barriers to a hydrogen technology: What slows proton conductors?
2004	DP0559636	Curtin University of Technology	Production of hydrogen from biomass by integrated catalytic aqueous hydrolysis and reforming in subcritical water
2005	DP0663321	RMIT University	Fundamental theoretical study of hydrogen interactions with novel nanostructures
2005	DP0663872	University of Melbourne	Coordination polymers and oligomers and labyrinthine molecular solids as materials for the sorption of gases/vapours, with emphasis on hydrogen
2005	DP0665275	University of New South Wales	P-type titanium dioxide for hydrogen generation from water using solar energy
2005	DP0665718	Australian National University	Structural and mechanistic studies of the oxygen evolving centre in photosystem II
2005	DP0666387	University of Queensland	Novel graphitic mesoporous carbon materials for next generation carbon catalyst supports and carbon electrodes
2005	DP0666488	University of Sydney	Selective generation of hydrogen from biomass and waste fuels
2006	DP0770278	University of Newcastle	Computational design of titanium dioxide-based ceramics for the renewable energy technology platform: Solar-hydrogen
2006	DP0770531	Monash University	Novel nanostructured alloy membranes for hydrogen permeation: Advanced materials technology for renewable energy
2006	DP0770631	University of Sydney	First principles catalyst design towards an environmentally clean and energy efficient future
2006	DP0771193	University of Wollongong	New concepts with multidisciplinary approach: Novel functionalised nanostructures for hydrogen storage
2006	DP0771700	Monash University	Bio-inspired catalysts for water oxidation
2006	DP0773490	University of Queensland	New pillared nanoporous materials for hydrogen production by photo-induced water splitting
2006	DP0773847	University of Sydney	Principles, synthesis and evaluation of molecular electronic devices
2006	DP0774669	University of Queensland	Hydrogen production from the anaerobic digestion of organic waste using a novel membrane
2002	LP0348807	University of New South Wales	Processing of reduced-band-gap titania for solar-hydrogen
2003	LP0455715	University of Queensland	Nano-scale catalyst systems for hydrogen generation for fuel cells

2004	LP0561833	University of New South Wales	Surface processing of photo-sensitive semiconducting oxides for solar-hydrogen
2004	LP0562173	University of Queensland	Hydrogen production by non-thermal plasma assisted catalytic pyrolysis of natural gas
2004	LP0562609	University of Queensland	Nanostrutured magnesium-base composites for high-density hydrogen storage
2005	LP0669245	University of Tasmania	Hybrid remote area power systems with hydrogen energy storage for isolated and regional communities
2005	LP0669748	University of Western Australia	Near zero-emission hydrogen and carbon production from natural gas and bio-methane
2006	LP0775109	University of Wollongong	Exploration of new catalyst materials for hydrogen/air fed proton exchange membrane fuel cells
2003	LX0453507	Curtin University of Technology	The investigation of the effects of catalyst doping, element substitution and defects design in carbon materials for hydrogen storage
2005	LX0665224	University of Queensland	Developing a competitive H_2 production system based on engineered cells of green algae
2007	DP0877108	Queensland University of Technology	Efficient one-dimensional photocatalysts from titanate nanofibres and nanotubes
2007	DP0877147	University of Queensland	Targeted bioengineering and systems biology for solar powered hydrogen production in green algal cells
2007	DP0877155	University of Queensland	New Mg-based hydrogen storage material with destabilised hydrides
2007	DP0877155	University of Wollongong	Novel 3D carbon architectures for fuel cell applications
2007	DP0877470	University of Melbourne	Understanding and controlling ion-neutral interactions
2007	DP0878661	University of Wollongong	Improvement and synthesis of advanced hydrogen storage materials for fuel cell applications
2007	DP0880199	University of New South Wales	Porous and magnetic networks: Functional materials by form and design
2007	DP0881174	University of New South Wales	Novel nanostructured $InVO_4$ and related vanadates photo catalysts for water splitting under visible light irradiation

Appendix C

Hydrogen search keywords

List of keywords and combinations used to identify hydrogen energy research publications by Australian and other researchers from the Thomson ISI Web of Knowledge Science Citation Index Expanded database.

Search string 1 – hydrogen economy

Hydrogen AND economy

Hydrogen AND economy AND (renewable energy OR climate change OR carbon dioxide OR carbon OR sequestration OR greenhouse gas* OR green energy)

Search string 2 – hydrogen production

TS=#4

TS=(Hydrogen) AND TS=(generation OR generat* OR evolution OR thermolysis OR thermochemical OR sorption OR reforming OR reformer-shift OR steam reforming OR fossil fuel* OR natural gas OR methane OR methanol OR methan* OR synthetic natural gas OR synthesis gas OR syngas OR water-gas OR biomass OR gasifiers OR coal gasification ORisasmelt OR hydromax OR microfluidics OR carbon monoxide OR COX-free OR ammonia decomposition OR turbostratic carbons OR mobile OR stationary OR exergy recovery OR alloy* OR hydriding OR dehydriding OR sodium borohydride OR hydrid* OR engines OR turbine OR titanium OR thermochemical)

TS=#5

TS=(Hydrogen) AND TS=(production OR evolution OR thermolysis OR thermochemical OR sorption OR reforming OR reformer-shift OR steam reforming OR fossil fuel* OR natural gas OR methane OR methanol OR methan* OR synthetic natural gas OR synthesis gas OR syngas OR water-gas OR biomass OR gasifiers OR coal gasification ORisasmelt OR hydromax OR microfluidics OR carbon monoxide OR COX-free OR ammonia decomposition OR turbostratic carbons OR mobile OR stationary OR exergy recovery OR alloy* OR hydriding OR dehydriding OR sodium borohydride OR hydrid* OR engines OR turbine OR titanium OR thermochemical)

TS=(#5 or #4) not TS=(mitochondria or superoxide or insulin or leukemia or alzheimer* or peroxide) not SO=(ASTROPHYSICAL JOURNAL OR ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES OR JOURNAL OF NUCLEAR MATERIALS OR JOURNAL OF PLANT BIOCHEMISTRY "AND" BIOTECHNOLOGY OR APPLIED BIOCHEMISTRY "AND" BIOTECHNOLOGY OR ASTRONOMY "AND" ASTROPHYSICS OR ANNUAL REVIEW OF ASTRONOMY "AND" ASTROPHYSICS OR ASTRONOMY "AND" ASTROPHYSICS REVIEW OR MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY OR MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY OR FUSION TECHNOLOGY OR DIAMOND "AND" RELATED MATERIALS OR GUT)

TS=(Hydrogen) AND (solar OR solar-thermal OR solar-reforming OR photovoltaic)

TS=(Hydrogen) AND (wind OR ocean currents)

TS=(Hydrogen) AND (biomass OR waste activated sludge OR anaerobic bacteria OR algae OR acid fermentation)

TS=(Hydrogen) AND (electrolysis OR electrolyser OR water OR Gratzel cell OR electrooxidation OR electrochemical OR electrocatalysis OR electro*)

TS=(Hydrogen SAME production) OR TS=(Hydrogen SAME generation) AND TS=(electrolysis OR electrolyser OR water OR Gratzel cell OR electrooxidation OR electrochemical OR electrocatalysis OR electro*)

TS=(Hydrogen) AND (photocatalysis OR photosynthetic OR biophotolysis OR photobioreactors OR photoelectrochemistry OR photoelectrolysis OR photo* OR photoelectro* OR photothermal OR photovoltaic)

TS=(Hydrogen) AND (sulfur-iodine OR calcium-bromine OR copper-chlorine)

Search string 3 – hydrogen separation

TS=(Hydrogen AND separation) AND (pressure swing adsorption OR PSA OR depressurisation OR repressurisation OR membrane OR non-porous membranes OR palladium-based membranes OR ion-transport membranes OR porous membranes OR microporous OR zeolite OR silica OR perovskites OR diffusion OR palladium OR niobium)

Search string 4 – hydrogen distribution and storage

TS=(Hydrogen AND distribution) AND (metal hydride OR complex hydrides OR hydride* OR nanomaterials OR nanoparticles OR carbon nanofibres OR carbon nanotubes OR batteries OR lead-acid battery OR boron OR La OR Mg OR Ni OR alloy)

TS=(Hydrogen AND storage) AND (adsorption OR adsorb* OR metal hydride OR complex hydrides OR hydride* OR nanomaterials OR nanoparticles OR carbon OR carbon nanofibres OR carbon nanotubes OR batteries OR lead-acid battery OR boron OR La OR Mg OR Ni OR alloy)

Search string 5 – hydrogen fuel cells

TS=(fuel* AND cell*) AND TS=(hydrogen OR membrane* OR ceramic OR polymer electrolyte membrane fuel cell OR PEMFC OR solid oxide OR SOFC OR phosphoric acid fuel cell OR POFC OR alkaline fuel cell OR AFC OR molten carbonate fuel cell OR MCFC OR direct methanol polymer electrolyte membrane OR DMPEM OR proton electrolyte membrane fuel cell OR solid polymer electrolyte OR Nafion OR silica OR zirconia OR micro fuel cells OR micro-reactor OR micro-PIV OR titanium phosphate OR ruthenium OR CMK-3 OR Tio2 OR platinum OR palladium OR Pd OR V OR magnesium OR Ni OR MG(0001) OR LIFEPO4 OR CeO2 OR zirconium OR ceria catalysts OR noble-metal catalysts OR cermet membrane* OR gas-diffusion OR Laves phase alloy OR uranium OR yttri*)

Search string 6 – facilitating technologies

TS=(Hydrogen) AND (batteries OR capacitors OR nickel-metal-hydride battery OR electrocapacitor OR supercapacitor OR ultracapacitor OR zinc-bromine battery)

Search string 7 – hydrogen engines

TS=(hydrogen same engine*) OR TS=(hydrogen same vehicle*) OR TS=(hydrogen same turbine*)

General exclusion

not TS=(mitochondria or superoxide or insulin or leukemia or alzheimer* or peroxide)

not SO=(ASTROPHYSICAL JOURNAL OR ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES OR JOURNAL OF NUCLEAR MATERIALS OR JOURNAL OF PLANT BIOCHEMISTRY "AND" BIOTECHNOLOGY OR APPLIED BIOCHEMISTRY "AND" BIOTECHNOLOGY OR ASTRONOMY "AND" ASTROPHYSICS OR ANNUAL REVIEW OF ASTRONOMY "AND" ASTROPHYSICS OR ASTRONOMY "AND" ASTROPHYSICS REVIEW OR MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY OR MONTHLY NOTICES OF THE ROYAL ASTRONOMICAL SOCIETY OR FUSION TECHNOLOGY OR DIAMOND "AND" RELATED MATERIALS OR GUT)

Appendix D

Hydrogen keywords search summary

Hydrogen sector	**Total number of publications**	**Number of publications with an Australian author**	
		Number	**% of sector total**
Hydrogen economy	483	11	2.28
Hydrogen production	75,654	1367	1.81
Hydrogen production solar	2883	79	2.74
Hydrogen production biomass	2,746	48	1.75
Hydrogen production wind or ocean currents	489	5	1.02
Hydrogen production electrolysis	6,749	119	1.76
Hydrogen production photocatalysis	1,139	22	1.93
Hydrogen production sulphur-iodine	14	0	0
Hydrogen separation	1,840	28	1.52
Hydrogen distribution	1,543	18	1.12
Hydrogen storage	5,146	105	2.04
Hydrogen fuel cells TS=(fuel* and cell*) and TS=(hydrogen OR membrane* …)	14,671	172	1.17
Hydrogen batteries	1,726	34	1.97
Hydrogen engines, vehicles, turbines	1059	12	1.13
Total (from WoS) which excludes duplicates	**93,331**	**1,573**	**1.69%**

List of abbreviations

AAS	Australian Academy of Science
ANSTO	Australian Nuclear Science and Technology Organisation
ARC	Australian Research Council
CCS	Carbon Capture and Storage
CNG	Compressed Natural Gas
CO_2	Carbon dioxide
COAG	Council of Australian Governments
CRC	Cooperative Research Centre
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DIISR	Department of Innovation, Industry, Science and Research (former Department of Industry, Tourism and Resources)
DRET	Department of Resources, Energy and Tourism
DITR	Department of Industry, Tourism and Resources (now Department of Innovation, Industry, Science and Research)
DTI	Department of Trade and Industry
EIA	Energy Information Administration
EU	European Union
GM	General Motors Corporation
HIA	Hydrogen Implementing Agreement
H_2	Hydrogen
IEA	International Energy Agency
ITC	Information Technology and Communications
OECD	Organisation for Economic Cooperation and Development
PEMFC	Proton Exchange Membrane Fuel Cell
R&D	Research and Development
RD&D	Research, Development and Demonstration
SOFC	Solid Oxide Fuel Cell
UK	United Kingdom
US DOE	United States Department of Energy
USA	United States of America

The Australian Academy of Science is an independent non-profit organisation of Australia's leading research scientists, elected for their personal contributions to science. Fellows occupy senior positions in universities, Government Research Agencies and industry.
The Academy recognises research excellence, advises government, organises scientific conferences, administers international exchange programs, fosters science education, publishes scientific books and journals, and promotes public awareness of science and technology.

Australian Academy of Science
GPO Box 738
Canberra ACT 2601

aas@science.org.au
www.science.org.au