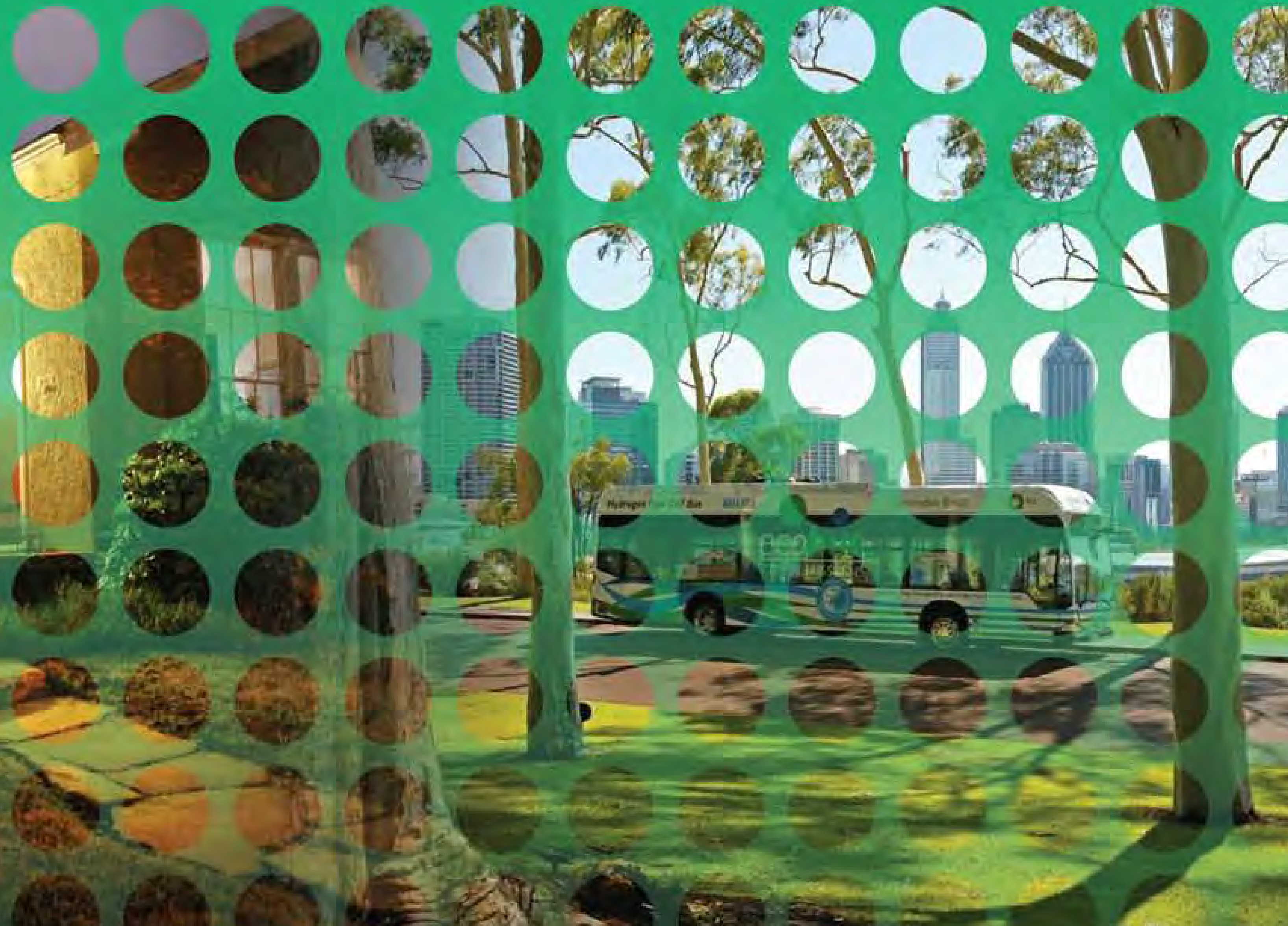
Australian Government

Department of Resources
Energy and Tourism

AUSTRALIAN HYDROGEN ACTIVITY 2008



AUSTRALIAN HYDROGEN ACTIVITY 2008

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

by

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ENHANCING AUSTRALIA'S ECONOMIC PROSPERITY

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FOREWORD

Ensuring Australia's energy security and encouraging the development of clean energy technologies are two of the Australian Government's highest priorities. Similarly, the Government is committed to encouraging Australian research and innovation to underpin sustainable economic growth. Australia's research and development of hydrogen and fuel cell technologies have the potential to play an important role in meeting these challenges.

In 2005, the then Department of Industry, Tourism and Resources released the first Australian Hydrogen Activity report. This report summarised Australia's research efforts and presented an explanatory description of the various technologies for hydrogen production, distribution, storage and utilisation in the context of a possible future hydrogen economy.

Since this first survey was published in 2005, there has been increasing international interest and activity in hydrogen and fuel cell technologies. There also have been significant developments that increase the potential for hydrogen use in the energy sector. Increased public interest in the effects of climate change and concerns with energy security and local emissions have focused attention worldwide on clean and sustainable means of energy production and supply. Australia has been an active member of the International Partnership for the Hydrogen Economy (IPHE) and a member of the International Energy Agency (IEA) Hydrogen Implementation Agreement. Australia also hosted the World Hydrogen Energy Conference in June 2008. In addition, the formation of the National Hydrogen Materials Alliance (NHMA) has given Australia's research and development capabilities in hydrogen greater impetus and coherence. The NHMA is an R&D cluster bringing together 12 university research groups and public research organisations, supported by the CSIRO Energy Transformed Flagship.

In this environment, the 2008 update will promote Australia's research into hydrogen and fuel cells, both domestically and internationally, at conferences and through international organisations, such as the IPHE and the IEA. The report is also intended to complement the release of the Hydrogen Technology Roadmap, which was developed for the Council of Australian Governments. The roadmap identifies, among other outputs, the potential role of Australian governments, industry and researchers in enabling and facilitating the development of a hydrogen economy in Australia. It recommends a range of strategies and initiatives suggests responsibilities for implementation and proposes a timeframe for implementation.

Copies of this report and the Hydrogen Technology Roadmap are available from the Department of Resources, Energy and Tourism website: www.ret.gov.au.

This updated report is in a similar format to the 2005 report prepared by Drs David Rand and Sukhvinder Badwal of CSIRO, and was prepared by conducting a survey across 92 candidate organisations around Australia (Appendix 1 lists contributing organisations). Despite the best efforts of those conducting the survey, some groups may have been missed. A database of contacts, therefore, has been established and new entries are encouraged by contacting the Department of Resources, Energy and Tourism at hydrogen@ret.gov.au

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1. ENERGY IN TRANSITION

The world relies heavily upon fossil fuels (coal, oil, natural gas) as its major sources of energy for heating, mechanical power and electricity generation. Fossil fuel resources are, however, finite and remaining reserves are becoming increasingly concentrated in regions of the world where there is political or economic instability. In the short- to medium-term, this exposes energy-importing countries to an increased risk of disruption to their energy supplies. Moreover, there is the fear that in the long-term there may not be sufficient energy to meet demand at anywhere near an economically acceptable price. These issues are compounded by growing concerns over the environmental implications of energy consumption that relate both to the impact on local air quality and the global problem of greenhouse gas emissions.

Hydrogen and fuel cells can play an important and increasing role in meeting the demand for clean and secure energy supplies, thereby providing a transition to a future hydrogen economy. Additionally, there are opportunities for industry to be involved in the development of hydrogen and fuel cells as demand increases. For these reasons, the Australian Government seeks to encourage research and development in hydrogen and fuel cells as part of the broader development of clean and renewable energy technologies.

1.1 Why Hydrogen?

Fossil fuels are remarkable in that they are not just fuels, but are also energy stores. Once mined and processed, fossil fuels may be transported and stored at the designated location. It is this vital storage capability that is lacking in most renewable forms of energy. Without such a facility, there is often a mismatch between where and when renewable energy is available, and where and when it is required. For instance, wind turbines work well when the wind is blowing and solar power is only available during daylight hours, but electricity is also needed when the wind speed is low and when the sun is not shining. Finding an economic means for storing energy – particularly electricity – is crucial to expanding the use of renewable energy.

Electricity can be stored either in a physical form (i.e., as thermal, potential, kinetic, electromagnetic, or electrostatic energy); or it can be stored as chemicals, especially as electrochemical materials in rechargeable batteries such as the lead–acid battery. Recently, however, there has been intense scientific, industrial and government interest in the development of a further form of chemical storage — hydrogen. Despite being the most abundant element in the universe, it is a mistake to consider hydrogen as an energy 'source' that exists freely in nature like coal, oil, or natural gas. Similar to electricity, it is an energy 'carrier' and energy storage medium that has to be generated either from fossil fuels or biomass by using their own embedded energy or from water by supplying energy.

The widespread use of hydrogen as both energy carrier and as an energy-storage medium, the so-called 'hydrogen economy' would offer the following advantages.

- Hydrogen can be produced from many primary sources, e.g., fossil fuels, renewables, and nuclear power;
- Hydrogen, by virtue of its exceptionally low density in both the gas and the liquid states, has the best energy-to-weight ratio ('heating value') of any fuel;
- Hydrogen may be transmitted over long distances in pipelines that to some degree also act as a storage medium;
- Hydrogen is ideal for use in fuel cells to regenerate energy, especially at distributed or end-use sites. This would enable the decentralisation of power generation;
- Hydrogen is colourless, odourless, tasteless and non-toxic;
- Hydrogen is oxidised cleanly to water; if it is produced from water using renewable energy, the fuel cycle is closed and no pollutants are formed in that process;
- Hydrogen can be used as a fuel for internal combustion engines; and
- Hydrogen is used as a raw material in a wide variety of industrial processes.

While a hydrogen economy represents a visionary strategy for our future energy security, its successful implementation is subject to two major requirements: (i) the individual technical steps must be connected by an infrastructure that provides seamless, safe and environmentally-acceptable transitions from production, to distribution and storage, and then to use; (ii) hydrogen as an energy carrier must be economically competitive.

2. HYDROGEN PRODUCTION

At present, over 500 billion m^3 per annum of hydrogen is generated globally. This accounts for only 1.5% of the total world energy demand, or about 5% of oil production. Over 90% of the hydrogen comes from raw fossil materials. The hydrogen is used mainly in making ammonia and fertilizers and, increasingly, in converting low-grade crude oils into transportation fuels. Lesser applications are found in the manufacture of other chemicals, as well as in the food, plastics, metals, electronics, glass, electric power and space industries. Only a small amount of hydrogen is used as an energy carrier.

As an energy carrier, the cost of hydrogen per unit of energy production at the delivery point is higher than that of hydrocarbon fuels, although it should be noted that the total life-cycle costs (fuel production, air quality, health, climate warming) are usually not taken into consideration for technologies based on fossil fuels. In addition, the well-developed infrastructure for oil, gas, coal and electricity will tend to keep the cost of energy low.

2.1 Hydrogen from Fossil Fuels

2.1.1 Steam reforming of natural gas

The steam reforming of natural gas is the most efficient and widely used process for making hydrogen today. At present, it is also the cheapest route. Steam reforming is the reaction of a hydrocarbon and steam. This endothermic reaction is normally carried out over a nickel catalyst at high temperatures (850 to 950 °C) and high pressure (3.5 MPa). The resulting product is known as 'synthesis gas' or 'syngas' (carbon monoxide and hydrogen) because it may be used for the preparation of a range of commercial products that include hydrogen, ammonia, methanol, and various organic chemicals. To increase the yield of hydrogen, the syngas from a reformer is usually cooled and further processed via the water-gas shift reaction.

Industrial scale steam reforming and shift reactors tend to be large and bulky. Typically, an industrial steam reformer plant has a capacity of 10^4 to 10^5 t of hydrogen per year (i.e., 10^8 to 10^9 m^3). Efforts are being made to reduce the size of these reactors and to improve heat management and system integration. The overall process is not environmentally benign due to the large emissions of carbon dioxide from the plant. In the USA alone, 90 billion cubic metres of hydrogen per year are produced by the steam reforming of fossil fuels, predominantly natural gas, for use in the petrochemicals and related industries. This represents 5% of the natural gas used in the USA.

Research and development challenges

Optimisation of the steam reforming of natural gas to produce cheap and clean hydrogen, especially at distributed sites (homes, fuelling stations, customer sites, etc.), is required. Thus, the development of smaller, compact and more efficient designs of natural gas reformer is essential. Although, hydrogen generation from natural gas at distributed sites would make the capture and disposal of carbon dioxide difficult and costly, a successful outcome would reduce the requirement for an upfront expensive transportation and distribution infrastructure. This would be a positive step in an early transition to a hydrogen economy.

Improvements in membrane technology for gas separation and cleaning are also required to produce high-grade hydrogen for use in polymer electrolyte membrane fuel cells a key technology for the transportation sector (see Section 4.1.4).

Australian projects

Like much of the world, most of the hydrogen produced in Australia comes from the steam reforming of natural gas. The hydrogen is used mainly in the manufacture of ammonia for fertilizers and in the refining of oil; smaller quantities are required by the food, chemical and metallurgical industries. Only one group reported studies of hydrocarbon gas reforming. Research is being conducted into advanced water-gas shift reactors as part of several gas separation technology programs (see Section 2.1.5).

Project:	**Methane Reforming in Micro-Channels: A Compact Fuel Reformer for the Production of Hydrogen for Fuel Cells**
Outline:	A compact micro-channel reactor is being developed for the production of hydrogen and synthesis gas from hydrogen-containing fuels. The reactor will integrate the endothermic reforming reactions with suitable exothermic processes (catalytic partial oxidation or total oxidation) by way of heat exchanger hardware separating the reaction zones. Optimisation of this reactor is sought through the development of a model integrating the fundamental thermo- and fluid dynamic properties of the system with the measured kinetic properties of the novel catalysts developed herein The project aims to develop a complete reformer system, combining heat generation with reforming and down stream reformate clean up via the water-gas shift reaction. The developed micro fuel processor is intended to generate sufficient hydrogen to power a 0.1-1.0 kW fuel cell. The timeframe of this project is 2005 to 2008 and the budget is approximately $ 150,000.
Organisation:	**The University of Queensland, Ceramic Fuel Cells Limited and Gas Technology Institute (USA).** Dr Andrew Dicks (a.dicks@uq.edu.au), Mr Dominic Alexander.

2.1.2 Gasification of coal

The oldest method for producing hydrogen is via the gasification of coal. When heated in a restricted supply of air (so-called ‘destructive distillation’ or ‘pyrolysis’), coal is converted to mixture of hydrogen, methane and carbon monoxide (typically, 50, 35 and 8%, respectively), together with coal tar and coke. Alternatively, when heated coal is reacted with steam the water-gas reaction occurs. The water-gas reaction is highly endothermic (heat absorbing) and thus soon ceases unless heat is supplied. Conversely, the combustion of coal or coke in air is highly exothermic. It is therefore usual to pair off the two reactions so as to balance the heat evolved with that absorbed. The resulting gas is a mixture of carbon monoxide, hydrogen, carbon dioxide, and nitrogen. A gas of higher calorific value can be obtained by using oxygen rather than air, but for many applications this is not economic.

The gas produced by the water-gas reaction may be upgraded in terms of hydrogen content by the water-gas shift reaction. By adjusting the fuel, the gases used and the operating conditions, it is possible to tailor-make a gas of desired composition. Two examples are: (i) ‘chemical synthesis gas’, a mixture of H_2 and CO used as chemical feedstock for the production of ammonia (as discussed above), methanol and other organic compounds; (ii) ‘synthetic natural gas’, which is largely methane and is produced by the reverse of this reaction. The latter gas may also be made directly by the reaction of hydrogen with coal.

The integrated gasification combined-cycle (IGCC) process for electricity generation from coal has the potential to increase thermal efficiencies to over 50% with greatly reduced emissions of greenhouse gases. Pulverised coal is reacted with oxygen and steam at temperatures up to 1850 °C to produce an impure mixture of hydrogen and carbon monoxide. Hydrogen sulphide (formed from sulphur impurity in the coal) is removed by adsorption, e.g., in a polyethylene-based solvent, to leave a mixture of hydrogen and carbon monoxide (synthesis gas). The mineral matter in the coal forms a slag at these high temperatures and is removed from the gasification reactor. The synthesis gas is used to produce liquid hydrocarbons and alcohols by catalytic synthesis (the 'gas-to-liquids' route), or is further reacted with additional steam to give a mixture of hydrogen and carbon dioxide. The carbon dioxide may then be separated in a form suitable for sequestration, e.g., in geological structures, while the hydrogen can be used for power generation in gas turbines, and/or in fuel cells resulting in 'zero-emissions' power from coal'.

Research and development challenges

Gasification: Optimisation of the gasification of coal for the efficient production of cheap and clean hydrogen is required.

Oxygen separation: The use of oxygen to gasify coal has the potential to reduce cost and increase overall system efficiency. If air is used instead, then the cost of downstream gas separation is very high (a large quantity of nitrogen has also to be separated in addition to the carbon dioxide). Since the use of a cryogenic plant for oxygen separation would be too expensive, alternative technologies based on ceramic or polymer membranes are attracting much attention. The cost of hydrogen production can be substantially reduced if oxygen can be separated or produced from air by cheap routes.

Hydrogen separation: Inexpensive and reliable technologies for hydrogen separation from carbon dioxide are required. At present, a range of options based on metal, ceramic or polymer membranes are under development.

Australian projects

There are several projects in this field under the auspices of the Cooperative Research Centre for Clean Coal from Lignite, the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC), the Centre for Low Emissions Technology (cLET), and Coal 21. Nevertheless, only a very small proportion of this work is directly relevant to hydrogen production. An exhaustive analysis of this work is available through the Carbon Sequestration Leadership Forum (www.cslforum.org).

Project:	**Hydrogen Purification and Carbon Capture from Gasification Processes**
Outline:	Production of hydrogen and CO (syngas) from coal gasification is one of the leading contenders for new "zero emission" energy production. The efficiency relies on capture and removal of CO2 from the synthesis gas at high temperature. This project explores the development of new adsorbent materials for CO2 capture and hydrogen purification from an IGCC stream at elevated temperature either before water gas shift or after water gas shift. Both materials and process development are being studied. The timeframe for this project is mid 2007 to 2010; the total budget is approximately $400,000.
Organisation:	**Monash University.** Prof. Paul A. Webley (paul.webley@eng.monash.edu.au), Dr. Andrew Hoadley, Dr. Simon Wilson, Dr. Ranjeet Singh and Assoc. Prof. Alan Chaffee.

Project:	**Films and Inorganic Membranes Laboratory (FIMLab) Coal Gasification Program**
Outline:	Based at the University of Queensland, FIMLab is involved in research into reaction engineering and the production of novel nanomaterials for energy technology applications. Currently, the group has five active projects concerned with the development of coal gasification technology. The first two projects are concerned with experimental aspects of gasification technology. Namely, oxygen separation and scale-up 'proof of concept' membrane reactor for downstream gas separation. Another project is concerned with Computational Fluid Dynamics modelling and validation of membranes and membrane reactors for coal gasification processes. The final two projects in this program focus on the economics and sustainability of coal gasification and an alternative to current coal utilisation.
Organisation:	**The University of Queensland.** Assoc. Prof. Dr Joe da Costa (joedac@cheque.uq.edu.au).

Project:	**Development of Zero Emission Coal Technology (Incorporating Enhanced H_2 Generation, CO_2 Capture and Fuel Cell Integration)**
Outline:	This project is concerned with the development of coal to hydrogen technologies, true zero emission energy production. It utilises cutting-edge technologies to generate electricity while capturing and permanently storing the carbon dioxide produced. The timeframe of this project is 2008 to 2012 and has a budget allocation of approximately $ 300,000.
Organisation:	**The University of Sydney and the University of New South Wales.** Dr Andrew Harris (a.harris@usyd.edu.au).

2.1.3 Hydrocarbon cracking

Hydrogen can also be produced by the direct thermocatalytic decomposition ('cracking') of methane or other hydrocarbons. It has been proposed to use heat generated by plasma burners or solar dishes and towers (see Sections 2.1.4 and 2.3.3). The energy requirement per mole of hydrogen is in fact less than for steam reforming and the process is simpler. In addition, a valuable by-product — clean solid carbon — is produced, which obviously can be captured and stored more easily than gaseous carbon dioxide. There is, however, the problem of progressive catalyst deactivation through carbon build-up; reactivation would result in unwanted emissions of carbon dioxide.

Australian projects

Project:	**Near Zero Emission Hydrogen and Carbon Production from Natural Gas and Bio-Methane**
Outline:	The aim of this project is to develop a novel catalytic cracking process to convert both natural gas and bio-methane into valuable graphitised carbon particles and clean hydrogen. The researchers have recently developed a promising catalytic technique that offers high methane conversion efficiency and hitherto unsurpassed catalyst lifespan. The ability to convert methane into graphitised carbon and hydrogen has caught the attention of Wesfarmers and, US based, XL Tech Group who are participating in this project. The project is expected to develop feasible reactor designs and fine-tuned catalytic systems for actual natural gas and bio-methane compositions that favour the synthesis of graphitised carbon and hydrogen. The timeframe for the project is 2006-9 and the budget is approximately $539,000.
Organisation:	**The University of Western Australia, Wesfarmers and XL Tech Group.** Assoc. Prof. Hui Tong Chua (htchua@mech.uwa.edu.a), Dr Lizhen Gao, Prof C. L. Raston.

Project:	**Hydrogen Production by Non-thermal Plasma Assisted Catalytic Pyrolysis of Natural Gas**
Outline:	This project aims to develop a cost effective technology for hydrogen production using catalytic pyrolysis of natural gas assisted by non-thermal plasma. The mechanism and kinetics of catalytic hydrocarbon decomposition on carbons produced in situ will be systematically studied. A fundamental understanding of the produced carbon nanostructures and their catalytic activities and stabilities will be sought to optimise the non-thermal plasma and the catalytic reactions used to achieve high conversion and catalytic stability. The project will lead to a new process combining effective carbon catalyst and low temperature plasma to produce pure hydrogen with high energy efficiency and no CO_2 emissions.
Organisation:	**The University of Queensland and Eden Energy.** Prof. John Zhu (z.zhu@uq.edu.au), Prof. Gaoqing Lu, Dr Greg Solomon.

2.1.4 Solar–thermal reforming of fossil fuels

Concentrated solar energy can be used to produce synthesis gas from methane-containing gases. As discussed above (see Section 2.1.1), the product gas can be reacted further with steam to form more hydrogen together with carbon dioxide. Candidate fuels include natural gas, coal-seam gas, and landfill gas. As the synthesis gas from this process contains a substantial amount of embodied solar energy (up to 25%), solar–thermal reforming offers the prospects } of high thermal efficiencies and greatly reduced emissions of carbon dioxide. Moreover, the emissions would be in a concentrated form and are therefore more amenable to sequestration. CSIRO has employed a solar dish to demonstrate the concept, Figure 2.2.

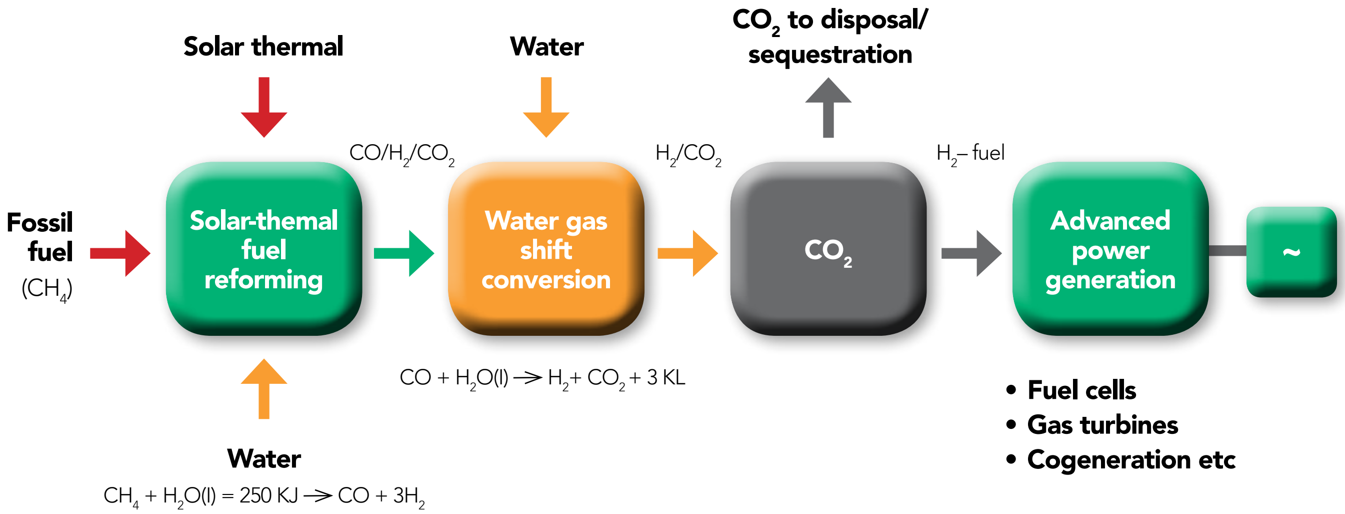

Figure 2.1 Schematic of Solar Thermal Reforming.

Figure 2.2 CSIRO Solar Collector. Composed of an array of 48 mirrors (area 107m^2), on a clear day the array can concentrate 91 kW of thermal energy. © CSIRO

Research and development challenges

The major challenges are in cost reduction of the overall process. Solar dish technology is currently too expensive. Further improvements to the solar heat receiver, the tracking system and the reformer would lead to cost reductions.

Australian projects

Project:	**Development of Advanced Fluidised Bed Reactors for Hydrogen Generation Using Solar Powered Fluidisation Reactors.**
Outline:	This project seeks to develop advanced fluidised bed reactor systems with the aid of computation fluid dynamic modelling. The reaction systems being developed will be used for the production of hydrogen from solid fuels using solar energy. The timeframe for this project is 2008 to 2011 and the budget is approximately $ 350,000.
Organisation:	**The University of Sydney and the University of NSW.** Dr Andrew Harris (a.harris@usyd.edu.au).

Project:	**Solar Thermal Gasification of Hydrocarbons**
Outline:	There are several different technologies to convert solid or liquid hydrocarbons into gas consisting of mainly hydrogen and carbon dioxide. Up to 30% of the energy stored in the product gas could come from the sun by using solar thermal applications to drive the conversion while the equivalent of 30% of the product gas would have to be burned using conventional approaches. Biomass gasification in supercritical water is being investigated. Initially investigations are with a bench-scale electrically heated reactor, which will be followed by first tests with a simple solar receiver. This project aims to demonstrate the potential for energy value adding to gasification and the technical feasibility of operating solar gasification of parabolic dish solar concentrators.
Organisation:	**The Australian National University, CSIRO and Wizard Power Pty Ltd.** Dr Keith Lovegrove (keith.lovegrove@anu.edu.au), Dr Michael Kingslund.

2.1.5 Hydrogen Separation Technologies

Membrane separators

Considerable research is being conducted on membrane separators as these offer the possibility of compact systems that are easier to integrate with chemical processes such as the steam reforming of natural gas and the water-gas shift reaction. Membrane separators can be used to achieve conversions in excess of equilibrium values by continuously removing the product hydrogen. The membrane separators available for hydrogen treatment may be classified as: (i) non-porous membranes, i.e., palladium-based and ion-transport membranes; (ii) porous membranes, i.e., ordered microporous membranes (e.g., zeolite membranes) and other microporous membranes (e.g., dense silica).

Metal-based, non-porous membranes can produce a hydrogen stream of very high purity (99%+) that can be directly utilised in a fuel cell. The separation process relies on the ability of the metal to allow only the diffusion of hydrogen. The most widely known metallic, hydrogen-permeable, membrane materials are palladium and its alloys. Although materials based on palladium and its alloys are commercially available, the cost of the metal is a major barrier to scale-up for large-scale hydrogen separation. Two options for reducing the cost are: (i) the use of very thin films (<10 μm) of palladium or its alloys supported on a metal or ceramic substrate that has controlled pore size and distribution; (ii) the use of cheaper amorphous alloys as alternatives to palladium.

A porous membrane the second category of hydrogen-separation membrane usually consists of a thin layer of a porous material such as silica, carbon or zeolite on a thicker, highly porous support. The hydrogen is transported through the porous structure of the membrane predominantly by molecular diffusion, which is a purely physical process with a characteristic that is determined by the pore diameter of the membrane. To separate hydrogen efficiently, the pores must be less than 1 nm in diameter. The hydrogen flux is proportional to the trans-membrane pressure, whereas in palladium membranes, where transport is limited by solution diffusion and ionization kinetics, the flux is proportional to the square root of the trans-membrane pressure.

A variety of established manufacturing techniques can be used to fabricate porous membranes on either ceramic or metallic supports. To maximise the flux, the membranes are usually fabricated as thin as the selected manufacturing technique can achieve; films with thicknesses below 10 µm are routinely made. Generally, one-to-three thin layers are applied to a porous support. Membranes are usually manufactured as tube and shell configurations that are assembled in multi-tube modules for efficient distribution of feed and product gases. The feed gas is introduced on the shell side and hydrogen product is withdrawn from the tube side. Metal support tubes are easier to install into modules and are more robust and not as prone to catastrophic failure as ceramic supports. On the other hand, metal supports are subject to the problem of thermal expansion mismatch.

The advantages of such membranes are that a wide range of materials are available and can be chosen on the basis of their compatibility with the operational environment. The choice is not limited to exotic materials and virtually any metal, alloy or ceramic may be used so that manufacturing costs are potentially much less. In addition, ceramic membranes can operate at much higher temperatures than metal membranes. (Note, the permeance of hydrogen has been shown to increase rapidly as the temperature is increased.) Because a perfect membrane with a discrete pore size is impossible to fabricate, an infinite separation factor is unachievable, compared with non-porous membranes that give perfect separation. Nevertheless, separation factors of up to 100 have been achieved and these would give a single-stage hydrogen purity of 99%. Higher purities would require a number of stages to be used, for example, two stages would result in 99.99% purity. Hybrid systems using porous membranes in combination with pressure swing adsorption may be required to reach the high purities required for fuel cells.

Research and development challenges

A range of technologies needs to be developed for separating and purifying hydrogen from other gases, especially when produced from fossil fuels via reforming or partial oxidation. Although some of these technologies exist for large-scale plants, they are not cost-effective or easily scaled down for distributed hydrogen production, for example, at homes, at service stations, and on-board vehicles. Membrane technologies promise a 30% reduction in the cost of separating hydrogen from carbon dioxide. Apart from issues associated with the fabrication of thin-film membrane reactors, key issues with metal membranes include: strength degradation from hydrogen embrittlement; hydrogen-entrapment within the structure that can lead to a drop in performance over time; maintenance of the proper defect-free structure during production of the membrane. Most of the research and development on microporous membranes is directed towards perfecting the use of a separating layer made of silica that is stable in the presence of steam up to 500 °C. While inorganic membranes and filters are currently being commercialized by some overseas companies, porous hydrogen membranes have not yet been commercialized for large industrial use. Strict control of pore size is a major issue.

Australian projects

Membrane technology for the separation of gases as a purification step in the production of hydrogen is receiving considerable research attention in Australia. Nearly one quarter of the projects identified in this study involved membrane separations. The University of Queensland, the University of Sydney, CSIRO Energy Technology and the Centre for Low Emission Technology (cLET) are involved in significant efforts to apply membrane separation technology to coal gasification and hydrocarbon reforming processes.

Australian projects

Project:	**Hydrogen Separation Membranes**
Outline:	A thin film metal membrane structure for separating hydrogen from coal derived syngas is being developed under this project with a view to integrate the membrane with commercial water-gas shift reactors so that the production of coal gasification based hydrogen, electricity and liquid fuels is not only simplified but zero Greenhouse gas emissions targets can be achieved for such process technologies.
Organisation:	**CSIRO Energy Technology.** Dr Narendra Dave (narendra.dave@csiro.au), Dr Fabio Ciacchi, Dr Michael Dolan, Dr Leigh Morpeth, Mr Richard Donelson, Dr Daniel Lang, Mr Michael Kellum, Dr Sukhvinder Badwal, Dr Brett Sexton, Ms Fiona Glen.

Project:	**Catalytic Membrane-Based Processes for Hydrogen Production and Purification from Oil Based Liquid Petroleum Fuels**
Outline:	This research project is focusing on the demonstration of novel proof-of-concept oil to hydrogen catalytic membrane processing using autothermal reforming, water shift and hydrogen purification technologies. The work is performed by the ARC Centre of Excellence for Functional Nanomaterials in partnership with the Saudi Aramco Oil Company based in Dhahran, Saudi Arabia. The overall objective of this proposal is to develop, build and demonstrate a proof-of-concept catalytic membrane-based process for the production of 0.150 Nm^3/hr of hydrogen from petroleum fuel sources. The timeframe for this project is 2007 to 2011, with a total budget of approximately $ 900,000.
Organisation:	**The University of Queensland.** Dr Jorge Beltramini (jorgeb@uq.edu.au), Prof. Max Lu, Dr Moses Adebajo, Dr Joe da Costa.

Project:	**Films and Inorganic Membranes Laboratory (FIMLab) Hydrogen Separation and Fuel Processing**
Outline:	Based at the University of Queensland, FIMLab is involved in research into reaction engineering and the production of novel nanomaterials for energy technology applications. Currently, the group has two active projects concerned with the development of membrane reactor technology for the separation hydrogen from fuel processing reactions. The first project is looking at hydrogen separation at high temperature (up to 500°C) using inorganic membranes. The second project is concerned with the development of Membrane reactors for syngas processing in the Water Gas Shift reaction.
Organisation:	**The University of Queensland.** Assoc. Prof. Dr Joe da Costa (joedac@cheque.uq.edu.au).

Project:	**Membrane Reactors for the High Temperature Synthesis and Separation of Hydrogen**
Outline:	Based at the University of Sydney, the Laboratory for Sustainable Technology has two current projects in the area of membrane reactor technology. The first project, in collaboration with the Australian Nuclear Science and Technology Organisation (ANSTO), aims to assess of the mechanism of membrane synthesis and hydrogen transportation using neutrons. The timeframe for this project is 2005 to 2009 and the approximate budget is $ 300,000. The second project is concerned with the development and characterisation of silicon carbide membranes for the high temperature separation of H_2 from other gases. The timeframe for this project is 2005 to 2011 and the budget is approximately $ 500,000.
Organisation:	**The University of Sydney, the University of NSW and ANSTO.** Dr Andrew Harris (a.harris@usyd.edu.au).

Project:	**Centre for Low Emissions Technology Membrane Reactor Program**
Outline:	The Centre for Low Emissions Technology (cLET) has four active projects in the area of membrane reactor technology for the production and separation of hydrogen. The first project targets development of a metal diffusion membrane material, which has acceptable permeability to hydrogen, is stable in syngas environments and is relatively low cost. Hydrogen dissociation / association layers may be required for non-Pd based membranes, and support structure with sufficient strength and chemical stability. Defect free metal membranes – self supporting or supported on a porous structure, will be manufactured. These will be employed in a lab-scale integrated water gas shift and hydrogen separation reactor. The timeframe of this project is 2005 to 2009, with an approximate budget of $ 3.514 million. The second project aims to deliver and validate membrane gas separation and membrane reactor modules for separating hydrogen from carbon dioxide, in a syngas after shift reaction, and prove the concept for a realistic syngas. The membrane to be developed will be a porous ceramic operating on a molecular sieve principle. The timeframe of this project is 2005 to 2009, with an approximate budget of $ 4.035 million. The third project aims to evaluate the suitability of commercially available catalysts for the water gas shift of coal-derived syngas, prior to hydrogen separation. This will lead to an understanding of the impacts that contaminants in coal-derived syngas can have on catalyst activity, quantify the level of upstream gas cleaning required to ensure reliable water gas shift reactor performance and allow optimum catalyst formulations for fixed-bed and packed-bed membrane reactors to be developed. The timeframe of this project is 2005 to 2009, with an approximate budget of $ 1.607 million. The fourth project aims to develop new water gas shift catalysts based on metal alloys or ceria supported metals suitable for operation at high temperatures, prior to hydrogen separation in a high temperature membrane reactor. There will be an evaluation of how these materials/catalysts can be incorporated into high temperature membrane water gas shift reactors for the processing of coal derived syngas. New designs for high temperature membrane reactor systems for this application are targeted. The timeframe of this project is 2005 to 2009, with an approximate budget of $ 1.509 million.
Organisation:	**CSIRO Energy Technology, Centre for Low Emission Technology and the University of Queensland.** Dr Graham Reed (graham.reed@csiro.au), Dr Michael Dolan, Dr Joe da Costa and Dr Greg Duffy.

2.2 Hydrogen from Biomass

2.2.1 Gasification of biomass

Bio-energy is seen as one of the options to mitigate greenhouse gas emissions and to substitute fossil fuels. Biomass gasification is a thermochemical process for conversion of biomass materials into a producer gas that contains carbon monoxide (15–30%), hydrogen (10–20%), methane (2–4%), water (6–8%), and the inert gases carbon dioxide (5–10%) and nitrogen (45–60%). Overall, the biomass gasification process is quite complex. In broad terms, the various steps involved are: processing of the biomass (chopping, cutting, and dehydration), pyrolysis / gasification, and gas cleaning (to remove tar and dust). The producer gas can be used to run an internal combustion engine at an efficiency which is 30–50% lower than that of a gasoline engine, or for power generation with a steam or gas turbine.

Biomass gasification to produce power is not a new technology. It flourished before and during World War II. It is claimed that in 1939 over 200 000 vehicles were operating on producer gas in Sweden alone. Most of the demand for biomass gasification was lost once gasoline and diesel became available in large quantities at a low cost. Nowadays, biomass is considered as an alternative to coal and natural gas because of its short regeneration and utilisation cycle. Biomass can also be considered to be greenhouse gas emission neutral. Unlike coal gasifiers, which are best suited for large centralised power generation plant; biomass gasifiers can be used for distributed energy conversion, and may be economical even for small-scale power generation in the range of 10 to 30 kW.

Typical biomass materials are: wood, charcoal, bio-waste (wood chips, forest residues, saw dust, etc.), sewage sludge, crop residues (cotton stalks, wheat and rice straw, coconut or nut shells, maize and jowar cobs, jute sticks, rice husks, etc.), garden prunings, and cultivated crops (hemp, silver grass, poplars, willows, etc.). Most biomass materials with water contents in the 5 to 30 wt% range are suitable for gasification, although some biomass materials may not lead to successful gasification.

There are several different versions of gasifiers to accommodate different types of biomass and designs of plant. Modern gasification plants are more sophisticated than those used in the 1930s, and utilise fixed- or fluidised-bed gasifiers. The combined heat and power-generation efficiency of a biomass gasifier coupled to a gas turbine can be in the range of 22 to 37%. By contrast, direct biomass combustion technologies that involve steam generation and steam turbines have efficiencies of 15 to 18%. The use of producer gas in low-temperature fuel cells would require the gasifiers to operate with oxygen, oxygen-enriched air or steam to generate gas with a high content of hydrogen. Also, the carbon monoxide component would need to be reduced to a low level, usually via the water-gas shift reaction, to produce more hydrogen.

Research and development challenges

Major research challenges relate to the design and optimisation of both the gasifier and the gasification process itself (air, oxygen or steam) for a given fuel. To lower the downstream cost of hydrogen separation from other gases, it would be desirable to gasify biomass with oxygen or steam. Additionally, gas purification technologies are required to produce gas suitable for use in low-temperature (e.g., polymer electrolyte membrane) fuel cells.

Australian projects

Three respondents catalogued several projects dealing with optimisation of the physical gasification process for various feedstocks.

Project:	**EnGen Institute Hydrogen Production**
Outline:	The EnGen Institute H_2GO Fuels program focus is to produce hydrogen fuels in sustainable micro-economies via electrolysis using renewable energy and pyrolysis of crop waste (producing Agri-char fertiliser as a by-product). EnGen Institute is developing Tidal Power Stations for bulk renewable energy (commercialised via HydroGen Power Industries Pty Ltd).
Organisation:	**EnGen Institute.** Dr William Hollier (will@engen.org.au).

Project:	**Enhanced Synthesis of Hydrogen from Biomass and Waste Materials**
Outline:	This project is concerned with the generation of hydrogen from renewable feedstocks using in situ CO_2 capture to boost hydrogen production. The project will include the development of novel CO_2 sorbents. The timeframe for this project is 2005 to 2010; the total budget allocation is approximately $ 650,000.
Organisation:	**The University of Sydney, Tokyo Metropolitan University (Japan), Hefei University of Technology (China) and the University of Newcastle.** Dr Andrew Harris (a.harris@usyd.edu.au).

Project:	**Gasification Technology for the Production of Hydrogen**
Outline:	Currently, there are three projects concerned with the development of technology for the production of hydrogen from bio-derived energy carriers underway at the ARC Centre of Excellence for Functional Nanomaterials. The first project is centred on the design, construction and commercialization of an innovative hydrogen production unit using liquid phase reforming of sugars, carbohydrates and biomass and includes the use of leading edge non precious metals supported on nano-ceramic materials developed by the ARC Centre of Excellence for Functional Nanomaterials. The timeframe for this project is 2003 to 2009 and the total budget allocation is approximately $ 500,000. The second project involves the production of hydrogen and liquid fuels directly from bio-gas generated in waste disposal treatment using small-scale, modular, relocatable conversion units with low capital cost. The timeframe for this project is 2003 to 2010 and the total budget allocation is approximately $ 400,000. The final project in this program involves the design, synthesis and catalytic characterization of metal supported nanomaterials for processing different carbon feedstocks using steam reforming, partial oxidation, autothermal reforming combined with shift reactions to generate hydrogen and oxygenated fuels (alcohols, dimethyl-ether (DME), di-ethyl ether (DEE)). The timeframe for this project is 2007 to 2011 and the total budget allocation is approximately $ 300,000.
Organisation:	**The University of Queensland and the ARC Centre for Excellence for functional Nanomaterials.** Dr Jorge Beltramini (jorgeb@uq.edu.au), Prof. Max Lu, Mr Akshat Tanksale.

2.2.2 Biological Hydrogen Production

Biological hydrogen production can be achieved by the use of micro-organisms. Photosynthetic or fermentative processes may be used. The main source of hydrogen during a biological, fermentative process is carbohydrates, while photosynthetic processes use solar energy to generate hydrogen from water.

Research and development challenges

Photo-biological hydrogen production has minimum greenhouse and pollution implications and is therefore a beneficial technology to pursue. It is, however, at an early stage of development such that present systems have low efficiency. Consequently, careful evaluation must be undertaken to establish a strategic direction for future research effort.

Fermentation of biomass is a more mature technology a fact reflected in the extent of research currently conducted in Australia. Challenges currently being addressed in the area of fermentation technology relate to the development of reaction systems with high hydrogen production rates and good selectivity and specificity towards the production of hydrogen vs. other anaerobic by-products.

Australian projects

Two projects in this area were identified. Both projects involve the production of hydrogen via anaerobic fermentation.

Project:	**Hydrogen Production by Novel Fermentative Bacteria**
Outline:	Biological systems provide a wide range of approaches to generate hydrogen including direct photolysis, photo-fermentations and dark-fermentations. Bacteria are able to produce hydrogen by anaerobic fermentation and can utilise a large number of carbohydrates frequently obtained as waste products. Mixed cultures for hydrogen fermentations are often obtained from environmental sources. Surprisingly, there are few systematic studies reported in the literature that seek to identify sources of high hydrogen-yielding bacterial isolates in the environment. The aims of this work are to develop a more targeted approach to isolating and characterising hydrogen producers in the future. The timeframe of this project is 2005 to 2009
Organisation:	**CSIRO Land & Water and the University of Sydney.** Dr Nicola Rogers (nicola.rogers@csiro.au), Mr Andrew Symonds, Dr Andrew Holmes and Dr Simon Apte.

Project:	**H_2 Production from the Anaerobic Digestion of Organic Waste using a Novel Membrane**
Outline:	Numerous researchers have attempted to maximise hydrogen production from solid organic waste in single stage processes optimised for fermentative hydrogen yields, achieving at most 30% of the potential hydrogen yield with most of the calorific content of the organic waste converted to volatile fatty acids. Yet, this by-product can be converted to more hydrogen in a 2nd stage process by anaerobic oxidising organisms. Hydrogen is inhibitory to the anaerobic oxidizers and is normally scavenged by methane forming organisms. The methanogens will be out-competed by new silica membranes that are selectively and highly permeable to hydrogen. Hydrogen will be removed from the other side of the membrane and stored using a metal hydride column.
Organisation:	**The University of Queensland.** Assoc. Prof. Bill Clarke (william.clarke@uq.edu.au), Assoc. Prof. Mikel Duke, Dr Cathryn O'Sullivan, Dr Raymond Zeng, Mr Hang Zheng.

Project:	**2nd Generation Microalgal Bio-H_2 Production**
Outline:	Microalgae have the ability to capture solar energy and convert in to chemical energy in the form of H_2. The H_2 gas can be produced from water or carbon sources. In 2007, The Solar Bio-fuels Consortium (www.solarbiofuels.org) was established to maximise the speed of development of high-efficiency 2nd generation microalgal biofuel systems. It now includes seven team leaders and conducts bio-discovery, marine biology, structural biology, molecular biology, microbiology, genomics, metabolomics, culture optimisation and bioreactor scale up within a coordinated research program of parallel research streams. The consortium also has a detailed IP management strategy in place and provides a single point of contact for industry partners. Solar powered H_2 production from water and waste carbon sources is a major focus of our work and includes patented technology. Significant advantages of the microalgal bio-H_2 process include that they can be produced on non-arable land (eliminating competition with food production), using saline water (reducing fresh water use) and that the process can contribute to atmospheric and industrial CO_2 sequestration initiatives. Currently the Australian work is supported by the ARC, with a budget of approximately (~$300,000).
Organisation:	**The University of Queensland, University of Bielefeld (Germany) and the Solar Bio-fuels Consortium.** Assoc. Prof. Ben Hankamer (b.hankamer@imb.uq.edu.au), Prof. Olaf Kruse (Bielefeld).

2.3 Hydrogen from Water

Water is the other huge store of hydrogen, but breaking down water to hydrogen also requires energy. Electrical, chemical, light or thermal energy can be employed.

2.3.1 Electrolysis

The electrolysis of water is compatible with a range of current and future electricity-generation technologies (coal and natural gas with carbon dioxide sequestration, or renewables). When using electricity generated from fossil fuels there is, however, a major drawback of a low overall thermal efficiency of 22–26% (i.e., 70–75% for electrolysis and 30–35% for coal fired plants). With advances in electrolysis achieving an efficiency of 90% and modern thermal power plants reaching 50–60% efficiency, the net efficiency for hydrogen production is predicted to rise to between 40 and 50%. The integration of water electrolysis with electricity from renewable energy sources (e.g., solar, wind, geothermal, tidal, wave, hydroelectric) offers a totally sustainable energy cycle. Water electrolysis can be easily coupled with an intermittent renewable energy source such as a wind turbine for large-scale hydrogen production, and can also provide load-levelling in stand-alone or electricity utility networks by using excess or off-peak electricity to generate hydrogen for later use.

Electrolysis is extremely energy-intensive; the faster the generation of hydrogen, the greater is the power required per kilogram produced. At best, smaller systems with polymer electrolytes can reach 80 to 85%, while large-scale units using alkaline electrolyte run at 70 to 75% efficiency. Steam electrolysers, in which some of the energy required to split water is supplied by heat, can achieve very high efficiencies (over 90%) but are presently not commercially feasible.

Consideration has also been given to operating fuel cells in reverse as electrolysers. The dual-function system is termed a ‘regenerative fuel cell’. Such technology would save on weight and costs compared with a power system that employs a separate fuel cell and electrolyser. It would also offer the prospect of using renewable energy (e.g., solar, wind, geothermal) to generate hydrogen that would be stored in the same unit for subsequent production of electricity. Commercial water electrolysers are today manufactured in varying sizes, with power consumptions in the range of kW to MW. The larger sizes are limited to alkaline electrolysers, and a unit capable of producing 500 m^3 of hydrogen per hour might consume about 2.3 MW of power. Large though this is, it is less than 1/400th of the size that would be suitable for coupling to a typical 1000-MW pressurised water nuclear reactor. By contrast, solar arrays with power outputs in the kW to MW range could readily be coupled to present-day water electrolysers.

Research and development challenges

On-site, on-demand hydrogen generation will remove the need for up-front expensive transmission and distribution infrastructure for hydrogen, and will assist with the early introduction of a hydrogen economy. In this regard, water electrolysis is considered to be the key technology for distributed hydrogen generation as it is compatible with existing power-generation technologies, as well as with new, environmentally friendly, alternatives. The major research challenges are in the development of low cost, compact and highly efficient electrolysis systems with demonstrated long life for distributed generation. Another major challenge is the integration of electrolysis plants with renewable energy sources. Reversible fuel-cell/electrolysis systems have the potential to reduce overall system cost by combining two functions in a single unit.

Australian projects

Two groups reported projects in the area of water electrolysis. The projects represent the two major considerations for truly renewable electrolytic hydrogen. The first project focuses on the materials technology side of the problem. Whilst the second project is concerned the feasibility and development of geothermal energy as a power source to drive the electrolytic process.

Project:	**Polymer Electrolyte Membrane Water Electrolysis for Hydrogen and Oxygen Generation and Integration with Renewable Energy Sources**
Outline:	The aim of this project is to develop electrolysis technology for distributed hydrogen generation on-demand at end- user sites (homes, service stations, remote areas, etc.). The current technology is capable of producing initial efficiency above 85% at 1A/cm^2 current density from single cells and stacks to 2kW equivalent hydrogen generation capacity. Lifetime testing has demonstrated 3000h operation for short stacks. Construction of a stand-alone renewable energy demonstrator complete with balance-of- plant and a 2kW stack for demonstration with renewable energy or grid electricity is planned.
Organisation:	**CSIRO Energy Technology.** Dr Sukhvinder Badwal (sukhvinder.badwal@csiro.au), Dr Sarb Giddey, Dr Robin Clarke and Dr Fabio Ciacchi.

Project:	**Scalable Opportunities for Geothermal Energy Harvesting that Follows Demand Cycles**
Outline:	South Australia has attracted a large majority of Australian investment in geothermal energy resources. The return on these investments will be a function of future electricity prices - prices that can vary substantially as a direct function of daily cycles in electricity demand. Many proposed and emerging system designs for "conventional" geothermal energy harvesting do not readily accommodate the ability of supply to follow demand cycles. Our project will analyse the prospects of storing energy as hydrogen at night when prices and demand are low and releasing it as additional electricity supply during the day when prices and demand are high. Further analysis of the exergy flows through various proposed energy release schemes, is planned to be undertaken as well as an estimate of preliminary costs. The timeframe for the initial analysis is April to June 2008 with an associated budget of $ 300,000.
Organisation:	**University of South Australia and Hydricity SA.** Dr Rob Dickinson (rob@dataspace.com.au), Prof. Graham (Gus) Nathan and Dr Peter Ashman.

2.3.2 Photoelectrolysis

Photoelectrolysis is one of three possible methods for the direct production of hydrogen via the harnessing of solar radiation. The other two methods are biophotolysis, (referred to in section 2.2.2) and thermolysis which is described in the next section. In photoelectrolysis, light is converted to electrical and chemical energy by using a semi-conducting oxide, such as titanium dioxide (TiO_2), to absorb photons and provide oxygen and electrons. The electrons flow through an external circuit to liberate hydrogen at a metal counter electrode such as platinum. By virtue of its relatively low cost, titanium dioxide is most attractive as a photovoltaic material. It does, however, have a somewhat high band-gap energy (~3.2 eV) and therefore absorbs light energy in the ultraviolet rather than in the visible part of the spectrum. Accordingly, present efficiencies for hydrogen production are only 1 to 2%, i.e., well below the commercial target of 10%. To achieve improvements in performance, research efforts are being directed towards finding a means to shift the spectral response of titanium dioxide into the visible region through modification of band-gap and light-absorption properties.

The possible benefits to be gained by using a photo electrochemical cell in tandem with a dye-sensitized solar cell ('Grätzel cell') are also being explored. The latter also employs titanium dioxide as a photovoltaic material and overcomes the band-gap problem by separating the optical-absorption and charge-generating functions. A dye, which is capable of being photo-excited, is adsorbed on to the surface of the oxide and acts as an electron-transfer sensitizer; the coated oxide serves as the negative electrode of the cell. The dye, after having been excited by a photon of light, transfers an electron to the conduction band of the underlying oxide ('injection process'), and itself becomes oxidised in the process. The cell electrolyte contains a 'redox mediator', i.e., a system, such as the iodide–tri-iodide couple, that can be oxidised and reduced electrochemically. Positive charge is transferred from the dye to the mediator and the dye is returned to the reduced state ('interception process'). The oxidised mediator diffuses to the positive counter-electrode, where it is returned to the reduced state by the electrons travelling around the external circuit. Such cells have demonstrated sunlight-to-electricity efficiencies of 10% in the laboratory and 5% in the field. Again, this cell technology is still under development. There are, in fact, many different possibilities for photoelectrochemical cells and this area of research is attracting much interest world-wide for the sustainable production of hydrogen.

Research and development challenges

Direct water-splitting is the 'Holy Grail' of hydrogen production. The technology offers many benefits in terms of direct conversion of sunlight to hydrogen. There are a number of scientific and technical barriers to be overcome before the technology can be commercialized. High cost, very low efficiency, operation with high solar insolation, manufacturing complexity, short life-time, low current density and hydrogen collection from a very large area are some of the issues that seriously have to be addressed.

Australian projects

CSIRO, Monash University, Queensland University of Technology, The University of Sydney and the University of Wollongong are all involved in research into the use of semiconductor based photocatalysts to generate hydrogen from water.

Project: **Hydrogen Generation from Water by Photocatalytic Semiconductor**

Outline: The quantum confinement effect is the broadening of a semiconductor's band gap when the semiconductor particle size is miniaturised to within a few nanometres in diameter. This research project investigates how this effect affects the photocatalytic properties of semiconductors such as cadmium sulphide, with the aim of designing a system that can generate hydrogen gas from water using sunlight. The project has investigated using ionic liquids for the synthesis of cadmium sulphide nanoparticles and their immobilisation in functionalised mesoporous silica host. These photocatalytic tests have shown that nanoparticle-silica composites performed several times better than commercially available bulk cadmium sulphide. The project's future direction will be in replicating these methodologies in other photocatalytic semiconductors that are more chemically stable than cadmium sulphide.

This research also investigates the design of photocatalytic reactors and the optimisation of the reactor configuration. Currently, a quartz tube reactor where irradiation is perpendicular to the reactor is being used. This catalyst and substrate (an aqueous sacrificial solution) are suspended inside the reactor by stirring. This configuration was chosen as it is easy to build and allows for facile comparison with other data in the literature. However, unsurprisingly, it has been found that this configuration is inefficient in terms of solar flux collection, since a large portion of light is simply transmitted without being harvested by the photocatalyst. Therefore, more advanced different reactor designs are also being investigated, including flat plates and possibly optic fibres as a means to direct light into the reaction centres. This is an ongoing project; the current budget is approximately $200,000.

Organisation: **The University of Sydney.**

Prof. Thomas Maschmeyer (th.maschmeyer@usyd.edu.au), Assoc. Prof. Anthony F. Masters, Mr Vincent Lau, Mr Lorenzo Costanzo, Ms Hui Lin Chen.

Project: **Photocatalytic Production of Hydrogen**

Outline: This project aims to develop catalysts which allow the solar driven production of hydrogen from aqueous solutions. The approach will focus on developing architectures which maximise the available surface area for photocatalytic reactions. Subsequently, the synthetic procedures will be used to produce catalysts which have both active surfaces for catalysis and provide a better overlap with the solar spectrum for higher efficient solar to hydrogen conversion. The materials are primarily metal oxides and doped metal oxides with extremely high surface areas. The timeframe of this project is July 2006 to July 2009, the total budget is $120,000.

Organisation: **Queensland University of Technology and CSIRO.**

Dr Geoffrey Will (g.will@qut.com), Prof. John Bell .

Project:	**Bio-inspired light driven water splitting devices**
Outline:	The objective of this project is to develop an efficient photo-electrochemical device that uses sunlight to generate energy, hydrogen and oxygen. Towards this end, the project is developing photoanodes which combine light absorbing antennae with a manganese molecular cluster to oxidise water into oxygen and hydrogen ions. The project Integrates these photoanodes with cathodes capable of efficiently converting hydrogen ions into hydrogen gas thereby producing a novel type of water splitting device. Global energy demand is currently met using predominantly fossil fuels – coal, oil and gas. The considerable problems associated with the use of fossil fuels – global warming, pollution and dwindling reserves leading to scarcity – are driving public, industrial and regulatory attention strongly towards renewable energy sources. Two such sources are solar energy and fuel cells. Solar energy relies on the capture and conversion of photons from sunlight into electrons, that is, electricity. Fuel cells, and in particular hydrogen fuel cells, work by combining oxygen and hydrogen in a reaction that produces clean energy and there fore require a source of hydrogen. This technology potentially offers a renewable energy source. It is effectively a hybrid between solar power and photo-electrochemical water splitting devices, the products of which (electrical current or hydrogen) are touted as a potentially viable alternative to fossil fuels. The potential advantage of the technology is that it combines the strengths of these two types of devices, mainly, it does not require the input of fossil fuels and can generate power at point of use using crude feedstock and therefore does not present the logistical supply issues around hydrogen fuel cells.
Organisation:	**Monash University, CSIRO, University of Wollongong and Princeton University (USA).** Prof. Leone Spiccia (leone.spiccia@sci.monash.edu), Mr Robin Brimblecombe (Monash), Dr Annette Koo (Postdoctoral Fellow, Monash), Prof. G Charles Dismukes (Princeton), Dr Gerry F Swiegers (CSIRO), Prof. Gordon G Wallace (University of Wollongong) and Dr Jun Chen (University of Wollongong).

2.3.3 Thermolysis

The dissociation of water is a highly endothermic reaction. At temperatures above 1500°C, water vapour starts to dissociate into hydrogen and oxygen with the extent of dissociation increasing with increasing temperature and decreasing pressure. For complete dissociation of water to hydrogen and oxygen, temperatures in excess of 3200°C are required. The required temperature for breaking down water directly into hydrogen and oxygen ('thermolysis') can be achieved by focusing the sun's rays from a large number (up to thousands) of individual mirrors on to a thermal receiver mounted on top of a central, tall 'solar tower'. In areas with poor access via road or rail large-scale hydrogen production is not usually practical and hydrogen is generated close to where it is needed. This requirement has stimulated the development of 'mini' solar towers with smaller footprints for the decentralized generation of hydrogen. Such infrastructure would be easier to install and is flexible in that units can be added over time to meet any growth in demand. The major problem with thermolysis plants are the very low conversion efficiency and high heat losses.

It has also been suggested that solar–thermal radiation could facilitate and improve the photoelectrochemical decomposition of water by enabling the process to be conducted at high temperatures and pressures. Much of solar radiation lies in the infra-red spectrum and is of too low energy to be utilised in photoelectrochemical reactions so that it is wasted. Radiation received by the solar tower would therefore be separated into an infra-red component to heat pressurised water to at least 300°C, and into visible/ultraviolet radiation to effect the water-splitting reaction. Given that thermodynamic calculations suggest that the required energy is substantially reduced at high temperature and pressure (as noted above), it is expected that overall efficiencies approaching 20% for the conversion of solar energy to hydrogen will be possible. (Note: solar towers may also be used for the steam reforming of coal gas or natural gas.)

Research and development challenges

The key technical and scientific challenges are the design of cost-effective systems, the discovery of materials that will reduce the dissociation temperature, and the development of an improved means for separating the gases so as to prevent recombination. In addition, heat losses must be reduced so that efficiency is increased substantially. Two projects in this area were identified.

Australian projects

Project:	**Scale-up of Catalytic Water Splitting Processes**
Outline:	This project is concerned with the development of a prototype reactor system for the catalytic generation of H_2 from water using solar energy. The timeframe of this project is 2008 to 2012 and the associated budget is approximately $ 1.1 million.
Organisation:	**The University of Sydney and the University of NSW.** Dr Andrew Harris (a.harris@usyd.edu.au), Prof. Thomas Maschmeyer.

Project:	**Alternative Energy International (AEI) Hydrogen Production**
Outline:	This project centres on the use of higher temperature reactions with steam to produce hydrogen. The timeframe of this project is July 2006 to July 2008; the total budget is approximately $ 600,000.
Organisation:	**Queensland University of Technology and AEI.** Dr Geoffrey Will (g.will@qut.com), Prof. John Bell.

3. HYDROGEN DISTRIBUTION AND STORAGE

There are certain safety issues which preclude the use of 'neat' gaseous or liquefied hydrogen. Transportation and personal portable applications are two obvious examples of where these issues may be a concern. Currently, the favoured solution to this problem is to render the hydrogen partially inert by reversible sequestration in so called storage materials. Broadly speaking, hydrogen storage materials can be separated into two categories (i) metal hydride based materials and (ii) porous materials.

3.1 Metal Hydrides

Certain metals and alloys absorb hydrogen reversibly to form metal hydrides. The key to the practical use of metal hydrides is the ability to absorb and release the hydrogen many times without deterioration. The quantity of hydrogen absorbed is expressed in terms of hydride composition, either on a molar or a weight-percent basis. Volumetrically, the hydrogen content may be as high as that in liquid hydrogen. Some of the metal hydrides are of quite variable composition (i.e., variable metal-to-hydrogen ratio), whereas others have only a narrow range of composition.

A great many alloys have been screened for hydrogen storage with respect to the following criteria: (i) reversible hydrogen capacity; (ii) ease of initial activation of the alloy; (iii) operating pressure–temperature range; (iv) reaction kinetics; (v) stability on repeated cycling of hydrogen; (vi) cost.

Magnesium hydride, MgH_2, contains the highest possible percentage of hydrogen by weight (7.65 wt.%) and is inexpensive. Nevertheless, it has drawbacks. A temperature above 300 °C is required for the release of hydrogen and the enthalpy of dissociation is high (75 kJ per mole H_2), which necessitates the transfer of considerable quantities of heat as the hydride is decomposed and reformed.

The following characteristics have been identified as being desirable for alloys to serve as practical hydrogen-storage media.

- The dissociation pressure of the alloy should have a value of 0.1 to 1 MPa at near-ambient temperature.
- The hydride should have a high hydrogen content per unit mass.
- The alloy should be of low cost and should be easily prepared.
- The system should exhibit favourable and reproducible reaction kinetics.
- The enthalpy of hydride formation should be as low as possible.
- The bed of reactant should have a high thermal conductivity.
- The alloy should not be poisoned by gaseous impurities.
- The system should be safe on exposure to air and should not ignite.

No one alloy meets all these specifications and the choice of alloy will be a compromise based upon the intended application.

Research and development challenges

The broad issues are: overcoming the high weight-to-volume storage capacity; achieving a fast response time for hydrogen release and a shorter refilling time; developing a capability to be cycled for several hundred operations. About 6 kg of hydrogen needs to be stored for a medium-size car to give an acceptable cruising range and to compete with gasoline or diesel engines. The response time of the hydrogen storage–delivery system has to be fast and must accommodate the needs of varying driver habits. The filling time for the storage tank has to be no more than 5–10 min with several hundred (>500) refilling / discharge cycles over the life of the storage tank.

Australian projects

Project:	**National Hydrogen Materials Alliance Hydrogen (NHMA) – Hydrogen Storage Projects: Metal Hydride Materials**
Outline:	There are four projects in the NHMA Hydrogen Storage program represent a multi-institutional effort to develop high performance materials for the storage of hydrogen. The projects focus on chemical (e.g. Metal Hydride) and physisorption (e.g. Carbon and Porous Materials) based storage. The NHMA projects dealing with metal hydride based chemical storage aim to develop materials based on Lithium and Magnesium (and alloys thereof). Generally, hydrogen capacity, long-term stability (reusability) and absorption/desorption kinetics are the areas receiving attention. In pursuit of this, new materials are being developed with tailored nano-structures and compositional variation (e.g. Lim-Mgn alloys) to optimise the intrinsic hydrogen storage characteristics. Project Budgets: Lithium Hydrides ($ 1.181 million), Magnesium Hydrides ($ 2.44 million).
Organisation:	**The University of Queensland, Griffith University, Monash University, Curtin University of Technology, Royal Melbourne Institute of Technology (RMIT) and ANSTO.** Prof. Evan Gray (e.gray@griffith.edu.au) Prof. Arne Dahle (UQ), Prof. Paul Webley (Monash), Prof. Craig Buckley (Curtin), Dr Sammy Chan (UNSW), Dr Vanessa Petersen (ANSTO), Prof. Irene Yarovsky (RMIT), Dr Kiyonori Suzuki (Monash), Prof. Hua Liu (Wollongong), Prof. Julian Gale (Curtin), Prof. Alan Chaffee (Monash), Dr John Dobson (Griffith), Dr Ian Snook (RMIT), Dr John Zhu (UQ).

Project:	**Fundamental Theoretical Study of Hydrogen Interactions with Novel Nanostructures**
Outline:	This project aims to develop a fundamental understanding of hydrogen interactions with novel nanostructured materials made from inexpensive light metals. Theoretical calculations will provide practical guidelines for the future design of compact, high-capacity hydrogen storage devices that are both safe and lightweight. The research will further develop theoretical methods enabling to address the issues of hydrogen storage capacity, device stability, and the speed of hydrogen recharge and release. The timeframe for this project is January 2006 to January 2009, with a total budget of approximately $234,000.
Organisation:	**RMIT and Kyoto University (Japan).** Prof. Irene Yarovsky (irene.yarovsky@rmit.edu.au), Dr David Henry (RMIT).

Project:	**Novel Mg-based hydrogen storage systems**
Outline:	Hydrexia is currently engaged in efforts to develop hydrogen storage systems based on proprietary, Mg-based hydrides. The target market for these systems is large stationary power generation systems. The timeframe for this project is approximately 2.5 years, with a total budget of $ 4.8 million.
Organisation:	**Hydrexia Pty Ltd and the University of Queensland.** Dr Jeffry Ng (jeff_ng@bigpond.net.au), Dr Kaz Nogita.

Project:	**Hydrogen Storage Materials**
Outline:	Griffith University is also involved in research into hydrogen storage materials that lies outside the scope of the National Hydrogen Materials Alliance (NHMA). Two projects are being undertaken, the first aims to devise, design and build the best instruments for measuring the amount of hydrogen absorbed/desorbed by candidate solid-state hydrogen storage materials. The second is a study into the fundamental metal-hydrogen interactions that result in physisorption of hydrogen by metals. The development of materials for hydrogen storage for automotive application is driven by targets set by the US Department of Energy. In pursuit of these targets, authoritative measurement of hydrogen storage capacity is of great importance. Critical analysis of currently favoured manometric and gravimetric techniques shows that they are vulnerable to significant errors when materials of low density are measured. As these are the materials most likely to meet the DoE energy density targets, authority of measurement becomes a central problem in comparing the achievements of laboratories worldwide. A new class of instrument, the Variable Volume Manometric Analyser, has been developed at Griffith University (patent applied for) that greatly ameliorates the sample density problem. Griffith University also participates in round-robin exercises to compare measurements of standard samples. This is an ongoing project with no fixed timeframe the budget for the project is approximately $ 200,000. The second project is concerned with an investigation into metal-hydrogen interactions and covers a range of activities aiming to improve our fundamental understanding of the interaction of hydrogen with metals. Microstructural investigations are conducted with in-situ (i.e. under hydrogen gas pressure) measurements using beams of neutrons, x-rays and positive muons at international and Australian centres. Neutron studies are currently performed under deuterium pressures to 2000 bar. This is also an ongoing project with an annual budget of $ 300,000.
Organisation:	**Griffith University, Institute for Energy Technology (Norway), University of Geneva (Switzerland), European Commission, the University of Queensland, Rutherford Appleton Laboratory (UK) and the Technical University of Berlin (Germany).** Prof. Evan Gray (e.gray@griffith.edu.au), Dr Jim Webb (Griffith), Dr Tomasz Blach (Griffith), Dr Claudia Zlotea (EC), Dr Mark Pitt (IFE), Dr Volodymyr Yartys (IFE), Dr Maria Orlova (Geneva), Dr Radovan Czerny (Geneva), Dr Klaus Yvon (Geneva), Dr Aris Chatzidimitriou-Dreismann (Berlin), Dr Jerry Meyers (RAL), Prof. Arne Dahle (UQ), Dr Andrej Atrens (UQ).

Project: **Novel Materials for Hydrogen Storage for Energy Technology**

Outline:

There are currently two projects concerned with the development of materials with a high capacity for and stability towards hydrogen storage underway at the University of Wollongong. The scope of the projects encompasses all aspects and types of hydrogen storage materials.

The first project aims to develop an understanding of the characteristics of novel hydrogen storage media based on a wide range materials including metal oxides, metal hydrides, carbons, metal-organic frameworks and nano-templated materials. In particular, the effect of surface modifications, induced defects, porosity, doping and complex or uneven shapes on the physico-chemical aspects of hydrogen absorption will be investigated. The timeframe for this project is approximately 2 years, with a total budget of $ 300,000.

The focus of the second project is the development of innovative materials with high hydrogen storage capacities (e.g. intermetallic hydrides, composite hydrides, catalysed complex metal hydrides, and new nanotubes). In pursuit of this, the phase structure, thermodynamic and kinetic parameters of the candidate materials will be explored in an effort to elucidate the mechanisms of the absorption and desorption processes. The timeframe for this project is approximately 2 years, with a total budget of $ 255,000.

Organisation: **University of Wollongong.**

Prof. Hua Kun Liu (hua@uow.edu.au), Dr Zaiping Guo, Prof. J.Y. Lee,
Prof. A. Zuettel, Prof. P.H.L. Notten.

Project: **Development of the Theory of Solid-State Diffusion and Nuclear Spin Relaxation of Hydrogen in Materials**

Outline:

This project aims to provide a theoretical basis to understand the microscopic details of diffusion in metal-hydrogen systems. Current work is developing accurate theory and numerical methods to enable the analysis of nuclear spin relaxation data of H in AB2 intermetallic compounds. The results supplant previously used simple approximations and enable a more complete and accurate analysis of the experimental data.

Organisation: **The University of New England.**

Assoc. Prof. Colin Scholl (csholl@une.edu.au)

Project:	**Computer Simulation of Materials for Hydrogen Storage**
Outline:	This project aims to explore the hydrogen storage capacity of a range of different materials through the use of theoretical and computational techniques. The research involves the use of both quantum mechanical and force field methods to simulate hydrogen physi- and chemi-sorption. Materials under investigation include carbon nanostructures, metal-organic frameworks and metal clusters. This is an ongoing project the current budget is approximately $ 285,000
Organisation:	**Curtin University of Technology and RMIT.** Prof. Julian Gale (julian@ivec.org), Prof. Irene Yarovsky (RMIT), Dr Akin Budi (RMIT).

3.2 Carbon Nanomaterials

Another possible approach to hydrogen storage stems from recent work on materials whose structural elements have dimensions in the nanoscale range. These so-called 'nanostructured' materials have high specific surface-areas (m^2 g^{-1}), which can be attained either by fabricating small particles or clusters where the surface-to-volume ratio of each particle is high, or by creating materials where the void surface area (porosity) is high compared with the amount of bulk support material. Intense interest in such materials commenced in the early 1990s with the discovery of techniques to produce various types of carbon nanostructures. It was further shown that at the nanoscale, materials exhibit chemical and physical properties that are characteristic of neither the isolated atoms or of the bulk material. Moreover, there is the opportunity to engineer the structural architecture to yield desired properties. With respect to hydrogen storage, the small size of nanostructured materials influences the thermodynamics and kinetics of hydrogen adsorption and dissociation by increasing the diffusion rate and decreasing the required diffusion length. Contrary to expectations, hydrogen storage in these materials requires either high pressure (> 10 MPa) or low temperature (at least below –100 °C).

The materials can be divided into two categories:

1. 'dissociative' materials, in which the hydrogen molecules are dissociated into atoms that bond with the lattice of the storage medium (chemi-sorption), e.g., metal hydrides, discussed above
2. 'non-dissociative' materials that by virtue of their high microporosity and high surface area store hydrogen in the molecular state via weak molecular–surface interactions (physisorption), e.g., carbon and boron nitride nanostructures, clathrates, metal–organic frameworks.

Clearly, physisorption is more desirable as it would moderate the pressure and temperature required for the respective uptake and release of hydrogen.

It has been shown theoretically that carbon, in the form of nanofibres or nanotubes (fullerenes), is capable of holding reasonable quantities of hydrogen. Various types of graphitic nanofibres have been investigated. These are grown by the decomposition of hydrocarbons or carbon monoxide over bi- and tri-metal catalysts of iron, nickel and copper. The fibre consists of graphene sheets aligned in a set direction (dictated by the choice of catalyst). Three distinct structures may be produced, namely: platelet, ribbon and herringbone. The structures are flexible and can expand to accommodate the hydrogen.

Carbon nanotubes are created by using a laser evaporation technique and are cylindrical or toroidal varieties of fullerene (the generic term used to describe a pure carbon molecule that consists of an empty cage of sixty or more carbon atoms) with lengths of up to about 100 μm. Each end is capped with half a spherical fullerene molecule. 'Single-walled' nanotubes are formed by only one graphite layer and have typical inner diameters of 0.7 to 3 nm. 'Multi-walled' nanotubes consist of multiple, concentric, graphite layers and show diameters of 30 to 50 nm.

Various pre-treatments have been suggested to enhance the storage capacity of such materials to several wt.% hydrogen. There is still considerable controversy over the findings, however, because of the difficulty in preparing homogeneous, well-defined, pure and reproducible samples. Nevertheless, strenuous efforts are being made to develop methods for producing nanotubes economically on a large scale.

Research and development challenges

Issues to be addressed include the high cost of fabrication, the preparation of homogeneous reproducible materials with large capacity for hydrogen storage, and scale-up of the production process.

Australian projects

Project:	**Hydrogen Storage in Carbon Materials**
Outline:	There are currently three projects concerned with the development of highly porous carbon materials with a high capacity for and stability towards hydrogen storage underway at the University of Queensland. The first project aims to investigate the mechanism of hydrogen storage in mesoporous carbons, with the intention to improve the hydrogen storage in these materials through metals doping and elemental substitution. Mesoporous carbons synthesised by template methods can have very large pore sizes and surface areas in excess of 2000 m^3.g-1, thus they are promising candidates for hydrogen adsorption. The high surface are also provide space for doping highly dispersed metal catalysts, and even for making nano-sized compounds. Project Budget: $180,000 over three years. The second project aims to investigate the storage capacity of hydrogen in carbon materials by doping catalysts, substituting elements and introducing designed defects into the structures of carbon materials, through both theoretical and experimental methods. This project also aims to foster a long-term linkage with the National Institute of Advanced Industrial Science and Technology (AIST) in Japan thus enhancing Australian Universities' integration with the research institutions overseas in research and development. Project budget $33,000 over four years. The final project aims to develop a fundamental understanding of the adsorption mechanism of hydrogen in carbon nanotubes through theoretical calculations and experimental studies. This addresses an important area of hydrogen storage in nanomaterials such as carbon nanotubes, which promises efficient and clean energy supply in the hydrogen economy in 15-20 years time. Specifically, the project aims to elucidate the effects of catalyst doping and defects in the carbon nanotube walls on the adsorption mechanism and capacity of hydrogen. Such an understanding is crucial to developing the improved carbon nanotubes with high adsorption capacity. Project Budget: $ 220,000 over three years.
Organisation:	**The University of Queensland and AIST (Japan).** Prof. John Zhu (z.zhu@uq.edu.au), Dr Hiroaki Hatori.

Project:	**National Hydrogen Materials Alliance Hydrogen (NHMA) – Hydrogen Storage Projects: Porous Materials**
Outline:	There are four projects in the NHMA Hydrogen Storage program represent a multi-institutional effort to develop high performance materials for the storage of hydrogen. The projects focus on chemical (e.g. Metal Hydride) and physisorption (e.g. Carbon and Porous Materials) based storage. The NHMA projects dealing with physisorption seek to develop porous materials with high affinity and capacity for hydrogen. Currently, carbon materials with extremely high surface area (e.g. Carbon nanotubes) have a relatively low capacity for hydrogen at room temperature (~2 to 3 weight percent). Efforts to improve this involve modelling (using density functional theory (DFT)) of the interactions between molecular hydrogen and selected carbon 'nano-forms' and subsequent modification of the structure of the materials to increase the storage capacity. High surface area materials not based on carbon are also under development for hydrogen storage. Selected Silicates, Metal-Organic frameworks and templated materials with high affinity for molecular hydrogen are being produced through the modification existing materials as well the development of completely new synthetic procedures. Project Budgets: Porous Carbons ($2.547 million) Porous non-Carbons ($ 544,000).
Organisation:	**The University of Queensland, Griffith University, Monash University, Curtin University of Technology, RMIT and ANSTO.** Prof. Evan Gray (e.gray@griffith.edu.au) Prof. Arne Dahle (UQ), Prof. Paul Webley (Monash), Prof. Craig Buckley (Curtin), Dr Sammy Chan (UNSW), Dr Vanessa Petersen (ANSTO), Prof. Irene Yarovsky (RMIT), Dr Kiyonori Suzuki (Monash), Prof. Hua Liu (Wollongong), Prof. Julian Gale (Curtin), Prof. Alan Chaffee (Monash), Dr John Dobson (Griffith), Dr Ian Snook (RMIT), Dr John Zhu (UQ).

Project:	**Nanoporous carbon materials for hydrogen storage**
Outline:	Carbon materials are promising hydrogen storage media because of their low weight and high surface area. Although very high surface areas have been reported, this does not necessarily lead to high hydrogen storage. Rather, very narrow pores are required and the presence of metals appears to improve hydrogen storage capacities. This project aims to synthesize and test a range of metal intercalated carbon materials to help understand the role of surface area, pore size and metal dosing on hydrogen storage. The timeframe for this project is June 2007 to December 2009, with a total budget of $200,000.
Organisation:	**Monash University and Argonne National Laboratory (USA).** Prof. Paul A. Webley (paul.webley@eng.monash.edu.au) Assoc. Prof Alan Chaffee, Dr Yunxia Yang.

3.3 Hydrogen-rich Materials

A number of substances, such as ammonia, cyclohexane, ethanol and methanol, can act as chemical carriers of hydrogen. The gas is subsequently recovered by catalytic decomposition. Methanol is usually manufactured from synthesis gas by the catalytic reaction of two molecules of hydrogen with one of carbon monoxide (i.e., via the gas-to-liquids' route). It is an extremely versatile chemical in its own right and is used to a limited extent as a motor fuel, particularly in certain classes of racing cars. Methanol derived from fossil fuels is, however, a candidate for use in fuel cells in road transportation and portable applications (see Section 4), and can also serve as a fuel for internal combustion engines. In general, it is uneconomical to store hydrogen produced by other means (e.g., by electrolytic or photoelectrolytic routes) in chemicals such as methanol, ethanol and ammonia (very energy intensive processes) unless waste heat or solar energy is embedded in the process. There is therefore very little incentive to develop these technologies as reversible hydrogen-storage systems.

Australian projects

Project:	**Thermochemical Storage of Solar Energy via Ammonia Dissociation**
Outline:	Improved solar reactors and overall system design are being developed by the Australian National University (ANU) in collaboration with Wizard Power. A first demonstration power station incorporating at least 4 of the second generation Big Dish solar concentrators with an ammonia based system is planned for Whyalla in South Australia. This project aims to demonstrate the technical and economic feasibility of closed loop energy storage for 24 hours power generation. An allocation of $14.4 million has been made for this project, $7.4 million of which has been provided by the federal government.
Organisation:	**Australian National University and Wizard Power Pty Ltd.** Dr Keith Lovegrove (keith.lovegrove@anu.edu.au), Mr Artur Zawadski (artur.zawadski@wizardpower.com.au).

4. HYDROGEN USE

Apart from the present use of hydrogen in ammonia and fertilizer production, refineries and metallurgical processes, the other potential major use of hydrogen is as an energy carrier. The energy in hydrogen can be extracted either by burning the gas in an internal combustion engine or turbine, or by electrochemically combing it with oxygen in a fuel cell to produce electricity, heat and water.

4.1 Fuel Cells

Fuel cell technology is evolving rapidly for both stationary and transport applications. The major advantages of fuel cells are low, or zero, chemical pollution (i.e., no emissions of NO_x, SO_x, hydrocarbons, and particulate matter), low noise, high efficiency (e.g., up to 90% with heat recovery in stationary applications), co-generation of heat and electricity, modularity, and high fuel flexibility. In fact, fuel cells are an excellent technology for distributed energy generation due to their ability to co-generate both heat and electricity. They offer the highest system efficiency compared with all other power-generation technologies and are the key enabling technology for a hydrogen economy. Nevertheless, research and development is still required to reduce costs, increase reliability and performance, and reduce performance degradation over time.

4.1.1 Principles of fuel cell operation

A fuel cell converts fuels (hydrogen, natural gas, methanol, coal gas, etc.) into electricity electrochemically. A fuel cell consists of an electrolyte (a liquid or a molten mass held in a matrix or a solid), and air and fuel electrodes. It operates like a battery except that it continuously produces power when supplied with fuel and air. Thus, fuel cells are energy-conversion devices, whereas batteries are storage devices. The generic name of the fuel cell is usually derived from the type of electrolyte used. Typically, a fuel cell generates about 1.0–1.2 V on open-circuit, as determined by the fuel and oxidant compositions, and the operating temperature. In the operating mode, at current densities around 300–500 mA cm^{-2}, the cell voltage reduces to about 0.7–0.8 V. A number of cells are connected in a stack arrangement in series and/or in parallel to increase the voltage and the total current.

4.1.2 Types of fuel cell and operating characteristics

The Alkaline Fuel Cell (AFC), Polymer Electrolyte Membrane Fuel Cell (PEMFC) and Phosphoric Acid Fuel Cell (PAFC) systems can only utilise hydrogen as the fuel source and therefore require an external fuel processor to convert easily available fuels (natural gas, liquefied petroleum gas, gasoline, diesel, methanol, ethanol) to hydrogen. The AFC and PEMFC systems require clean hydrogen fuel that is relatively free of carbon monoxide (typically <10–20 ppm). This is because the low operating temperature leads to easy poisoning of the platinum catalyst. In the case of AFC units, carbon dioxide has to be removed from both the air and the fuel to avoid degradation of the electrolyte. The PAFC can tolerate higher levels of carbon monoxide (100 to 150 ppm) due to the higher cell temperature (200–215°C).

Fuel cell	Electrolyte	Fuel	Temperature (°C)		Efficiency (%)	
			Operating	Exhaust	Electric	System
Alkaline (AFC)	potassium hydroxide	hydrogen	70–90	50–60	40–45 (60-70)	–
Phosphoric acid (PAFC)	phosphoric acid	hydrogen	190–215	100–150	35–45 (60–70)	70–80
Polymer electrolyte membrane (PEMFC)	proton conducting polymer (e.g., Nafion™)	hydrogen	70–110	40–60	35–45 (60–70)	70–80
Direct methanol (DMFC)	proton conducting polymers (e.g., Nafion™)	methanol	70–110	40–60	20–40	–
Molten carbonate (MCFC)	mixture of sodium and potassium carbonates	hydrogen, carbon monoxide, methane + steam	650	500–600	50–55	70–80
Solid oxide (SOFC)	doped zirconia	hydrogen, carbon monoxide, methane + steam	700–900	600–750	>50	80–90

Table 4.1 Fuel Cell Operating Characteristics

The Molten Carbonate Fuel Cell (MCFC) and the Solid Oxide Fuel Cell (SOFC) systems allow simultaneous electrochemical conversion of both hydrogen and carbon monoxide (present in the reformate from fossil fuels). Direct internal-reforming of natural gas is possible in both MCFC and SOFC systems because of their high operating temperatures, however either suitable catalytic electrodes are required or a high steam-to-methane ratio (well above the stoichiometric ratio) must be used to avoid carbon deposition inside the cell compartment. If present in fuels, sulphur must be removed as it poisons the system components of all types of fuel cell.

Another technology under development is the direct methanol PEMFC (DMFC) which involves direct oxidation of methanol in the electrochemical process rather than reforming or partial oxidation of methanol to generate hydrogen. Portable power, remote-area power and vehicle power sources are possible uses for this type of fuel cell.

The high-temperature (SOFC and MCFC) fuel cells offer the maximum potential for base load power generation (100 kW to low MW); although SOFCs offer some potential in small co-generation applications such as residential or small buildings where the demand for the heat load relative to the electric load is high. The PAFC technology is ideal for co-generation applications.

The PEMFC system offers the widest range of potential applications: portable power, transportation (cars, buses, scooters, and small transporters), residential and remote-area power, and medium-size units for co-generation. The fuel cells have fast start–stop response and excellent cycling and load-following capabilities. The major disadvantages are the requirement for very high purity hydrogen and the production of low-grade heat (60–80°C) that has limited use, e.g., heating buildings or providing hot water.

Research and development challenges

The present price of all types of fuel cell is high but it is coming down with the use of less-expensive materials, reduced quantities of noble metal catalyst in low-temperature fuel cells (PAFC, PEMFC), the development of low-cost fabrication technologies, and with the entry of more component and systems manufacturers into the market. Nevertheless, the unit price is expected to remain high for several more years, as usually is the case with new technologies. Cost reduction through the use of improved materials, fabrication methods, and novel system design, means there are many opportunities for fuel cell R&D. Table 4.2 lists some of the research challenges for the different fuel cell types.

Fuel cell	Key issues
Alkaline (AFC)	The extreme sensitivity of alkaline electrolyte to carbon dioxide requires fuel and oxidant to be free of this gas. Only small units have been developed.
Phosphoric acid (PAFC)	Major focus is on cost reduction for the technology to compete with other means of power generation. Some low-level activity relates to decreasing both the corrosion of the cathode support (carbon) and the loss of catalyst (Pt) due to sintering. With time, lower maintenance requirements will also reduce cost
Polymerelectrolyte membrane (PEMFC)	• Present electrocatalysts are easily poisoned by carbon monoxide and sulphur and this imposes stringent fuel-cleaning (pure hydrogen) requirements. New catalysts (non-noble metals, if possible, to reduce cost) with a higher tolerance are required. • Lower loadings of the noble metal catalyst for similar cell performance. • Membrane improvement, particularly in terms of its ability to withstand dehydration and high temperatures. Higher operating temperatures would allow higher concentrations of carbon monoxide in the fuel gas. • Improvement in techniques for membrane manufacture to reduce the cost. • Decrease in the thickness, weight and cost of interconnect plates.
Direct methanol polymer electrolyte (DMPEMFC)	• New catalysts that accelerate the kinetics of methanol oxidation and are more tolerant to intermediate by-products of the cell reaction. • Proton conducting polymer membranes that are more impervious to methanol cross-over. • Membrane improvement, particularly the ability to withstand dehydration and higher temperatures as the latter increase the kinetics of methanol oxidation and the catalyst would therefore be less prone to poisoning by intermediate by-products.
Molten carbonate (MCFC)	• New, improved and cost-competitive anode, cathode and bipolar plate materials that can withstand the operating environment. • Long-term durability tests have been hindered thus far by corrosion-related failure of cell stacks. Cell degradation during operation is exceptionally high. • Catalysts for internal reforming of methane in the stack are required. • Long start-up/shut-down cycles and limited thermal cycling ability constrains available applications.
Solid oxide (SOFC): tubular design	• High cell and stack fabrication costs. • Long start-up/shut-down times (up to several hours). • Thermal shielding required to avoid heat loss. • Difficulties in the management of electrical and thermal load demands, as well as in temperature maintenance.
Solid oxide (SOFC): planar design	• Selection and poor life-time of interconnect and sealing materials. • Lower operating temperature so cheap metallic interconnect materials can be used with minimal cell degradation. • Poor thermal cycling capability sealing and thermal compatibility issues. • High rates of cell degradation during operation. • Long start-up/shut-down times (up to several hours). • Significant thermal shielding required to avoid heat losses. • Difficulties in electrical and thermal load demand, as well as in temperature maintenance.

Table 4.2 Research and development challenges for fuel cells

Australian projects

Project:	**Exploration of New Catalyst Materials for Hydrogen/Air Fed PEMFC**
Outline:	This research project aims to develop new catalyst materials and supporting matrix materials for hydrogen/air fed proton exchange membrane fuel cells. The alloy catalysts will be theoretically designed based on density functional theory, followed by experimental synthesis and comprehensive characterisation. The newly developed alloy catalysts are expected to have low platinum content whilst maintaining high catalytic activity, thus significantly reducing the cost of fuel cell technology. Numerical modelling will also be conducted on the fuel cell system to provide novel designs for fuel cell stack manufacturing. The timeframe for this project is 2007 to 2009; the total budget is approximately $300,000.
Organisation:	**University of Wollongong.** Dr Guoxiu Wang (gwang@uow.edu.au), Prof. Hua Kun Liu, Prof. Konstantin Konstantinov, Dr J. Wang, Dr D. Wexler, Dr O. Savadogo.

Project:	**Advanced Materials for Hydrogen Fuel Cells**
Outline:	The University of Queensland and the Australian National University are currently collaborating on research into advanced electrolyte and membrane electrode assemblies for fuel cells. The development of materials for SOFCs is the focus of one aspect of this collaboration. The objectives are to develop low cost catalyst materials for internal reforming un-solid oxide fuel cells, focussing on Australia's strength in nano-materials, to develop novel oxide materials for SOFCs that involve advanced plasma processing to enable more efficient operating temperatures, and to develop complete assemblies of SOFCs to allow effective testing. The timeframe for this project which is supported by CSIRO under the National Hydrogen Materials Alliance is 2007 to 2009, with a total budget of $ 640,000. The other aspect of the collaboration attempts to resolve a number of long standing problems associate with the development of efficient fuel cells and to be able to develop, in Australia, membrane-electrode assemblies for low temperature proton exchange membrane fuel cells. The development focuses on the use of very thin films of platinum deposited into porous carbon membranes for the electro-catalysts, together with electrolytes fabricated from nano-composite materials. The electro-catalyst development will be carried out at ANU and the electrolyte development at the University of Queensland (UQ). The timeframe for this project is 2005 to 2008, with a total budget of $ 900,000.
Organisation:	**The University of Queensland and Australian National University.** Prof. Rod Boswell (rod.boswell@anu.edu.au), Dr Andrew Dicks, Dr Cormac Corr and Dr Christine Charles.

Project:	**CSIRO – Manufacturing Technology PEMFC Program**
Outline:	Currently the CSIRO Manufacturing Technology division based at the University of South Australia (Ian Wark Research Institute) has two projects in the area of PEMFC research. The first project aims to develop a family of novel proton conducting polymer membranes for high temperature PEMFC applications. The ability to produce polymeric proton exchange membrane with fast proton conduction at elevated temperature represents significant impact on next-generation sustainable energy conversion devices. Current membranes lose water and proton conductivity at elevated temperature. This approach towards this goal focuses on inorganic modification of self-assemblies of unique ionic block copolymers and understanding the role of micro-structure/morphology of such hybrids on proton conduction mechanism. A range of novel chemistries will be used based on in-situ grown highly organized inorganic nano-network in the supramolecular assembly of ionic block copolymers. Use of such strategic chemical design will allow both high temperature property and fast proton conduction to be attained simultaneously. These materials provide the structural platform of novel proton exchange membranes with outstanding properties. The project will translate the superior material properties to membranes for electrochemical devices e.g. fuel cell, gas diffusion electrodes, etc. The timeframe for this project is 2005 to 2009. The total budget is $ 600,000. The second project is concerned with the development of a novel class of catalyst materials for PEMFC electrode applications. A family of harmonized, catalytically active heterostructure will be created from noble metal nanoparticle-loaded on unique carbon materials using a combination of electrospinning and block copolymer self assembly approach. Novel hybrid structure will demonstrate high electroactive surface area and electrocatalytic activity and will remarkably decrease the overpotential and suppress the electrode surface fouling due to faster electron-transfer rate. The timeframe for this project is 2006 to 2009 and the total budget is $80,000.
Organisation:	**CSIRO–Manufacturing Technology and Ian Wark Research Institute (Uni of SA).** Dr Naba K. Dutta (naba.dutta@csiro.au), Prof. Namita Roy Choudhury, Prof. S. Holdcroft and Dr A. Hill.

Project:	**Films and Inorganic Membranes Laboratory (FIMLab) PEMFC Program**
Outline:	Based at the University of Queensland, FIMLab is involved in research into reaction engineering and the production of novel nanomaterials for energy technology applications. Currently, the group has two active projects concerned with the development of electrolyte materials for proton-exchange membrane fuel cells. The first project aims to develop new nanomaterials and Nafion™ hybrid membranes for proton exchange membrane fuel cells. The second project is concerned with the development of functionalised inorganic nanomaterials with enhanced proton conduction characteristics for proton exchange membrane fuel cell applications.
Organisation:	**The University of Queensland.** Assoc Prof. Dr Joe da Costa (joedac@cheque.uq.edu.au).

4.1.3 Stationary applications

Although small (low kW) fuel cells, especially alkaline types, have been employed in space missions since the 1960s, general progress in fuel-cell technology has been slow. It is only since 1990 that fuel cells have been demonstrated in common stationary applications. The most promising developments in stationary power generation have been in the area of Solid Oxide Fuel Cells. The overall output efficiency of such units is frequently improved through integration with other systems with high energy demand (e.g. household heating). An example of this type of integration is embodied in the CFCL Net~Gen Combined Heat and Power System shown below (Figure 4.2)

Australian Projects

In Australia, commercial effort in fuel cell technology is relatively small and is concentrated mainly on the SOFC technology of Ceramic Fuel Cells Ltd (CFCL). CSIRO has conducted research and development on both SOFCs and PEMFCs. CSIRO is looking at commercializing the PEMFC technology that it has been developing since 1998.

The SOFC system offers high efficiency with natural gas and can take advantage of its high operating temperature to perform steam reforming of natural gas within the stack itself. If hydrogen is the available fuel, however, the energy component available for conversion to electric energy at 900-1000°C is only about 70% of the total energy content of the fuel. Thus, the efficiency of SOFCs is considerably lower than that of low-temperature fuel cells based on hydrogen fuel and no major advantages are to be gained by using SOFC technology with this fuel.

Ergon Energy is involved in a major project to demonstrate the use of a large stationary fuel cell to supplement the supply of electricity during periods of peak power consumption.

Figure 4.1 Ceramic Fuel Cells Limited 1 kW Net~Gen Combiner Heat and Power SOFC System. (Image courtesy of CFCL).

Project:	**Ergon Energy Fuel Cell Technology Trial**
Outline:	Ergon Energy is an electricity distributor whose territory encompasses 97% of the state of Queensland. Ergon Energy has recognised the potential that hydrogen fuel cells possess, with their on-demand generation capability, to benefit remote and fringe of grid power networks by reducing infrastructure costs and meeting relatively short periods of high demand. Ergon Energy will be connecting a hydrogen fuel cell to the supply network at a display home to demonstrate the use of distributor owned and operated, residential sized generation to flatten out demand spikes at peak times. The fuel cell will operate two hours a day to demonstrate the supply of electricity direct to the customers premise from on-site generation at times of peak power consumption thus reducing the overall demand for load on the supply network. Ergon Energy will use this demonstration project to provide knowledge and capability with fuel cells to their staff and to educate industry and the public on hydrogen fuel cell technology and the use of localised generation as an alternative method of ensuring reliable and efficient power supply. The timeframe for the project is 2006 to 2009, and the project has a budget of $1 million.
Organisation:	**Ergon Energy.** Ms Jenny Gannon (jennifer.gannon@ergon.com.au).

Project:	**Hybrid Remote Area Power Systems with Hydrogen Energy Storage for Isolated and Regional Communities**
Outline:	The project aims to develop hybrid stand-alone power systems with wind as the renewable energy source and hydrogen as the primary energy storage medium. Innovative and practical technologies will be developed for cost-effective operation and control of hybrid remote area power systems. Reduced diesel fuel consumption and air pollution will be achieved by injecting electrolytic hydrogen and diesel into the engine. Such a hybrid system will produce reliable, high quality power under all conditions to fulfil customer demands at a reduced cost. The budget for this project is approximately $ 462,000.
Organisation:	**The University of Tasmania (UTas) and Hydro Tasmania (HydroTas).** Prof. Michael Negnevitsky (michael.negnevitsky@utas.edu.au), Assoc. Prof. Kashem Muttaqi (Wollongong), Assoc. Prof. Vishy Karri (UTas), Dr Marian Piekutowski (HydroTas), Mr Patrick Burke (HydroTas).

Project:	**Commercialization of Solid Oxide Fuel Cells**
Outline:	Ceramic Fuel Cells Limited (CFCL) is a world leader in developing solid oxide fuel cell (SOFC) technology to provide reliable, energy efficient, high quality, and low-emission electricity from widely available natural gas and renewable fuels. CFCL is developing SOFC products for small-scale on-site micro combined heat and power (mCHP) and distributed generation units that co-generate electricity and heat for domestic use. The market entry product will be a grid parallel, 1-kW$_e$ mCHP system in which a fuel cell is combined with a domestic water-heater to provide both electricity and hot water. This will be followed by a 5-kW$_e$ distributed generator for grid-independent power security, remote-area power.
Organisation:	**Ceramic Fuel Cells Limited.** Dr Karl Foger (karlf@cfcl.com.au).

4.1.4 Transportation applications

Most automobile companies are developing fuel cell vehicles. These vehicles are usually equipped with batteries or supercapacitors that supply boost power during acceleration and hill-climbing. Several prototype vehicles are now undergoing trials with different forms of on-board hydrogen storage, namely, gas pressurised to 35 MPa, liquid hydrogen, or metal hydrides. Many of the car manufacturers believe that commercialization will occur between 2015 and 2020. At the World Hydrogen Conference held in Yokohama, Japan in June 2004, eight manufacturers displayed their prototype fuel cell vehicles. The Japanese government has set targets for fuel cell vehicles of 50 000 by 2010, 5 million by 2020, and 15 million by 2030.

Australian Projects

In September 2007, the Western Australian Government Department for Planning and Infrastructure completed a three year trial of three hydrogen fuel cell buses in the Perth public transport fleet. The trial successfully demonstrated the technical feasibility and public acceptance of this low emissions transport technology. Considerable challenges remain in achieving commercial viability and in developing low emissions supply sources and distribution infrastructure for hydrogen fuel. Elected in September 2008, the new Western Australian Government's transport policy for the election included a commitment to "employing new technologies such as hydrogen fuel cell vehicles to achieve greater economic and environmental benefits." The state government is currently considering options for giving effect to this commitment. For more information see: www.dpi.wa.gov.au/greentransport/19524.asp

Figure 4.2 Hydrogen Fuel Cell Buses used in the Perth Trial. (Image courtesy of WA DPI)

Project:	**Efficient and Practical Hydrogen Fuelled Vehicle Technologies**
Outline:	Currently proposed hydrogen fuelled vehicles are often criticised as likely to be excessively expensive and impractical. The overall objective of this research is therefore to develop cost effective and practical technologies that may help enable the hydrogen economy. The project addresses two particular challenges. The first is the redesign of current, engine manufactured in Victoria, which should achieve the world's highest efficiency for a hydrogen-fuelled internal combustion engine. The University of Melbourne has been developing an advanced combustion technology over more than a decade that should enable very high engine efficiencies. This efficiency will be similar to current fuel cell demonstration vehicles, but will be achieved using production hardware that is a fraction of the cost of a fuel cell, and far more easily prepared for market. Second, a severe limitation of hydrogen as a transport fuel is that it carries substantially less energy per cubic metre than gasoline and other hydrocarbon fuels when stored at practical pressures. Existing storage methods, such as pressurisation of H_2 to 350-700 atmospheres, do not show a clear path to meeting automotive requirements, and are excessively large, very heavy or unaffordable. This project seeks to investigate a novel approach to high-density storage of hydrogen in common and inexpensive liquid mixtures at pressures that allow use of conventional storage equipment. The aim is to achieve acceptable vehicle range without requiring excessive fuel volume or prohibitive cost of compression and storage. The timeframe for this project is January 2008 to December 2010, with a total budget of $ 3 million.
Organisation:	**The University of Melbourne, Ford Motor Company of Australia, Haskell Australasia and University of North Florida (USA).** Dr Michael Brear (mjbrear@unimelb.edu.au), Prof. Will Ducker, Dr. Chris Manzie, Prof. Dragan Nesic and Prof. Harry Watson.

Project:	**EnGen Institute Hydrogen Technology**
Outline:	The EnGen Institute is a non-profit research and education body whose expertise lies in the areas of sustainability engineering. The Institute researches and develops life support systems and life sustaining engineered environments for remote locations. The Institute's response to climate change includes researching and developing technology for sustainable micro economies. Currently, the institute has two active projects in the area of energy technology based on hydrogen. Part of the sustainable micro economies program is hydrogen-fuelled transportation, which includes two main sub-programs hydrogen vehicles and hydrogen fuels to be commercialised as H2GO Fuels. EnGen Institute produced a Roadmap to the Hydrogen Economy in 2003 and has been executing it ever since. The other project is the Hydrogen Vehicle project. This project is concerned with developing a multi-fuel Mini Moke that runs on petrol, natural gas, pure hydrogen, hythane (hydrogen CNG mixture) or hydrogen enriched gaseous hydrocarbon fuels produced via pyrolysis. Initially, the goal is conversion of Mini Mokes to CNG and Hydrogen operation, then Multi-fuel Moke manufacturing. Subsequently developing a hydrogen hybrid hypercar (very light vehicle).
Organisation:	**EnGen Institute.** Dr William Hollier (will@engen.org.au).

4.1.5 Portable applications

Designs of PEMFC that operate on hydrogen or methanol fuel and have power outputs of 1–50 W are under development for portable power applications, e.g., soldier packs, laptops, cellular phones, electronic appliances, remote communications equipment, emergency lighting. These so-called 'micro fuel cells' can provide over ten times more electrical energy (Wh) than the best batteries of comparable mass, albeit with a lower power output. They are, however, subject to specific and stringent requirements in terms of operation at near room temperature, accomplishing close to 100% fuel utilisation, minimum balance-of-plant items, self air-breathing (no forced air supply), self heat- and water-management, no membrane humidification, and compact size (no more than that of a battery pack of equivalent power).

The potential market, for portable fuel cells, including the battery replacement market, is forecast to be over $6 billion per annum. A large number of battery and electronic appliance companies are now developing the technology for both hydrogen and methanol fuels. A typical unit comprises a fuel cell sub-assembly, a fuel cartridge, a fuel flow-regulator, and a DC–DC converter. Prototypes to power cellular phones or laptop computers have already been released and have a power output that is sufficient to recharge the batteries. Indeed, manufacturers consider that the first successful application of micro-PEMFCs will be in the form of a portable battery charger rather than as a battery replacement.

Australian Projects

Project:	**Direct Hydrogen Micro and Small Fuel Cells (1 to 500 Watts)**
Outline:	CSIRO Energy Technology is presently engaged in the development of proton exchange membrane fuel cells for use as small-scale portable power sources. Proton exchange membrane fuel cells developed to date have demonstrated a power density above 100mW/cm^2 and hydrogen utilisation approaching 100 % over 10 000 hour stack tests using no fuel humidification or external air supply. The timeframe for this project is 2005 to 2012.
Organisation:	**CSIRO Energy Technology.** Dr Sukhvinder Badwal (sukhvinder.badwal@csiro.au), Dr Sarb Giddey, Dr Brett Sexton, Dr Robin Clarke, Dr Fabio Ciacchi, Dr Daniel Fini, Dr Fiona Glen and Dr John Beatty.

5. FACILITATING TECHNOLOGIES

5.1 Electric Drive Systems

Due to its intrinsic high energy conversion efficiency, and low atmospheric emissions, fuel cell technology is being used to launch a new generation of electric propulsion and power systems for transport applications. Electric motor driven vehicles using fuel-cell systems are more environmentally friendly because of fuel savings, low noise, and zero pollutant and carbon-dioxide emissions. In spite of the fuel cell's efficiency benefit, to produce the same drive power, current fuel cell powered electric drive systems are considerably heavier than conventional systems.

Research and development challenges

Increasing the overall power-to-weight efficiency and reliability of the electric drive system is an area of considerable research effort. An example of an innovation to address this is regenerative braking (when the vehicle decelerates, the motor reverses field, becoming an electricity generator that can recharge a battery pack during braking events).

Australian projects

CSIRO Materials Science and Engineering are developing an electric drive system for hydrogen fuel cell powered vehicles.

Project:	**Electric drive systems for low emission vehicles**
Outline:	The development of high-efficiency, high-torque per unit volume, compact electric drive machines and related control electronics is a key facilitating technology for electric drive trains for hybrid, battery electric and fuel cell vehicles. The project addresses electric power train requirements for the transition from current generation petrol and diesel internal combustion engines through progressive electrification of vehicle systems, to vehicles that have greatly reduced carbon dioxide emissions and eventually to cost effective electric and hydrogen fuel cell vehicles. This is achieved by developing technologies that will facilitate, in the future, a new generation of low emission vehicles, including hybrid, plug-in hybrid and electric vehicles. The technology in its ultimate form will be critical to the development of electric vehicles powered by hydrogen/air fuel cells. The timeframe for this project is approximately 5 years (July 2005 to June 2010), with an annual budget of approximately $ 950,000.
Organisation:	**CSIRO Materials Science and Engineering.** Dr Stephen Collocott (stephen.collocott@csiro.au).

APPENDIX I

List of Contributors

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APPENDIX II

Survey Form

Project Title
Project Objectives
Short Project Abstract
Project Timeframe (start date and end date)
Organisation(s) Involved
Project Leader
Other Researchers Involved
International Linkages (if applicable)
Approx Budget ($K)
Contact Details

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