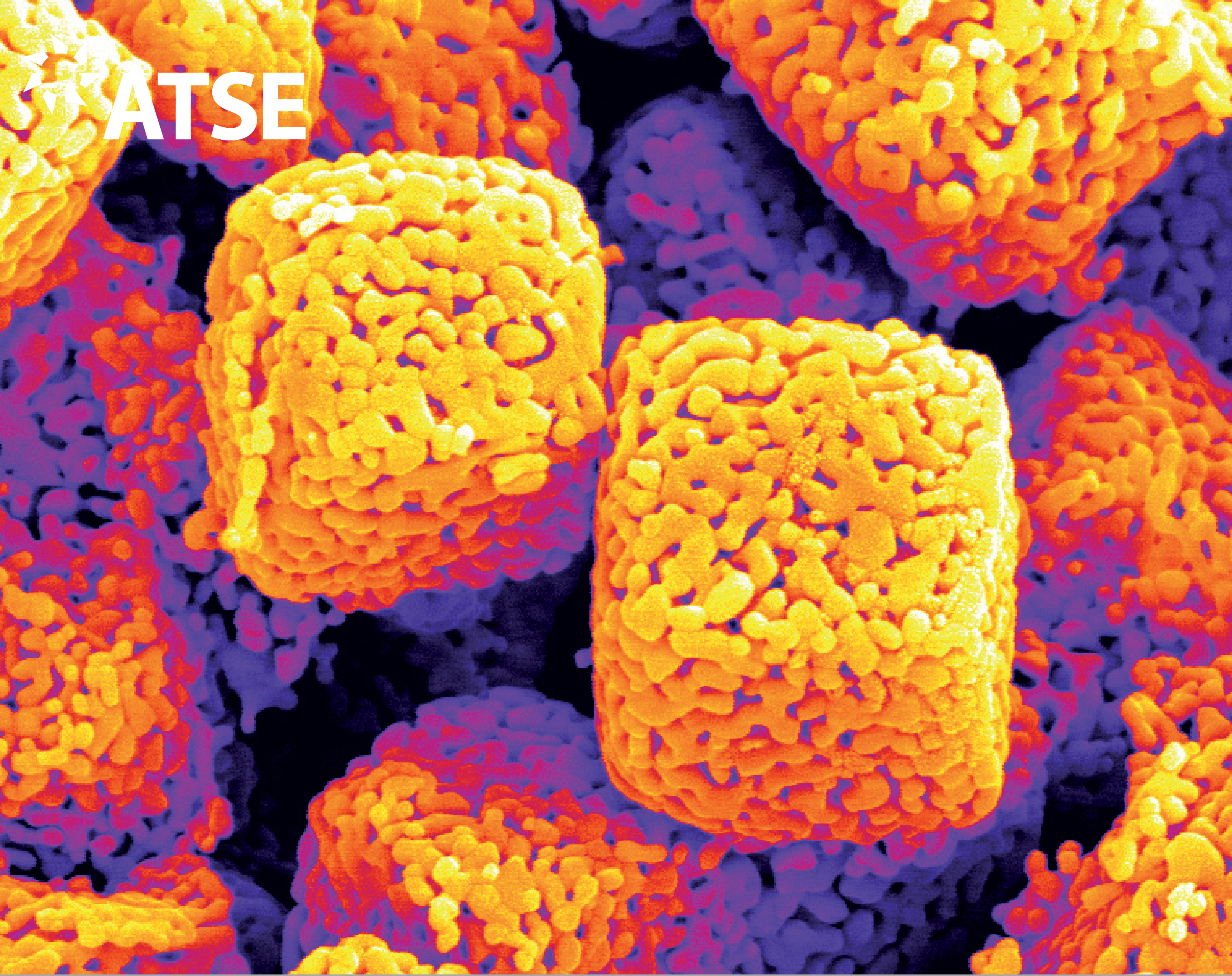

ENERGY AND NANOTECHNOLOGIES: STRATEGY FOR AUSTRALIA'S FUTURE

REPORT OF A STUDY BY THE AUSTRALIAN ACADEMY OF TECHNOLOGICAL SCIENCES AND ENGINEERING (ATSE) 2008

ATSE – in brief

The Academy of Technological Sciences and Engineering (ATSE) is an independent, non-government organisation, promoting the development and adoption of existing and new technologies that will improve and sustain our society and economy.

ATSE consists of more than 750 eminent Australian Fellows and was founded in 1976 to recognise and promote the outstanding achievement of Australian scientists, engineers and technologists.

ATSE provides a national forum for discussion and debate of critical issues about Australia's future, especially the impact of science, engineering and technology on quality of life.

ATSE links Australia with leading international bodies and worldwide expertise in the technological sciences and engineering.

ATSE fosters excellence in science, engineering and technology research and the critical education systems that underpin Australia's capacity in these areas.

ATSE tackles many of the most difficult issues governing our future, by offering fresh ideas, practical solutions and sound policy advice – and putting them on the public record.

ENERGY AND NANOTECHNOLOGIES: STRATEGY FOR AUSTRALIA'S FUTURE

The key finding in this report, by the Australian Academy of Technological Sciences and Engineering, is that nanotechnologies are a growing group of enabling technologies, dealing with engineering at the molecular level, which can make a substantial impact on all areas of energy conversion, storage and distribution.

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Cover: Nanostructured manganese oxide (Mn_2O_3) cubes used in energy storage applications, such as batteries and supercapacitors.

Executive Summary

The key finding of this report, by the Academy of Technological Sciences and Engineering (ATSE) is that **"Nanotechnologies are a growing group of enabling technologies, dealing with engineering at the molecular level, which can make a substantial impact on all areas of energy, including conversion, storage and distribution."** There is a substantial investment in research and development capacity in this area in Australia but more needs to be done to maintain and strengthen this effort and to ensure that the research outcomes are put to practical use for Australia's sustainable energy future.

Energy is essential to virtually every aspect of human activity and the increasing world population and the rapid economic growth of many developing countries, particularly China and India, will require an increasing world energy supply. Concerns over security of supply, sustainability of resources and increasing greenhouse gas emissions linked to climate change have led to a worldwide effort to develop improved use of existing fossil fuels, together with new approaches to energy production and usage from a range of non-fossil and renewable sources such as solar, wind , nuclear, geothermal, biomass and tidal. Projections of energy demand indicate that no single technological "silver bullet" will suffice and that an integrated approach is needed.

In Australia the dominant energy source has been black and brown coal. Indigenous supplies are adequate for several centuries. The same is roughly true for natural gas, but oil supplies are in decline. Australian energy strategy will need to be technology-based around increased energy conservation and clean coal technology, combined with capture and storage of carbon dioxide, as well as substantial contributions from non-fossil and renewable energy sources.

All the elementary steps of energy conversion (charge transfer, molecular rearrangement, chemical reactions, etc) occur at the nanoscale (a nanometre is one billionth of a meter) - the scale of atoms and molecules. In recent years a major new area of science and technology (nanoscience and nanotechnologies) has been created around engineering at the molecular level. The potential of this area is enormous and there are many fields in electronics, photonics, biotechnology, medicine and materials where new disciplines are being created. Australia has a strong research effort in a number of these fields and it has become clear that nanotechnologies are a growing, enabling group of technologies that could change all areas of Australian energy activity, including conversion, storage, transmission and use.

The present study has identified areas for particular attention in Australia in the application of nanotechnologies to energy systems. These areas are discussed in terms of short-term, medium-term and long-term realisation as:

- short-term (less than five years) – energy conservation; environmental management; catalysts for combustion; photovoltaic cells.
- medium-term (5-15 years) – catalysts for conversion of biomass, gas and coal; fuel cells; advanced photovoltaics using engineered nanomaterials.
- long-term (greater than 15 years) – hydrogen production; hydrogen storage and use.

To realise the potential of nanotechnologies in these energy areas in Australia, significant effort in research, development and demonstration is needed over a sustained period. National coordination is essential to make best use of Australia's limited research resources and to build up the skills base needed to sustain a new industry sector. Major investment, both public and private, will be needed for a national research, development and demonstration program to enable commercial exploitation of promising technologies. Australia, in common with many other developed countries, has difficulties with commercialisation of basic research and this is an issue being addressed in the current review of the Innovation System in Australia.

Recommendations

Based on the results of the inputs from several workshops involving Academy Fellows and invited experts and a study of the relevant literature, a number of recommendations for action can be made.

RECOMMENDATION 1

Recognition Needed

Nanotechnologies need to be recognised by the Australian and State Governments and industry as a growing group of enabling technologies which can make a substantial impact in all areas of energy conversion, storage, distribution and use in Australia.

The timeframes identified in the Executive Summary of this Report (short-term, medium-term and long-term), are an excellent starting point for a national strategy for nanotechnologies in energy.

RECOMMENDATION 2

National Coordination

There needs to be national coordination of programs by the Australian and State Governments to ensure optimum use of limited research and capital resources.

While there is a major energy thrust under the CSIRO Energy Technology Flagship and internationally prominent research groups in photovoltaics exist at ANU and UNSW, there are a number of other areas being pursued by universities, CRCs and industry which are below critical mass. In the short term there are four key areas in which Australia has fragmented efforts, namely: organic photovoltaics, dye-sensitised photovoltaics, energy catalysts, and energy conservation using nanomaterials and sensors, all of which need coordination. In the longer term, hydrogen production and use needs to be coordinated as advocated in the National Hydrogen Study recommendations in 2003.

RECOMMENDATION 3

Skilled Workforce, Codified Knowledge

The primary thrust of Australian university activity in nanotechnologies must be the development of a skilled workforce and the production of codified knowledge which can be applied where possible in industry.

There is a lack of skills at all levels to support the development of nanotechnology-based businesses and activities. Coordination of the existing nanotechnology degrees into a coherent framework is needed to maximise the output of nanotechnology-aware and capable graduates. Where economically feasible, innovative nanotechnologies in energy arising from university research should be exploited either by setting up spin-off companies or by licensing to established companies in Australia or overseas.

RECOMMENDATION 4

Integration

The private sector must be actively encouraged by the Australian and State Governments and industry associations to play the key role in integrating nanotechnologies into existing energy systems and activities.

To this end the Australian Government must take a lead in funding demonstration projects and in setting-up public–private partnerships (PPPs) to exploit nanotechnologies in Australian energy systems and in private and commercial activities.

RECOMMENDATION 5

National Nanotechnology Strategy

The Australian Government should embrace the concept of a Strategy for Nanotechnologies in Energy as one of the components of a National Nanotechnology Strategy.

This would be in line with the thrust of the National Nanotechnology Initiative in the US. This initiative must be supported by the Australian and State governments, industry and researchers.

RECOMMENDATION 6

Increased Awareness

Since nanotechnologies can contribute in a variety of ways to development of current and future energy systems, there needs to be an increased awareness of their potential across industry and society.

This can be achieved by a close linkage of a Strategy for Nanotechnologies in Energy with an overall National Energy Strategy defining Australian energy priorities.

RECOMMENDATION 7

International Participation

Australia should actively seek to participate in international programs where nanotechnologies are being applied to energy systems.

Links with IEA and OECD need to be strengthened together with the US and Asia. In particular, Australia's strong role in the APEC Energy Working Group offers an excellent opportunity to work with countries around the Pacific rim.

RECOMMENDATION 8

Codes and Standards

Australia must continue to play an active role in the formulation of international codes and standards relating to nanotechnologies to ensure that Australia is not disadvantaged in exploiting locally developed technologies and nanomaterials in its energy systems

Intense international activity is occurring as new standards for nomenclature of nanomaterials, nanometrology, and health and safety issues associated with nanomaterials are being developed through the International Standards Organisation. Standards Australia has set up a National Committee to input to ISO.

Implementation of these recommendations will provide a strong base from which Australia can exploit the benefits of the application of nanotechnologies in current and future energy systems and contribute to allaying national concerns over security of supply, sustainability of resources and impacts of climate change associated with increased use of fossil fuels.

Acknowledgements

The Australian Academy of Technological Sciences and Engineering (ATSE) wishes to express its thanks to those Fellows and other experts who contributed to the preparation of the report. The four ATSE Workshops that were held in Brisbane, Sydney, Melbourne and Canberra (see Appendices A and B) provided many new insights.

A Steering Committee, composed of Fellows and invited experts, was established to provide oversight of the project. The Steering Committee also provided many valuable suggestions to steer the report through several iterations to its final format. The Steering Committee comprised the following members:

- Mr Peter Laver AM FTSE (Chair)
- Dr Vaughan Beck FTSE
- Dr Peter Binks
- Professor Andrew Blakers FTSE
- Dr Calum Drummond FTSE
- Professor Max Lu FTSE
- Professor John Ralston FAA FTSE
- Dr John Soderbaum
- Professor Greg Tegart AM FTSE

The Project was established and managed for ATSE by Dr Vaughan Beck, FTSE, Technical Director, ATSE. The production of this publication was overseen by Mr Bill Mackey, Communications Director, ATSE.

The Australian Academy of Technological Sciences and Engineering gratefully acknowledges the funding provided by the Australian Research Council (ARC) under the Linkage Learned Academies Special Projects program to support the conduct of this project.

CONDUCT OF STUDY

Each year the Australian Research Council invites bids from the four Learned Academies in Australia to propose projects for funding under the Linkage Learned Academies Special Projects Scheme. These are aimed to utilise the expertise of Fellows of the Academies in broad-ranging topics relevant to Australia. In 2007 the Australian Academy of Technological Sciences and Engineering (ATSE) was awarded a grant on the potential for application of nanotechnologies in future energy systems for Australia.

The aim of this project was to bring together energy and nanotechnology researchers and technologists to produce a definitive report on breakthrough energy solutions based on nanotechnology and to examine routes to commercialisation. Because of the broad membership of ATSE with Fellows elected from leaders of industry, industrial researchers, academics and Government researchers, there was a unique span of expertise to draw on when considering such a forward-looking, cross-disciplinary project.

Professor Greg Tegart AM FTSE was the Principal Lead Investigator with Professor Max Lu FTSE as Co-Lead Investigator. A Steering Committee was established and consisted of Academy Fellows and external experts.

Based around a short review paper, workshops were held in Brisbane, Melbourne, Sydney and Canberra with attendances of Fellows and invitees, while a questionnaire was circulated more widely with some 60 responses. The expert opinions expressed in the discussions have been explored further through an extensive literature survey.

Four meetings of the Steering Committee considered drafts of the report.

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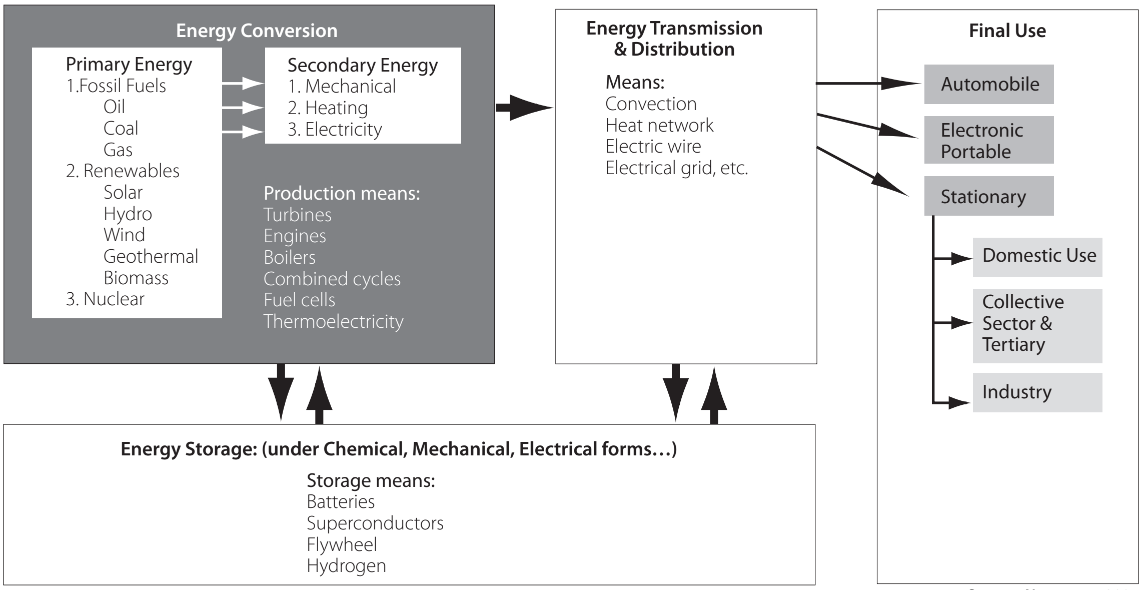
1 Introduction

1.1 ENERGY CONCERNS

Energy is an essential input into virtually every aspect of human activity and the increasing world population and the rising standards of living of many developing countries mean that the world energy demand will continue to increase for the foreseeable future despite efforts in the developed countries to contain their energy demand.

Energy patterns are complex because energy sources are not typically in a form suitable for end use. The energy system can be divided into two areas: the first associated with extraction and conversion of non-renewable and renewable energy resources, and the second with the distribution, storage and use of the converted energy. The details of these areas are set out in Figure 1 and aspects of these are examined in this report.

Figure 1. The components of the energy system



Source: Naumanen 2004

The critical role of energy in economic and social activity has prompted numerous studies to examine global and regional energy futures and to identify future energy sources and technologies to cope with projected increased demands (IEA 2003, APEC CTF 2006, IEA 2006, IAC 2007, WEC 2007, Wehnert *et al* 2007). In considering energy futures, three major concerns have been identified:

- security and sustainability of energy supply;
- the link between combustion of fossil fuels and climate change; and
- availability of technological innovation in energy conversion, transmission and use.

In the case of **security and sustainability of supply** of non-renewable energy resources the international community has faced a most difficult energy market in the past two decades. Oil price volatility has experienced record swings, with prices reaching more than US$100 per barrel. The future stability of the Middle East, with 60 per cent of the world's known reserves, remains uncertain. Guaranteed energy resources are vital to sustain worldwide economic growth, social progress and security. The rate of growth in demand, particularly in India and China with increased populations and rapid economic development, runs the risk of outpacing supplies unless we increase not only conservation and evolutionary improvements to existing technologies, but also develop new approaches in the energy field.

The need for breakthrough energy solutions is all the more important because most scientists have become increasingly convinced that the consequences of continuing to burn fossil fuel at current or expanded rates will lead to significant **climate change**. The Intergovernmental Panel on Climate Change (IPCC) has been studying the role of anthropogenic inputs on climate change since 1988 and has issued a series of reports detailing the sources leading to increases in the atmospheric concentrations of a number of gases, particularly carbon dioxide and methane (so-called greenhouse gases)(IPCC 2007). These have been associated with changing the radiative balance of heat in the Earth's atmosphere. This change has been linked to increase in global surface temperature over the past few decades and changes in rainfall patterns and increase of sea levels. The increasing combustion of solid, liquid and gaseous fossil fuels has been identified as the major source of the increasing carbon dioxide concentration. Such predictions have led to calls for limitation of carbon dioxide emissions by developing and applying low-emission technologies for use of fossil fuels, particularly coal, and by developing new approaches to energy production and use based on renewable sources of energy.

The role of **technological innovation** is critical in such developments. In July 2005 the leaders of the G8 group of nations addressed the concerns posed by future energy needs and agreed on a plan of action. They requested the International Energy Agency (IEA) to produce a detailed analysis of key energy technologies over the next 50 years and, in particular, how these technologies could be deployed to achieve climate stabilisation by 2050. The report was published in 2006 (IEA 2006). The IEA report uses so-called Accelerated Technology (ACT) scenarios to demonstrate that, by employing technologies that already exist or are under development, the world could be brought into a much more sustainable energy path. The scenarios indicate that energy-related CO_2 emissions could be returned to their current level by 2050 while energy efficiency measures could reduce projected electricity demand by about a third. The substantial changes in such scenarios are built around:

- strong energy efficiency gains in the transport, industry and buildings sectors;
- electricity supply becoming significantly decarbonised as the power-generation mix moves towards nuclear power, renewable energy sources, natural gas and coal with CO_2 capture and storage; and
- increased use of biofuels for road transport.

Three major concerns in meeting future world energy demand are: security and sustainability of energy supply, the link between combustion of fossil fuels and climate change and the availability of technological innovations in energy conversion, transmission and use. There is no single technological "silver bullet" to solve the world's energy concerns. An integrated approach is needed in which various energy technologies can make significant contributions.

1.2 KEY TECHNOLOGIES OF ENERGY PRODUCTION AND USE

The recent OECD/ IEA report (IEA 2006) sets out a detailed review of current and future technologies for energy production and use. There is a range of views on the timing of energy technology development and diffusion and Table 1 shows one view for transport and energy production technologies (Sheehan *et al* 2007).

Four aspects of Table 1 are important.

First, a wide range of technologies currently in extensive use or in the early stages of diffusion could substantially reduce energy use and/or emissions if they were extensively used. Examples shown include hybrid electric vehicles, combined heat and power systems, and wind.

Second, few major new technologies are undergoing large-scale focused development. New products and processes need critical mass to reduce costs to competitive levels, but achieving this is constrained by long asset lives for existing plants and by the number of competing technologies. A radical change of policy is needed to ensure that new major technologies that could change either energy use or emissions intensity of energy production are likely to be widely used before 2030.

Third, by 2030 many technologies – such as ultra-lightweight hybrid or fuel cell vehicles, improved building systems, advanced fossil fuel power generation, carbon capture and storage and a variety of renewable energy technologies – are likely to be available. By about 2050 the most successful of these should be mature with growing market share.

Fourth, other technologies, including advanced hydrogen technologies and nuclear fusion, may become commercially viable after 2050.

Table 1. The Status of New Technologies for Energy Production and Use

Transport	Non-renewable Energy	Renewable Energy
Currently in commercial use – diffusion underway		
Biofuels from sugar Hybrid electric vehicles Advanced two-stroke engines Other technologies for road vehicles and aircraft	Efficient power plants Combined heat and power (CHP) systems	Wind energy – onshore Solar photovoltaics Geothermal energy
Commercially available – diffusion beginning		
Lightweight materials Electronic road pricing Advanced transit systems	Advanced sensors and controls Improved electricity transmission/ distribution Advanced gas turbines	Advanced hydropower systems
Commercial prospects beyond 2030		
Biofuels from cellulosic fibres Fuel-cell road vehicles Intelligent vehicle highway systems Self-driving cars Ultra lightweight vehicles	Advanced CHP systems Power electronics Integrated energy production and use systems (energyplexes) Superconducting cables Carbon capture/storage	New designs for nuclear power Advanced bioenergy and biomass systems Hydrogen from fossil fuels Advanced solar photovoltaics energy storage Solar thermal energy Wave, offshore wind energy, marine currents Geothermal hot dry rock Integrated hydrogen systems and storage
Commercial prospects beyond 2050		
Hydrogen-fuelled aircraft Alternative fuel marine vessels New urban freight systems	Wide diffusion of energyplexes Diffusion of carbon capture and storage technologies	Nuclear fusion technologies Trapping the ocean salt-gradient New hydrogen production methods Solid hydrogen storage

Source: Sheehan *et al* (2007)

To reinforce the points made above regarding infrastructure lifetimes being a major factor in the rate at which new technologies enter the economy, Table 2 shows some indicative lifetimes.

Table 2. Typical Infrastructure Lifetimes

Infrastructure	Expected lifetime (years)
Hydro power plant	75+
Commercial building	45+
Coal-fired power plant	45+
Nuclear power plant	30-60
Gas turbine	25
Motor vehicle	12-20

Source: Energy Futures Forum 2006

Many technologies are potentially available for energy production and use and thus countries need to make priority decisions about the mix of technologies to ensure security and sustainability in their energy supplies. Ideally these should be low carbon emission solutions to minimise the impacts of rapid climate change.

1.3 THE AUSTRALIAN SITUATION

(Energy Futures Forum 2006, Kaspura 2007)

Australia has large energy resources, particularly of fossil fuels. Thus black coal reserves have a potential life of 100 years and brown coal of 500 years. Natural gas reserves are about 60 years while oil is declining rapidly. Uranium reserves are sufficient for about 50 to 100 years. These resources have been exploited to provide energy at low cost as a major driver of economic growth. Current contributions from renewable energy sources such as hydro, biomass and wind are small.

National energy policy stresses energy competitiveness, energy security and energy sustainability (Australian Government 2004). There is a need to improve efficiency of existing energy use and to develop new energy sources. In considering technology options for Australia's energy future the 2004 Energy White Paper (Australian Government 2004) made an assessment of the possibilities for Australia to utilise the technologies listed in Table 1.

The assessments are listed in Table 3 in three broad categories:

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

These assessments were seen as a strategic framework when assessing innovation priorities for energy.

Table 3 Assessments of Technologies as Possibilities in Australia

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

Source: Australian Government (2004)

An approach to future energy production and use based on a range of technology options for fossil fuels and renewable energy sources offers substantial social and environmental benefits to Australia. The development of low-emission technologies for fossil fuel combustion would support continuing exports of black coal, while new approaches to energy production and usage such as solar and wind could lead to development of new industry sectors based on advanced technology.

2 A Role for Nanotechnologies

2.1 SCIENCE AND TECHNOLOGY AT THE NANOSCALE (NAF 2006)

We are at the start of a new era in creation and application of materials. This has resulted from the convergence of the traditional fields of chemistry, physics, biology and engineering to form the new field of nanotechnology. This is the term given to those areas of science and engineering where phenomena that take place at dimensions in the nanoscale (a nanometre is one billionth of a metre) are utilised in the design, characterisation, production and application of materials, structures, devices and systems. At this size level, materials show different physical, chemical and biological properties. Although many technologies have incidentally involved nanoscale structures for many years, it is only in the past two decades that it has been possible to actively and intentionally modify molecules and structures within this size range. For example, the feature sizes on silicon chips are now about 60nm; nanoparticles of zinc oxide used in transparent sunscreens are about 30nm.

The report of the Royal Society/Royal Academy of Engineering in the UK (RS/RAE 2004) has the following definitions:

- *Nanoscience* is the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.
- *Nanotechnologies* are the design, characterisation, production and application of structures, devices and systems by controlling shape and size at nanometre levels.

The significant feature is that nanotechnology is a set of tools and processes for manipulating matter at the nanometre level which can be applied to any manufactured product. There is considerable confusion over the concept of a nanotechnology industry. It needs to be stressed that there is no discrete nanotechnology industry but a set of different industry sectors, each with its discrete set of issues, particularly in the production and use of nanomaterials.

Creative materials and surface science is critical to further advancement of nanotechnologies. One of the interesting properties of particles of materials such as metals or ceramics at the nanometre size level is their very high surface area per unit volume which has potential for speeding up catalytic reactions and biochemical and pharmaceutical separations, and thus improving the efficiency of many processes. Reduction in size to the nanoscale level results in an enormous increase of surface area, so that relatively more atoms or molecules are present on the surface, thus enhancing the intrinsic reactivity. The definition of nanoparticles as being less than 100nm is perhaps too simple, since it does not take account of the dramatic size effects in the range below 100nm. For example, a particle of size 30nm has 5 per cent of its atoms on its surface, at 10nm 20 per cent of its atoms and at 3nm 50 per cent of its atoms.

Nanomaterials can be produced from a variety of material classes as: carbon-based nanomaterials, nanocomposites, metals and alloys, biological nanomaterials, nanopolymers, nanoglasses and nanoceramics. Each covers a wide range of different chemical compositions and of hazardous and non-hazardous forms. Some of these are manufactured and sold in bulk to intermediate companies making specialised products while others are manufactured as part of an integrated production process.

Most of the material classes can be produced in a variety of shapes as: nanoscale in one dimension (for example, thin films, layers and surfaces); nanoscale in two dimensions (for example, nanowires and graphene sheets which can be rolled into nanotubes); nanoscale in three dimensions (for example, nanoparticles of regular or irregular shape, fullerenes [spherical molecules about 1nm in diameter, comprising 60 carbon atoms arranged in a cage structure], graphite sheets, dendrimers [polymeric molecules] and quantum dots [small nanoscale particles of semiconductors whose optical properties can be controlled by size]). Such nanomaterials are generally produced by the 'bottom-up' approach – building-up from individual atoms or molecules through chemical synthesis self-assembly or positional assembly; another route is the 'top-down' approach – breaking-up bulk materials into nanoparticles through grinding, milling or precision etching.

Products based on nanomaterials are already widely used (for example, paints, pharmaceuticals, microelectronic devices and composite materials) and the global markets are estimated to be worth more than US$40 billion. The seven largest areas of current demand are: IT peripherals, medical and biomedical applications, automotive and industrial equipment, telecommunications, process control, environmental monitoring and household products. Rapid market growth in these and new areas is anticipated, possibly to US$1 trillion by 2015–20 (see Chapter 6).

Nanotechnology is engineering at the molecular (groups of atoms) level. It is the collective term for a range of technologies, techniques and processes that involve the manipulation of matter at the smallest scale (from 1 to 100nm). The potential markets are enormous.

2.2 OPPORTUNITY AREAS FOR APPLICATION OF NANOTECHNOLOGIES TO ENERGY PRODUCTION AND USE IDENTIFIED IN OVERSEAS STUDIES

There is a growing awareness overseas that nanoscience and nanotechnologies can have a profound effect on energy generation, storage and utilisation by exploiting the significant differences of energy states and transport in nanostructures. The root of the opportunities provided by nanotechnologies to impact our energy security is the fact that all the elementary steps of energy conversion (charge transfer, molecular rearrangement, chemical reactions, etc) take place on the nanoscale. Thus the development of new nanoscale materials, as well as the methods to characterise , manipulate and assemble them, creates an entirely new paradigm for developing new and revolutionary energy technologies.

The global focus on nanotechnology applications in energy is growing. An EU Nano Road Map exercise in 2005 (ION 2006) identified areas of significant impact as: solar cells, thermoelectricity, batteries and supercapacitors, and insulation. These areas were also identified in a UK report in 2005 (Technology Tracking 2005) as solar cells, hydrogen storage, supercapacitors and rechargeable batteries. Another UK report examining environmentally beneficial nanotechnologies identified fuel additives, solar cells, the hydrogen economy, batteries and supercapacitors, and insulation as the five most attractive areas for reduction of greenhouse gas emissions (Oakdene Hollins 2007). This pattern is reinforced by another UK analysis (Cientifica 2007b) which identifies the market as: energy conversion – hydrogen fuel cells and thin film and organic photovoltaics; energy storage – batteries, hydrogen storage and supercapacitors; energy use – insulation, solid state lighting, reduction of vehicle weight and improved combustion of fossil fuels.

Possible applications of nanotechnologies in the areas of the energy system in can thus be identified as:

- energy conversion – solar cells, thermo-electric devices, catalysts for conversion, environmental management, fuel cells, hydrogen production, carbon dioxide capture;
- energy storage – supercapacitors, batteries, hydrogen storage;
- energy transmission – superconducting systems, hydrogen distribution; and
- energy use – conservation in industry and construction, materials for transport, fuel cells, catalysts for combustion.

The Environmental Protection Agency in the US has recently given an estimate of the potential energy savings in the US from application of nanotechnologies as shown in Table 4.

Table 4. Potential US Energy Savings from Eight Nanotechnology Applications

Nanotechnology application	Estimated Reduction in Total Annual US Energy Consumption (%)
Strong, lightweight materials in transport	6.2
Solid state lighting (such as LEDS)	3.5
Self-optimising motor systems	2.1
Smart roofs (temperature-dependent reflectivity)	1.2
Novel energy efficient separation membranes	0.8
Energy-efficient distillation through supercomputing	0.3
Molecular-level control of industrial catalysis	0.2
Transmission line conductance	0.2
Total	**14.5**

Source: EPA (2007)

A recent major conference in the US (Rice University 2005) identified a number of grand challenges in which nanotechnologies could contribute to improve economics and performance of energy systems as:

- lower the costs of photovoltaic power tenfold;
- achieve commercial photocatalytic reduction of CO_2 to methanol;
- develop a commercial process for direct photo-conversion of light and water to produce hydrogen;
- lower the cost of fuel cells between tenfold and a hundredfold with new materials;
- improve the efficiency and storage capacity of batteries and supercapacitors between tenfold and a hundredfold for automotive and distributed generation situations;
- develop new lightweight materials for pressure tanks for hydrogen storage and an easily reversible hydrogen chemisorption system;
- develop power cables to enable more efficient transmission of electricity;
- develop commercial thermochemical processes with catalysts to generate hydrogen from water at temperatures below 9000°C;
- develop efficient lighting to replace incandescent and fluorescent lights;
- develop materials that will enable deep drilling at lower costs to tap energy resources, including geothermal heat, in deep strata; and
- develop CO_2 mineralisation methods that can work on a large scale without waste streams.

These are ambitious targets and a breakthrough on the scale posed is unlikely in the near term for many of them. However they provide a framework for countries to make choices on the most promising areas for research and development in their national innovation systems.

Two approaches to quantifying the impact of nanotechnologies in these technology areas on CO_2 emissions have been reported recently (Oakdene Hollins 2007, Cientifica 2007a). Thus Cientifica takes a short-term approach and suggests that available technologies have the potential to directly reduce world carbon emissions by over one million tons by 2014, chiefly through weight savings and improved combustion in transport applications and through improvements in building insulation. Oakdene Hollins is more optimistic and suggests that, in the UK, the nanotechnologies listed in Table 5 have the potential to reduce emissions with available technologies by about six million tonnes CO_2 per annum in five to eight years (about two per cent of emissions). In the longer term up to 2050, about 20 per cent is seen as a possible saving from improved storage and a hydrogen economy. These rough estimates are only a small fraction of the projected emissions but represent a lower limit since breakthroughs could provide further savings.

Table 5. Assessment of Some Environmentally Beneficial Nanotechnologies in the UK

Application	Impact of nanotech in area[1]	Infrastructural changes[2]	Benefit (Mte CO_2 per annum)[3]	Timescale for implementation (years)[4]
Fuel efficiency	Critical	Low	< 3	< 5
Insulation	Moderate	Low	< 3	3-8
Photovoltaics	High	Moderate	c. 6	> 5
Electricity storage	High	High	10-42	10-40
Hydrogen economy	Critical	Very High	29-120	20-40

Notes:
1. Impact of nanotechnology describes the effect nanotechnology is likely to have in the area compared to other technologies.
2. Infrastructural changes indicate the effort to bring the nanotechnology to market.
3. Benefit is the maximum potential CO_2 saving by implementing the technology.
4. Timescale for implementation is the estimated time to full implementation.

Source: Oakdene Hollins (2007)

Nanotechnologies have the potential to make a contribution to the improvement of current energy systems and to the development of new ones. Initially these contributions are likely to be small but there is potential for major growth and the challenge is for each country to select the areas where its R&D can be best directed. A corollary is that the contribution of nanotechnologies to the reduction of greenhouse gas emissions will be small initially but has the potential to grow enormously over the next decades.

2.3 IDENTIFICATION OF OPPORTUNITY AREAS FOR APPLICATION OF NANOTECHNOLOGIES IN ENERGY IN AUSTRALIA

ATSE conducted a study to identify areas of opportunities for the application of nanotechnologies in Australia (see "Conduct of Study"). To assess the most promising areas for application of nanotechnologies in energy in Australia, all the possibilities raised in Section 2.2 were compared using a matrix approach, rating several significant factors as listed below:

1. Potential market in Australia for the technology area,
2. The potential contribution of the area to reduction of CO_2 emissions,
3. The contribution of nanotechnologies to developing more efficient systems,
4. The capability in R&D in nanotechnologies in the area,
5. The capability to manufacture systems involving nanotechnologies in Australia, and
6. The long-term potential beyond 10 years which demands a strategic investment in the area.

These were rated on the basis of the next five to 10 years as L (low), M (medium), H (high); the results are shown in Table 6.

Table 6. Assessment of Technology Areas in the Australian Context in Next 10 Years

Technology Area	Market in Australia	Contribution to CO_2 reduction	Contribution of nanotech	R&D capability	Manufacturing capability	Future potential
ENERGY CONVERSION						
Photovoltaic Cells	M	M	H	H	L/M	H
Thermoelectric devices	L	L	M	L	L	L
Catalysts for conversion	M/H	M	H	L	L	H
Environmental management	M/H	M	L/M	L/M	M	H
Fuel Cells (stationary)	M	M	L/M	M	L/M	M
Hydrogen production	L	L	L/M	L	L	M/H
CO_2 capture and storage	H	H	L/M	H	L/M	H
ENERGY STORAGE						
Supercapacitors	L/M	L	L/M	M	L/M	M
Batteries	H	M	L/M	M/H	M	H
Hydrogen storage	L	L	M/H	L/M	L	H
ENERGY TRANSMISSION						
Superconducting systems	L	L	L	L	L	M
ENERGY USE						
Energy conservation	H	H	M	L/M	L	H
Materials for transport	H	H	H	M/H	L	H
Fuel cells (transport)	L	L	M	M	L	H
Catalysts for fuel combustion (transport)	H	L/M	H	L	L	H

This assessment, together with the discussion of current nanotechnology activities in Australia that were held in as part of four ATSE Workshops (see Appendix B for details; Appendix A provides a list of the workshop attendees), identified the opportunities for applications of nanotechnologies in the energy area in Australia as follows:

- short term (less than 5 years) – energy conservation, environmental management, catalysts for combustion, photovoltaic cells;
- medium term (5 to 15 years) – catalysts for conversion of biomass, gas and coal, fuel cells, advanced photovoltaics using engineered nanomaterials; and
- long term (greater than 15 years) – hydrogen production, storage and use.

These opportunities are discussed in the following chapters.

3 Short Term Opportunities for Australia

3.1 ENERGY CONSERVATION (ION 2006, Oakdene Hollins 2007)

We consider here the areas of transport, insulation and lighting .

3.1.1 Transport

Nanocomposite materials have applications as lighter, stronger materials, particularly in the transport sector, to reduce weight and hence fuel consumption and greenhouse gas emissions.

The traditional automotive industry rule is that a 10 per cent reduction in weight gives a 5 per cent increase in fuel efficiency, but the adoption of composites across the vehicle from engine parts to body panels has increased this saving (Cientifica 2007a). Thus a 10 per cent reduction in weight now leads to a 10 per cent saving in fuel. Polymer and clay composites have been trialled in vehicles.

Carbon nanotubes are attractive as reinforcements in metals and polymers but availability and cost are the main obstacles to widespread use. This point highlights the need for substantial investment in production plants able to cheaply produce large quantities of nanomaterials in order to gain benefits. Given that sufficient nanomaterials become available the potential market is estimated to be about 40 per cent of the vehicle materials mix by 2015 (Frost and Sullivan 2004).

The benefits of weight reduction on emissions can be further realised if coupled to a hybrid or electric vehicle. Current hybrid vehicles can reduce petrol consumption by about a third. The critical factor is energy storage either in batteries or in supercapacitors. In both of these areas, nanotechnologies offer promise to increase performance. Thus nanostructured electrodes for batteries are being developed to speed up charging (Oakdene Hollins 2007).

It is likely that increasing numbers of vehicles using composite (increasingly nanocomposite) materials will be imported into Australia but that large-scale application of nanocomposites in automotive manufacture in Australia will take considerable time to introduce. Substantial experience in polymer composite fabrication and design exists through the CRC for Advanced Composites Structures – and in aerospace component manufacturers. Hybrids and electric vehicles are being imported in small numbers but large-scale manufacture in Australia is unlikely in the short term. CSIRO, through its Energy Transformed Flagship, has capability in concept car design and batteries and has links to the automotive industry. CSIRO has a strong capability in nanomaterial development.

3.1.2 Insulation

Thermal insulation is incorporated into buildings to reduce heat transfer either by reducing internal temperatures during summer and hence air conditioning loads or to maintain high temperatures during winter and hence reduce power. There are two ways of achieving this reduction: using a porous material which traps air, or applying a coating to reflect heat, particularly on glass. Traditional mass insulation products are glass fibre, rock wool, slag wool and cellulose and these are being upgraded to improve insulation (for example, by coating fibres to maintain air spaces).

An attractive alternative are aerogels which are low-density and highly porous materials with nanoscale pores. They are not new but there is considerable activity in Europe to produce carbon and silica aerogels which are used in specialised applications. Transparent aerogels have been produced and may find use as fire-resistant windows. Costs are still high but can possibly be reduced. There does not appear to be any activity in Australia but the potential applications are attractive in reducing energy consumption.

The major advance in glazing technology in recent years has been in the use of large-area, low-cost, multilayer nanoscale coatings. Initially the main aim was to provide a transparent coating but this has expanded into the development of spectrally sensitive films which respond to their environment so-called Smart Glazing. This is the term coined for glass that reacts and responds to its environment primarily by altering its transparency and translucency. This alteration in opacity can have great energy saving effects.

Smart Glazing can be classed as either thermochromic, whereby it responds to temperature changes, or photochromic, whereby it responds to alterations in light intensity. The former can be used to block solar gain and reduce air conditioning loads. The latter alters the transmitting properties of the glass and on sunny, cold days absorbs solar heat and transmits to the interior, reducing heating loads. Another type of smart glazing is electrochromic where the transmission through a film (often of tungstic oxide) is altered by application of a voltage. These are being actively researched and commercialised in Europe and the US.

In Australia in 2004 such products were demonstrated in a joint CSIRO and University of Technology project, the Nanohouse, which showcased a number of nanoproducts aimed at reducing energy consumption by up to 50 per cent. This activity has ceased and there is little basic or applied research in this area in Australia. Given the significant potential contribution of energy conservation to reduction of greenhouse gas emissions, work on nanosensors and nanocoatings to control heat and light transmission needs to be encouraged.

However there has been development in industry. In late 2006 Pilkington (Australia) Ltd, which has a major manufacturing plant in Victoria, announced the investment of $130 million in a new batch plant and an advanced coating line. The upgrade incorporates a state-of-the-art, five-beam chemical vapour deposition coater, which will enable production of new environmentally efficient glass products including energy-saving glass for buildings, self-cleaning glass and glass for solar energy systems. The coatings technology is based on the application of nanometre-thick films which can be varied to control heat and light transmission. An R&D centre is being set up in Victoria to support further development.

Pilkington will manufacture a self-cleaning glass which is marketed in Europe and North America under the trade name Pilkington Activ. This acts in two stages – the first stage is photocatalytic, in which a titanium dioxide nanocoating reacts with UV radiation from sunlight to oxidise and break down organic dirt. The second stage is hydrophilic, in which the rainwater forms an even sheet on the glass instead of forming droplets and thus washes away the loosened dirt, drying evenly. This technology reduces cleaning costs and the use of chemical cleaners.

3.1.3 Lighting

Between 60 and 80 per cent of electricity is used to power light bulbs. Conventional bulbs only use about 10 per cent for light with the rest dissipated as heat. To improve efficiency of lighting, attention has been focused on ‘next-generation’ lighting based around light emitting diodes (LED). These have been present in consumer products for some time in Japan and US and are being used in traffic lights and road signs. The potential world market for LED technology in commercial and domestic markets is enormous. One estimate is US$1 billion per annum. Current LED technology is based on silicon chips and the challenge is to reduce costs. One possibility is organic LEDs which are made of 100nm organic layers. These are very cheap and can be produced in large areas.

In Australia there has been work on light pipes – plastic rods containing LEDs – at University of Technology, Sydney. These have applications in commercial and emergency lighting and are manufactured in Queensland by Poly Optics. Given the considerable expertise in organic films in Australia there appears to be scope for more research on organic LEDs.

Research at Macquarie University has led to the development of a low-temperature growth process for depositing gallium nitride on glass instead of sapphire as the basis for very efficient LEDs. This could lead to significant cost reductions, with greater light efficiency than fluorescent lights, and the process is being developed by BluGlass, a company spun out of Macquarie University (Butcher 2008).

There are immediate opportunities in Australia for substantial energy savings using available technology but these can be amplified by the increased application of nanotechnologies in transport and domestic and commercial construction. Research on lightweight nanocomposite structures and nanosensors needs to be strengthened.

3.2 ENVIRONMENTAL MANAGEMENT – WATER REMEDIATION

A major driver for environmental management of current energy systems is clearly the need to reduce emissions of greenhouse gases to mitigate the impacts of climate change. Another driver is the reduction of pollution in cities from a range of combustion products from mobile and stationary sources and yet another important factor is the supply of suitable water for cooling in thermal and nuclear power stations. Nanotechnologies can play a role in all of these. The approach to capture and storage of CO_2 will be discussed in Chapter 4 as a medium-term option and approaches to dealing with air pollution through catalysts are discussed in the next section. Here we concentrate on the issue of water remediation.

The recent droughts in the US and Australia have highlighted the vulnerability of current power stations to adequate supplies of water in that stations have been forced to shut down or run at substantially reduced capacity due to lack of water (EPRI 2007b). The power plants of several decades ago used once-through cooling – a process which takes the water, uses it to condense steam from the turbine and returns it to the original water source some 10°C warmer. Some 30 per cent of power plants in the US still use this process (see life of plants in Table 2). Newer units have used evaporative cooling towers for so-called 'wet cooling' which withdraws less than 5 per cent of the water used for once-through cooling.

The result is that power generation accounts for roughly 40 per cent of freshwater withdrawals in the US, but only accounts for about three per cent of consumption. However, the once-through plants need the withdrawal to operate and thus may have to shut down in droughts. Dry and hybrid cooling methods have been developed but these bring higher prices for electricity in terms of higher capital cost and reduced efficiency of operation.

Water already used in the plants can be recycled to reduce overall water usage. This water is usually contaminated but nanotechnologies offer possibilities for treatment using membranes. A major potential market is desalination of seawater. Research shows that gas and water flow more rapidly through membranes that use carbon nanotubes as pores than through conventional membranes with 10 times larger (Anon 2007a). There is potential for selective separation of molecules.

In Australia there is a major thrust on water research in CSIRO through the Water for a Healthy Country Flagship. An initiative of this Flagship has been the establishment of the Advanced Membrane Technologies for Water Treatment Cluster. This brings together scientists from CSIRO and nine universities to work cooperatively on eight research themes. Three of these are aimed at new membrane materials based on nanomaterials, including biomimetic materials at UNSW, zeolite nanocrystals at Monash and oxide nanocrystals in ion-conducting polymers at the University of Queensland.

Research on nanomaterials for membranes for water purification will offer opportunities in Australia for more efficient use of energy both in recirculation of water in power plants and in recycling of water for domestic and industrial needs.

3.3 CATALYSTS FOR PROCESSING AND COMBUSTION OF FOSSIL FUELS

Most secondary energy use such as electricity, heat or transport is currently produced by combustion of coal, gas or petroleum products. Considerable room for energy savings is possible as both production of these fuels and their combustion are inefficient processes. Catalysts are widely used in the production of these fuels and also in large-scale manufacture of chemicals. Fuel processing is a good example in that the petrol in cars requires at least 10 different catalysts during its production from crude oil.

In heterogeneous catalysis the reacting molecules adsorb on the catalytically active solid surface and reaction takes place there. Zeolites with nanopores have been used for decades but most of the heterogeneous catalysts used in industry today consist of small particles of a catalytically active material, typically with a diameter of 1 to 10nm, anchored on a porous support. The use of nanoparticles results in a large contact area between the active material of the catalyst and the surrounding gas or liquid phase. This ensures that the catalytic material is used effectively.

Maximising the surface area is not the only reason for using nanoparticles as heterogeneous catalysts. As noted earlier, materials can change properties dramatically from the macro to the nanometre scale and new opportunities are opened up. For example, gold is considered chemically inert but research has shown that that nanosized particles (less than 5nm) can be very effective catalysts (see review by Hvolbaek *et al* 2007). Such materials can improve energy efficiency in processing and also in combustion by reducing emissions and lowering the volume of industrial waste by using lower temperatures for shorter periods. The possibilities for engineered nanocatalysts with pore sizes in the 1nm range are extremely large.

An innovative strategy is to use nanoparticles as additives in fuels to improve combustion efficiency and reduce emissions. A commercial system, Envirox, based on cerium oxide, has been developed for diesel fuels in the UK by Oxonica Ltd. Long term trials in the UK have indicated improvements in fuel efficiency up to 10 per cent and a reduction in soot emissions of about 15 per cent . The catalyst is blended into diesel fuel at about five ppm and changes the burn pattern of the fuel. Concern has been expressed that ceria nanoparticles may be discharged from the exhaust but it appears that the cerium oxide decomposes under the heat and pressure of combustion. There is potential for large reductions in carbon particulates and in CO_2 emissions (Oakdene Hollins 2007). In the vehicle area the penetration of nanomaterials into the catalysts and fuel additives market is anticipated to be about 70 per cent by 2015 (Frost and Sullivan 2004).

In Australia there is little manufacturing capability as most catalysts are imported and most research is carried out in the US and Europe. However, there are strong groups at the University of NSW and University of Queensland, which are linked to the ARC Centre of Excellence in Functional Nanomaterials. An emphasis is on the production of TiO_2 nanocatalysts by different techniques. There is also research on the structure of nanocatalysts at several universities. This area links to the work in Chapter 5.1.

The fuel additives are not available in Australia yet but the initial supplies of cerium oxide for Oxonica were produced by an Australian company, Advanced Technology in Perth. Recently Oxonica have had problems with a major contract in Turkey but Advanced Technology are now supplying another company, Energenics in Singapore.

The use of nanocatalysts as fuel additives has considerable potential for reduction of greenhouse gas emissions from transport in Australia and research in this area needs to be strengthened.

3.4 PHOTOVOLTAIC CELLS

(Naumanen 2004, ION 2006, Oakdene Hollins 2007)

Photovoltaic technologies offer a potentially unlimited source of emission-free, renewable energy by converting sunlight into energy. The efficiency of this process depends on the conversion technology and the geographic location. A photovoltaic solar cell consists of a diode made of semiconducting materials sandwiched between two electrical contact layers. Sunlight passes through the top contact layer, is absorbed by the semiconductor and generates electrons and holes, which diffuse to the different contacts. The electrons and holes are separated by the diode and these charges drive a current in the circuit. The spectrum of light which can be utilised depends on the materials used.

The global market for photovoltaic cells is growing exponentially by an average of 48 per cent each year since 2002 and in 2006 was valued at US$15 billion. The top five PV-producing countries are Japan, China, Germany, Taiwan and the US. Recent growth in production in China is most astonishing: after almost tripling production in 2006, it is believed to have more than doubled output in 2007. Some 90 per cent of this is exported, mainly to Germany and Spain. The demand in Germany has been stimulated by a feed-in tariff scheme which guarantees a premium for renewable electricity generated over a 20-year period. The extra costs involved are spread among all consumers adding less than 0.1 Euro cents per kW/hr to the average bill. The scheme has stimulated investment in manufacturing facilities and created 10,000 jobs (Green 2007).

The current world market is dominated by silicon solar cells which command about 90 per cent of the market. This can be broken down into polycrystalline silicon (58 per cent), single crystal silicon (32 per cent) and thin films (seven per cent). This reflects the balance of efficiency against price in applications. Thus single crystal silicon is slightly more expensive than polycrystalline but single crystal cells are slightly more efficient. Silicon cells are coupled together in modules for power generation. The efficiency of silicon solar cells can be increased by concentrating light using focused collectors. These systems use tracking devices to ensure optimum exposure.

There is a shortage of hyperpure silicon caused by rapid and sustained development of the industry. This shortage has led to an acceleration of activity on thin films based on materials such as copper indium diselenide or cadmium telluride, which are cheaper per square metre but currently are less efficient (about eight to nine per cent). There is potential for improvement by adding other elements, (for example, gallium). They can be applied to different substrates, often flexible, and used over large areas as integrated building panels. Such materials are in production in the US.

Thin crystalline silicon solar cells, using less than 10 per cent of the normal amount of silicon, are the subject of substantial research, notably in Australia. These cells offer opportunities for reducing the demand for hyperpure silicon. SLIVER solar cell technology, where very thin slices are cut from wafers, is one approach while crystalline silicon-on-glass technology, where the active silicon layer is deposited directly onto glass, is another

A longer-term alternative for cost reduction is Dye Sensitised Cells (DSC) or Graetzel cells, after Professor Graetzel who announced the principle in 1991.These consist of thin layers of titanium dioxide nanoparticles onto which organic ruthenium dye molecules are adsorbed which are sandwiched between two substrates, one of which is transparent, and an aqueous or gel-like electrolyte. The process of energy conversion is analogous to that of photosynthesis in that electron transfer occurs via dye molecules to the titania nanoparticles under irradiation by sunlight. Different dye molecules absorb different wavelengths of sunlight. However, while the DSC materials are cheaper than silicon, efficiencies are much lower. Some latest research breakthroughs at the University of Queensland in making single crystal TiO_2 photocatalyst, lift the hope in this direction, which would lead to much enhanced solar cells and solar water splitting for hydrogen production (Yang *et al* 2008).

Other possibilities being examined are organic photovoltaics based on encapsulation of organic nanoscale materials in polymers (Goh *et al* 2007).These have low efficiencies of conversion (one to three per cent). Combinations of organic and inorganic materials are being tested to improve efficiency. Thus additions of single-walled carbon nanotubes and fullerenes to conducting polymers show promise. These facilitate charge transfer thus increasing efficiency, possibly to six per cent. The fact that electrical properties can be enhanced while retaining the attractive mechanical properties of the polymer composites indicates the important influence that intermolecular interactions and nanostructure can have on such physical properties.

Another area being researched is quantum dots, which are nanoscale crystals of semiconductor material such as silicon, GaAs, CdSe or CdTe which have different absorption and emission spectra determined by quantum effects related to particle size. They are potentially more efficient than conventional silicon since up to three electrons can be created for each photon in contrast to one for silicon. They can be incorporated in different matrices and deposited as thin films. By using different sizes in stacked layers a larger portion of the spectrum of sunlight can be absorbed with a theoretical maximum efficiency of about 86 per cent.

The average price for a PV-module, excluding installation and system costs, has dropped from almost

US$100 per watt in 1975 to less than US$4 by the end of 2006. With expanding polycrystalline silicon supplies anticipated by 2010, prices are projected to drop to US$2 per watt. Thin film technologies could take the price to US$1 per watt by 2010 (Dorn 2007).

Australia is very active in development of photovoltaic cells but has relatively low local production and usage. Most PV research and development in Australia is at UNSW and ANU, involving some 120 people. The University of NSW group introduced the buried contact cell to the market. The technology has been commercialised in Spain. In addition, UNSW has several large contracts with Asian companies, often based around former graduates. Thus, with strong funding in China, one graduate has built up one of the largest photovoltaic manufacturing operations in the world, Suntech Power Holdings. UNSW has also commercialised crystalline silicon-on- glass technology in Germany

The ANU group works in the area of thin silicon cells and PV-thermal concentrator systems. The production costs of single crystal cells need to be reduced further by a factor of three to five to encourage widespread use and the ANU group has developed a technique for slicing into micro-thin wafers termed SLIVER technology (Anon 2007b). This produces a much larger area of solar cells with a higher efficiency from an initial volume of silicon. The process is being developed by Origin Energy with a pilot plant in Adelaide and the company has invested upwards of $50 million in preparing for commercialisation.

A thin-film approach based on thin-film organic solar cells is being researched at the University of Melbourne. Another program is underway at the Queensland University of Technology based on single-wall carbon nanotubes in a conjugated polymer matrix (Goh *et al* 2007). This is an area which is reaching commercialisation in the US.

The DCS technology developed in Switzerland is being exploited by an Australian company Dyesol Ltd and also Dyesol International. The company has signed a number of agreements with companies and organisations in China, Thailand, Singapore, Japan and the UK and is supplying materials and test equipment around the world. It is expanding its operations in Canberra and a major program to deposit thin DCS films on steel sheet for use in building construction is underway in Wales. This is an example of an industry developing with little of the research being carried out in Australian universities.

Solar Systems has developed high concentration PV systems based on dishes and fields of mirrors. Concentrated sunlight is used to create electricity in expensive but highly efficient triple junction GaAs-based cells. Such concentrators will be important for deployment of the very expensive, but highly efficient (more than 50 per cent) nano-engineered photovoltaic systems of the future.

There is a strong effort in Australia on photovoltaic cells which is the leading area for application of nanotechnologies in renewable energy systems. Various options are being pursued particularly in the use of silicon. However the potential of organic films needs to be explored more actively and other advanced systems using engineered nanomaterials will emerge in the medium term. Future development is strongly dependent on Government policy on supporting sustained R&D and sustained market development measures such as feed-in tariffs.

4 Medium-Term Opportunities for Australia

4.1 CATALYSTS FOR CONVERSION OF BIOMASS, NATURAL GAS AND COAL

As noted in Chapter 1, demands for liquid fuels, particularly for transport, will continue to increase, both in developed countries and in developing countries with the growth in China and India being the main driver for the latter. Whether or not new supplies are found, there will be a need to supplement existing resources as a contribution to the overall energy needs. There is a huge investment in existing oil infrastructure which can be adapted to alternative liquid hydrocarbons. Various possibilities exist for conversion of carbonaceous materials to liquid fuels and there is an extensive literature (APEC CTF 2006, IEA 2006, Lux Research 2007b). In all of these conversion processes the performance of the catalyst is critical and there are clearly opportunities for improvements using nanostructured materials with highly active surfaces.

Biofuels are being reviewed by ATSE in a current ARC-funded project and will not be considered here. The current process to produce ethanol is based on fermentation but more advanced processes will be based on lignocellulose with gasification and conversion using similar technology to that discussed below.

The technology of production of syngas as an intermediate from coal by the Fischer-Tropsch method for subsequent conversion to liquids has been known for many years but the problem has been cost of both plant and product. It has been used to a limited extent to produce liquids from coal . Natural gas is a more attractive feedstock and there has been extensive R&D to adapt the process to natural gas to optimise the critical factors of cost, quantity of emissions and environmental impact (Trimm 2002, Trimm 2007)).

To improve the economics of the operation the first generation of plants have been sited on existing oil or gas fields where waste gas is burnt to the atmosphere - so-called 'flaring'. A small GTL plant with a capacity of 12,500 barrels of diesel per day has been in operation in Malaysia for about two decades. However, with increased oil prices and security of supply becoming critical, major plants are being installed. Thus in Qatar, SASOL is building a 22,000 bpd plant while Shell will build a 140,000 bpd plant there over the next three years. CHEVRON has announced that it will build a 34,000 bpd plant in Nigeria. The GTL fuel is very clean without the sulphur problems of refined diesel and reduces CO_2 emissions by 50 per cent and particulates by 60 per cent compared to normal diesel. It is predicted to provide five per cent of world diesel needs by 2010.

A continued high oil price could also encourage the conversion of coal or oil shale. The environmental impacts are much greater with these than with conversion of natural gas. Despite this issue, several coal gasification plants are in operation or are planned in the US but the major expansion will be in China. The Shenhua Group, China's largest coal producer, is planning to build at least eight coal gasification and coal to liquid plants by 2020 (Lux Research 2007a).

Australia is fortunate to have large reserves of natural gas of which a considerable fraction has been developed for domestic use and for export as LNG. However much of the estimated reserves are in areas hard to access – so-called "stranded gas reserves". Most of these are offshore in areas where it uneconomic or difficult to access via a pipeline. The options are then a floating facility or an anchored concrete structure which limits the size of the processing equipment. The objective is to produce liquids which can be transported by a tanker. The cost of processing is offset by the lower gas price at the wellhead. It may be possible to ship and process on land.

There are exciting opportunities for new approaches to processing particularly with more efficient catalysts based on nanomaterials (Trimm 2002). The critical factor is the price of oil - if this remains high then even existing processes give a good return on investment. Teams at CSIRO Petroleum and the University of New South Wales are working in this area (Trimm 2007).

Conversion of both black and brown coal and of oilshale to liquids has been carried out in Australia on several occasions over the past decades but has not been economic. This fact, together with adverse environmental impacts, has inhibited activity in this area. CISRO has activity in coal gasification which could be the basis for future work on coal conversion to liquids if required.

The substantial stranded reserves of natural gas in Australia offer commercial and strategic opportunities for conversion to liquids for transport fuels. The use of nanostructured catalysts could improve the economic viability of processing and there is a need to strengthen overall research in nanocatalysts in Australia.

4.2 FUEL CELLS

(Nanoforum 2004, IEA 2005, Jolley 2006)

Fuel cells are electrochemical devices that convert the energy of a chemical reaction directly into electricity, with heat as a by-product. They are similar in principle to a battery except that the fuel and the oxidant are stored externally, enabling them to operate as long as fuel and oxidant (oxygen) are supplied. Each cell consists of two electrodes with an electrolyte in between. In a fuel cell, hydrogen and oxygen are combined in a controlled reaction yielding water and electricity. A catalyst controls the reaction and the electrons flowing from electrodes are fed into an electrical circuit. Practical cells produce a voltage of about 0.7–0.8 volts and power outputs of tens to hundreds of watts. Such cells need to assembled into stacks to provide a large power source. Energy sources other than pure hydrogen such as natural gas, biogas or ethanol can be used after reforming to a syngas of hydrogen and CO_2.

The principle is not new and a number of approaches have been used to develop commercial fuel cells. Several of these are on the market for stationary and transport applications but currently they are expensive compared to conventional systems. Despite the cost, some US$340 million sales were made in 2003 and the market is anticipated to grow substantially in the future. Fuel cells are one of the most highly funded technology areas in IEA countries, with a total budget of about US$1 billion per year.

The choice of fuel, electrode and electrolyte materials dictate the operational temperature and thus the performance. Six types can be distinguished according to working temperature and electrolyte. There are four types working at low temperatures: alkaline fuel cells (AFC less than 90˚C), polymer electrolyte fuel cells or proton exchange membrane fuel cells (PEFC or PEMFC less than 80˚C), direct methanol fuel cells (DMFC 160–220˚C), and phosphoric acid fuel cells (PAFC 160–220˚C). There are two types of high temperature fuel cells: molten carbonate fuel cells (MCFC 620–650˚C) and solid oxide fuel cells (SOFC 750–1000˚C). Some are best suited for portable application and others for stationary applications. Essential features are noted below.

PAFCs represent the first generation of commercial fuel cells. Primarily used in stationary situations they have also been used to power buses. They tolerate impurities in the hydrogen input and can achieve efficiencies of about 40 per cent. Large-scale trials in the US in defence bases have demonstrated their reliability. However they are expensive because they use a platinum catalyst.

PEMFCs are particularly suited to powering vehicles due to their fast start-up time and their power/weight ratio. Their disadvantages are that they require cooling to prevent overheating and they also use a platinum catalyst which is sensitive to poisoning by carbon monoxide.

MCFCs use a molten carbonate-salt electrolyte suspended in a porous inert ceramic matrix. They are being developed to be fuelled by natural gas rather than hydrogen. They do not use precious metal catalysts which help to reduce costs. Life is limited by high operating temperatures and corrosion.

Another variant is the direct-carbon fuel cell based on electrochemical oxidation of solid carbon. One version uses a recycling molten sodium carbonate electrolyte which reacts with carbon at an anode to form CO, CO_2 and Na. These circulate in the system and are reconstituted with incoming air at the cathode. The four electrons from the oxidation process give a current efficiency of the system much higher than with a hydrogen feedstock and cell materials are cheaper

SOFCs use a non-porous ceramic electrolyte and can achieve high efficiencies of about 70 per cent. They do not use precious metal catalysts but there are cost problems associated with design of cells for high temperatures and slow start-up times. The current life is low, perhaps 4500 hours for small scale residential systems, and the aim is to increase this by a factor of 10.

Critical areas for reduction of costs are in production, since fuel cell stacks are still not suited to mass production and in materials development both for cells at high temperatures and for catalysts. Nanotechnologies show promise in these areas. Thus the use of ceramic nanopowders can improve fabrication of solid state ceramic membranes for SOFCs. For PEFCS, catalysts of carbon nanotubes coated with precious metals in the range 1-5nm have been developed. In PMFCs the development of cheap, nanoporous polymer membranes is a key factor for cost reduction. A variety of approaches to nano- and micro-engineering has begun to yield portable fuel cells based on direct methanol with dramatic cost and size advantages for niche markets such as consumer electronics products, military and off-grid applications (Doe 2007). These are coming onto the market in the US, Europe and Asia.

In Australia there has been a strong thrust on SOFCs for a number of years. This stemmed from CSIRO research on doped high temperature zirconia ceramics in the 1980s. Ceramic Fuel Cells Ltd in Melbourne was formed in 1992 to exploit the technology with the backing of major companies and utilities. It has developed small-scale (up to five kW) units for domestic use and has one kW prototypes under test with utilities and appliance manufacturers. The company is using ceramic nanopowders to create functional interface layers.

At ANU, plasma processing techniques have been applied to reduce costs in PMFCs (Ramdutt *et al* 2007). The conventional technique is to spray or brush a slurry of platinum and nanocarbon particles onto a porous carbon backing layer while the membrane is cast from polymerising liquids. The membrane and two electrodes are then hot pressed to form a membrane electrode assembly. However the catalyst particles are distributed evenly through the layer and only the surface layers are actually involved with the gas supply. By using plasma sputtering the distribution of platinum can be controlled to be densest near the surface and thus save platinum. The ANU group is working on the use of carbon and boron nitride nanotubes as supports for sputtered platinum to produce increased activity catalysts.

The University of Queensland (UQ) has an active group in the ARC Centre of Excellence for Functional Nanomaterials working on proton-conducting composite materials for hydrogen and direct alcohol fuel cell applications. These use functionalised silicon oxide nanoparticles in the pores of proton-conducting polymers (Jin *et al* 2007). There is a strong thrust on nanostructured materials in Australia which can provide an input to future fuel cell development. Overseas there is considerable activity on fuel cells using hydrogen for the automotive industry and major manufacturers have made massive investments which will initially be reflected in imported vehicles. Given that the penetration of fuel cells into the automotive market is projected to be only 15 per cent by 2015 (Frost and Sullivan 2004), production in Australia will be some years away.

There is a strong effort in the application of nanomaterials in fuel cells which needs to be maintained to ensure that Australia can benefit from potential savings in greenhouse gas emissions in transport and more flexible energy generation systems.

4.3 CAPTURE AND STORAGE OF CARBON DIOXIDE
(Cook 2006, EPRI 2007a)

The most promising technology for significantly reducing emissions from large-scale fossil fuel stationary sources of CO_2 (coal-fired power stations, cement plants, gas processing facilities, etc) involves separation and capture of the CO_2, compression and then storage of it in geological formations where it cannot leak back to the atmosphere.

Capture is widely used in the natural gas industry after stripping of CO_2 to increase calorific value of the gas. Low-cost opportunities exist for urea, steel and cement plants but power plants are more difficult.

Currently in the case of coal-fired power stations the capture is post-combustion by using a solvent to interact with flue gas and absorb CO_2. This approach using the current monoethanolamine process reduces net power by about 30 per cent and raises cost of electricity by 65 per cent. Other methods being examined for separation include physical and chemical solvents such as chilled ammonia, membranes, adsorption onto porous solids, and cryogenic separation. The critical factor is cost which currently is about A$40 to A$50 per tonne of CO_2. This is unlikely to be an acceptable option in the short-term.

In the longer-term the capture process can be improved by moving from post-combustion capture to pre-combustion capture. This depends on new combustion technology currently under consideration. There is a need to increase the efficiency and reduce the capital cost of pulverised coal and integrated gasification combined-cycle technologies since the addition of post-capture to existing designs would raise the cost of electricity by 40 to 50 per cent.

A promising cost reduction option is the use of membrane technology for separating the CO_2 from syngas which could enable a substantial reduction in cost. The greatest reduction in future emissions from the US electricity sector will be gained by applying carbon capture and storage technologies to all new plants coming on-line after 2020 (EPRI 2007a). Given the rate of expansion of coal-fired stations in India and China (a one GW station every four days!), it is vital that this technology be demonstrated and installed as soon as possible to reduce global emissions.

Once the CO_2 is captured from a major stationary source of emissions, it is compressed, usually to a dense supercritical fluid, transported by pipeline to a suitable location and then injected into suitable rock formations (sediments) at depths of 800 to 100 metres or greater. This process of geosequestration ensures that the CO_2 will remain stored either as a supercritical fluid or in solution in groundwater. The technique has been used by the oil and gas industry without problems for the past 50 years to enhance oil recovery and to dispose of sour gas. A number of carbon capture and geosequestration projects are underway or in an advanced state of planning around the world (Cook 2006).

Australia has a strong R&D capability in the improved combustion processes needed for efficient carbon capture based on a long history of work on black and brown coal. The latter is a resource which cannot be exported but which provides a vital electricity source for Victoria, but with major CO_2 emissions. A very diverse and well-resourced program of research is underway at CSIRO Energy Technology, the CRC for Coal in Sustainable Development and the Queensland Centre for Advanced Technologies, which houses the Centre for Low Emissions Technology. Clean coal technologies are feasible now but come at a relatively high cost and the research is aimed at reducing costs (Brockway 2007) and examining a range of options (Toohey 2007).

The major research on carbon capture and storage is being made by the CRC for Greenhouse Gas Technologies (CO2CRC) with a program of research at institutions around Australia. The CRC has been active in investigating separation technologies and in determining suitable sites for geological storage of CO_2 in Australia. There are many potentially excellent sites such as the sedimentary basins currently producing oil and gas in the Gippsland Basin and on the North-West Shelf, as well as basins with deep saline formations.

The CRC is undertaking a large-scale demonstration of geological storage of CO_2 in the Otway Basin of Western Victoria, with injection of up to100,000 tonnes of CO_2. The project involves CO_2 production from a natural gas well; transport by pipeline; injection into a deep porous formation overlain by an impermeable seal and the monitoring and verification of the behaviour of the stored CO_2-rich gas. The project will have a total cost of about A$35 to A$40 million (Cook 2006). A recent publication of the CRC lists 13 major projects amounting to several billion dollars being planned in the next five to 10 years around Australia (CO2CRC 2008).

UQ has been active in developing new approaches to membranes for gas separation. Membranes, made of polymer or ceramics, can be used to effectively sieve out CO_2 from gas streams. The membrane material is specifically designed to preferentially separate the molecules in the mixture. Carbon nanotubes are being used at UQ to process gas streams at rates up to 100 times greater than current membranes and show promise as a commercial product.

While nanotechnologies may only play a limited role in carbon geosequestration overall, it is important to ensure that Australia uses the best available technology in gas separation based on nanomaterials in its future fossil energy production systems.

5 Long-Term Opportunities for Australia

5.1 HYDROGEN PRODUCTION

(Oakdene Hollins 2007, Jolley 2006, DITR 2003, IEA 2005, DITR 2005, AAS 2008)

The attraction of hydrogen as an energy carrier is that its combustion produces only water and thus it is a clean fuel. Hydrogen can be burnt in a combustion chamber like conventional fuel or used in fuel cells to generate electricity with water as a by-product as discussed above. These attributes have led to the concept of a "hydrogen economy" as the long term replacement for the present hydrocarbon economy. This envisages hydrogen produced by clean or renewable energy sources and used in stationary or transport applications. Various estimates suggest that this could occur between 2030 and 2050.

There are three areas in the hydrogen economy where nanotechnology can play a leading role: the generation of hydrogen, the storage of hydrogen, and the controlled reaction of hydrogen to produce electricity (as discussed in Chapter 5 under Fuel Cells).

A critical factor is the supply of sufficient hydrogen. Currently some 500 billion cubic metres (50 million tonnes) of hydrogen are produced worldwide, about 1.5 per cent of the world's energy consumption. However most of it is produced and used in the chemical industry. Fossil fuels such as coal, oil and natural gas and many petroleum derivatives can be used as feedstocks. As an indication of the demand in a hydrogen economy, the replacement of the entire UK fossil-fuel-based energy system would require 4.8 million tonnes of hydrogen – a major expansion in production (Oakdene Hollins 2007).

Hydrogen can be produced from natural gas by:

- steam reforming – in this process methane reacts with water vapour at high temperatures to produce hydrogen and carbon monoxide with the latter being converted to carbon dioxide and hydrogen through the water-gas shift reaction; or
- partial oxidation – here methane reacts with oxygen to produce hydrogen and carbon monoxide with the latter further reacting with steam to produce additional hydrogen and carbon dioxide.

For moderate levels of hydrogen demand with a dispersed market, decentralised production from natural gas could be more economical than large-scale production, although CO_2 sequestration could be expensive.

Hydrogen can be produced from coal through a variety of gasification processes producing syngas as noted in Chapter 5. This process is more complex than production of hydrogen from natural gas since it is necessary to use pure oxygen for the reaction and this increases the cost of the hydrogen produced. However the large-scale production of hydrogen from integrated gasification combined-cycle plants with CO_2 sequestration appears to be an attractive proposition for centralised hydrogen production. Gasification of biomass is another route under investigation for decentralised plants.

Another option is to break up water into hydrogen and oxygen. Various electrolysis processes have been developed based on low-, medium- and high-temperature processes with the dominant one being alkaline electrolysis. Another is polymer electrolyte membrane technology. Both can be improved in efficiency and operating life by the application of nanotechnology for improving electrode surface area and membrane materials.

At present only a small percentage of total hydrogen production is by electrolysis. When using electricity from fossil fuel plants, efficiency is relatively low at around 25 per cent (that is, 70 to 75 per cent for electrolysis and 30 to 35 per cent for coal fired plants). With improvements in both of these, including nanostructured electrodes, the overall efficiency could reach 40 to 50 per cent. However electrolysis provides an attractive sustainable option for electricity storage from intermittent renewable sources such as photovoltaics and wind power on a decentralised basis.

Another approach is use high-temperature heat directly to decompose water. Various processes have been developed but efficiency is low and high-temperature materials are needed. Thermochemical cycles such as the sulphur-iodine cycle look promising and nuclear reactors are being examined as suitable heat sources. A contrasting low-temperature process is photolysis using sunlight to directly split water into hydrogen and oxygen. The critical need is for a suitable catalyst to speed up the reaction and improve efficiency. Photocatalytic nanotubes such as porphyrin nanotubes with particles of platinum coated onto the surface may provide an answer. The use of arrays of nanowires is another approach.

There is considerable activity in hydrogen research in Australia which was summarised in 2005 (DITR 2005) and a technology roadmap report has been commissioned recently. Not surprisingly, given earlier discussion, CSIRO Energy Transformed Flagship is a major player. The extensive CSIRO work on reforming of natural gas and on coal gasification directly links to hydrogen production. There is activity in a number of universities, notably Curtin, Queensland and Newcastle, on aspects of gasification of fossil fuels and biomass. Australia appears well placed to support a major move into hydrogen production.

5.2 HYDROGEN STORAGE AND USE

(Oakdene Hollins 2007, DITR 2003, DITR 2005, IEA 2005, Jolley 2006, AAS 2008)

Hydrogen has high calorific value by mass but low calorific value by volume. Thus it needs to be compressed for distribution, storage and use. It has been suggested that hydrogen could replace natural gas as a fuel for use in engines and that the current pipeline network could be used. However there are problems with this approach over long distances as the energy required for compression of hydrogen is greater than natural gas and also hydrogen can embrittle the steels used in pipelines. Some short pipelines are in use for special applications but long distance pipeline transport is unlikely. Storage in cylinders of either steel or composite materials for local use in electricity generation or vehicles is also very inefficient.

Another option is liquefaction and transport by special tankers or storage in insulated pressure vessels. Again this is very energy intensive and expensive. A limited number of demonstrations of hydrogen distribution and storage for transport applications exist in Europe, Japan and the US.

Certain metals and alloys absorb hydrogen reversibly to form metal hydrides. The key to practical use of these is the ability to absorb and release the hydrogen many times without deterioration. A large number of alloys in granular form have been examined for their ability to store hydrogen and these operate over a wide range of temperatures and pressures for absorption and release. Storage by physical absorption at low temperatures (below 80˚C has a poor gravimetric performance of one to two per cent wt . In high temperature metal hydrides (less than 300˚C) the absorption is chemical and storage capacities up to four per cent are possible.

Clearly a good storage material must have a very high surface area for maximum absorption and nanoscale materials offer interesting possibilities (Berube *et al* 2007). The challenge is to increase absorption to get higher density of storage of hydrogen yet not have the hydrogen bonded too strongly so that more energy is needed for desorption..

Considerable promise has been shown by nanocrystalline material produced by high energy milling with high temperature metal hydrides reaching seven per cent storage at high rates of absorption (Nanoforum 2003).

Considerable time and effort has been invested into using carbon nanotubes for hydrogen storage. This material was initially reported as a potential solution some years ago with very high values of storage. However, more recent work indicates a much lower range of storage capacity of 1.5 to three per cent at ambient temperatures and moderate pressures (Dogani, R. 2002). This figure can be doubled at lower temperatures but is not economic for transport applications. Carbon nanotubes doped with metals such as titanium and platinum show promise but more research is needed.

The uses to which hydrogen will be put will determine which of the technologies is used and which should be a priority area. Thus hydrogen for stationary power generation has less restrictions for storage than hydrogen for transport where weight is a major constraint. Applications can either be direct combustion or fuel cells for hybrid or electric vehicles. To achieve a hydrogen economy there will clearly be a need to make a shift in infrastructure for distribution with storage as the critical area.

The recent reviews of hydrogen activity in Australia (DITR 2005, AAS200), list a number of projects on hydrogen storage and use. Efficient hydrogen storage technologies are the key to widespread use of hydrogen and nanomaterials, which show promise as storage materials. Recent work at the ARC Centre for Functional Nanomaterials at the University of Queensland, has produced nanocomposites by milling doped MgH_2 with carbon nanotubes. These show storage capacities of about five per cent at 200˚C with rapid desorption. A spin-off company from the university, Hydrexia Pty Ltd, has received funding from the Queensland Government and AusIndustry to develop this technology. A Roadmap for the Development of Hydrogen Technology in Australia has been commissioned by COAG (Council of Australian Governments) and should be available soon. This will provide detailed guidance for government and industry on hydrogen energy R&D capabilities in Australia and identify priority areas.

There is considerable activity in hydrogen research in Australia, as reported in 2005 (DITR 2005) and more recently by an Australian Academy of Science review (AAS 2008). Australia is the 16th largest producer of hydrogen energy research publications in the world. The majority of research is carried out by universities and CSIRO. The former are linked through the National Hydrogen Materials Alliance (NMHA), which is a research cluster of 11 universities, together with ANSTO (Australian Nuclear Science and Technology Organisation). The aim of NHMA is to develop new materials that improve the efficiency and economics of hydrogen generation, storage and use. In CSIRO, hydrogen research is undertaken by the CSIRO Energy Transformed Flagship. The CSIRO Hydrogen Technologies program includes fabrication of polymer electrolyte membrane fuel cells up to several kilowatts in size; gas cleaning and separation technologies for gasification of fossil fuels or biomass, and solar energy in the reforming of natural gas. Australia appears well placed to support a major move into hydrogen production, based on low emission coal and gas technologies.

6 Markets and Commercialisation of Nanotechnologies for Energy Applications

6.1 MARKETS FOR NANOTECHNOLOGIES IN ENERGY SYSTEMS

The US National Science Foundation predicted in 2001 that the worldwide market for nanotechnologies would be about US$1 trillion by 2011–16 (Roco 2001). Because the term nanotechnology covers a diverse range of enabling technologies rather than a stand-alone industry there has been some scepticism about this figure. However, a more recent estimate agrees that the trillion dollar market could be reached by 2013 if semiconductors are included or by 2015 if they are excluded (Cientifica 2007c). This implies a very rapid growth of the market. Most of the growth occurs not, as now, in production of basic nanomaterials but in the ability of industries such as pharmaceuticals and semiconductors to transform these into high-value added products.

Thus in 2015 some 80 per cent of the market will be in the pharmaceuticals and health sectors. A more optimistic estimate has predicted that global sales of products incorporating emerging nanotechnologies would total US$2.6 trillion by 2014 (Lux Research 2007b). This would be about 15 per cent of global manufacturing output.

In the short term, an analysis of the global energy market for 2014 (Cientifica 2007c) suggests that the primary impact of nanotechnologies will be in more efficient use of existing resources than the creation of new supplies from solar and hydrogen-based technologies. Thus solid-state lighting, nanocomposite materials, aerogels and fuel-borne catalysts are seen as having about 75 per cent of the nanotechnology share of the global energy market in 2014. Energy saving technologies are estimated at about US$50 billion and applications in transport about another US$50 billion. In the medium and longer term the commercialisation of energy generation systems such as photovoltaics and focused solar systems, followed by hydrogen fuel cells, which incorporate nanotechnologies will take a much greater share of the energy market. Thus one estimate suggests that the market for thin film and organic photovoltaics could be worth over US$2.3 billion in 2011 (NanoMarkets 2006).

6.2 COMMERCIALISATION OF NANOTECHNOLOGIES

There are a number of special features associated with translation of nanotechnologies from research to commercialisation (Tegart 2006, Tolfree 2006). The nanotechnology value chain starts with the production of nanomaterials (nanoscale structures in unprocessed form) which then become nano-intermediates (intermediate products with nanoscale features) and finally nano-enabled products (finished goods incorporating nanotechnologies).

Taking these in order, significant technical barriers associated with production of nanomaterials stem from a lack of understanding of nanoscale properties and the ability to characterise and engineer them to from useful materials and products. Other barriers are those relating to regulation such as classification and standardisation of nanomaterials and processes, and the management of health, safety and environmental risks. Free particles in the nanometre range raise particular health and safety issues since their toxicology cannot be deduced from that of the same material at the macroscale. This arises from two factors dependent on size. The large surface/volume ratio leading to increased biological activity and the potential for nanoparticles to penetrate cells more easily than larger particles and travel to organs in the body. These considerations flow on to the fabrication step of nano-intermediates. Finally the use of nano-enabled products is dependent on acceptance by society of possible risks in use and in disposal (NAF 2006). There is a need for a holistic approach from production through to disposal. The open discussion of these issues is critical to the future of commercialisation of nanotechnologies.

Nanotechnologies will appear in a variety of forms from simple isolated structures to complex integrated technologies. An approach to classification of these has been suggested as shown in Table 7 (Oakdene Hollins 2006). The grid allows a simple estimation of the technical challenge in commercialisation. In general, simple nanotechnologies are easier to handle than complex technologies. Similarly, isolated technologies are easier to develop than integrated systems.

The grid is useful for indicating the relative challenges which the nanotechnological aspect of a product will bring to the overall development. Thus it is possible to highlight the potential barriers specific to a subdivision (Table 8). Simple isolated technologies are the easiest to commercialise, for example through university spin-off companies or venture capital support, but still are difficult and have a high failure rate. The majority of those that survive are essentially nanomaterials suppliers or manufacturers of upgraded simple products. Once these need to be integrated into systems, the small companies have neither the skills nor the money to carry them through. This is where large scale investment by government or an entrepreneurial firm interested in building new manufacturing techniques is needed.

Table 7. A Subdivision of Nanotechnologies by Complexity of the Nanostructure and the Level of Integration into a Larger System

Measure of complexity of developing product	**Integrated**	Simple nanotechnologies with a high degree of integration into a larger system. For example, nanoparticles in photovoltaic cells	True integration of complex nanotechnologies with real world systems. For example, the ideal NEMS systems or site-selective nanosensors integrated into larger arrays.
	Isolated	Nanoparticles or thin films in simplistic uses. For example, fuel additives and spray-on window catalysts.	Complex molecular machines which operate autonomously from a larger system. For example, chemical sensors/ indicators for detection of specified toxins.
		Simple	**Assemblies**
		Measure of complexity of nanotechnology or science behind nanotechnology	

Source: Oakdene Hollins (2006).

Table 8. Barriers Preventing the Development of Nanotechnologies

Measure of difficulty of developing product	**Integrated**	Difficulties in translating technology into workable devices. Fundamental science is thriving but needs enablers to drive the technology to prototype.	Fundamental research is in the early stages: integration is a major issue. Difficulty in finding true benefits due to early stage research
	Isolated	University/SME/start-up/ VC/industry infrastructure in place to exploit technology. Public acceptability and risk are an issue.	Translating 'bench top' nanotechnology into production is difficult. Large scale manufacturing techniques are lacking.
		Simple	**Assemblies**
		Measure of complexity of nanotechnology or science behind nanotechnology	

Source: Oakdene Hollins (2006)

6.3 REALISATION OF THE POTENTIAL FOR NANOTECHNOLOGIES IN ENERGY IN AUSTRALIA

The discussions of Chapters 3 to 5 have clearly shown the potential for the application of nanotechnologies to energy systems in Australia in terms of making contributions to reduction of greenhouse gas emissions, to security of energy supply and to sustainability. They also indicate the strength of Australian research in a number of areas. The challenge is to seize the opportunity to gain the benefits from nanotechnologies in energy and to create new industry sectors around these strengths.

Given that Australia currently accounts for one per cent of world manufacturing and 2.3 per cent of scientific publications, it has been estimated that a reasonable target for an Australian nanotechnology industry would be between A$13 and A$79 billion by 2015 with a conservative figure of A$30 billion (Kambouris 2006). Based on an estimate of revenue of A$250,000 per employee in the biotechnology industry, this median figure would imply the employment of 120,000 people. Based on the Cientifica figures above the value of nanotechnology in the Australian energy sector by 2015 could be about A$3 billion.

The total figure for nanotechnologies research in Australia was estimated at A$100 million in 2003 (PMSEIC 2003) and is probably at least twice that now. The latest Nanotechnology Capability Report (Invest Australia 2007) states that there are over 75 research organisations and some 80 nanotechnology companies. This strong research base provides an excellent opportunity for Australia to become a market leader in the region. There are already a small number of established companies listed in the energy field which depend on nanotechnologies such as Cap-XX, Ceramic Fuel Cells, Dyesol, Origin Energy and Hydrexia.

The development of a large market for nanotechnologies in energy in Australia will occur in two ways: by adaptation and change of existing processes and products, and by sales of completely new products. However, to achieve the estimated potential, there needs to be changes in the Australian innovation system (Kambouris 2006, Hughes 2006).

The current policy thinking, influenced by US experience, is that high technology producing sectors are seen as key drivers of productivity growth – for example, the recent report of the Productivity Commission (Productivity Commission 2007). Thus public funding bodies are pressing CSIRO, universities and CRCs to commercialise all suitable research and in response these bodies are forming companies and seeking seed and start-up capital to put new processes and products into the new market. In practice, only limited amounts of private capital funding are supporting commercialisation efforts and many promising developments disappear in the funding gap between applied research and market development, as noted above. Overall contribution from the survivors is small. The current review of Innovation in Australia offers an opportunity to change this situation.

A recent analysis of Australian cleantech venture capital and private equity investments (Cleantech Network 2007) showed that cleantech investments accounted for an average of only three per cent of total Australian venture capital investments by amount – roughly A$65 million per annum. However, this is projected to rise very rapidly, driven by increasing concerns about climate change. Thus, while investments have been made in energy storage through Ceramic Fuel Cells and Cap-XX, and in energy generation through geothermal and biofuel companies, there was only one investment in solar with Dyesol. However several major investments in new solar photovoltaic systems companies have recently been announced, including A$420 million by Solar Systems in a solar power station in Victoria.

Analysis of the US economy (Hughes 2006) shows that the drivers of recent productivity growth are relatively low tech sectors which utilise high technology if it is seen to be advantageous. These are: retailing, finance and insurance, wholesaling, administrative and support services, real estate and miscellaneous professional and scientific services – with computer and electronic products as the only high technology sector. Thus it is necessary to diffuse new technologies into existing companies to transform them.

The overwhelming evidence is that the institutions in the research sector are not the way to do this. This is particularly true in the energy sector where existing industry is heavily committed to expensive infrastructure on a long-term basis (Table 2). Universities have a role to play through education and training of a skilled workforce and through building up codified knowledge for use by industry but not in directly influencing strategy of existing companies or in setting up new ones. The Business Council of

Australia has recognised this in recent reports (BCA 2006 a, b).

In the case of energy companies the role of governments in Australia, both Federal and State, is the critical factor in adoption of new technologies. This is stressed in a recent publication on accelerating the deployment of low-emission technologies in Australia (ABCG 2007). The Group strongly supported the adoption of an integrated National Climate Change Response which draws together a number of responses. One of these is a National Low Emission Technology Strategy in which government works closely with industry to drive essential step-wise technological change.

The Group reinforced the problems of negotiating the gap between applied research and commercial development and identified six barriers to project developers seeking finance. These are:

- low levels of community acceptance and understanding – community consultation is essential to increase awareness of new technologies and their benefits and costs;
- regulatory uncertainty – some technologies need new and complex regulatory frameworks. For example, carbon capture and storage involves the licensing of carbon dioxide storage sites, approvals for critical infrastructure such as pipelines, and the decommissioning and long-term liabilities associated with storage facilities. (The CO2CRC is currently dealing with such issues in its Otway Geosequestration Project);
- insufficient funding for technology demonstration - these are required to prove and optimise new technologies but are less than commercial and often are redundant after trials. However they are costly and substantial funding must be found. Often companies are reluctant to take the risks associated with demonstration plants;
- lack of public/private partnership framework for initial commercial deployment – the scale-up to the first commercial plant involves risks and the plant may not be as efficient and cost-effective as later plants;
- insufficient funding for infrastructure requirements - the widespread acceptance of new technology may mean additional infrastructure: for example, gas pipelines for CO_2 or a new electricity distribution network to deal with intermittent loading from variable renewable energy sources; and
- skills deficit – problems of availability of skilled people make it difficult to develop a trained work force with skills needed in new technologies. Furthermore the training can be expensive. As an example the growth of the photovoltaic industry in Australia has required significant investment in a skilled workforce (Green 2007).

The markets for nanotechnologies in energy systems in Australia are currently small but, based on overseas projections, they are likely to grow rapidly. Through CSIRO and the universities Australia has built up a broad research base on nanotechnologies in energy systems and this must be further developed to support the changes needed to decarbonise its energy system by reducing dependence on fossil fuels and creating renewable energy systems. Thus the universities need to strengthen their activities in basic research on nanotechnologies and energy and the training of skilled people through both universities and the TAFE system needs to be enhanced to provide the necessary workforce.

A major effort is needed by the Australian Government and industry associations in diffusing new technologies into existing companies to radically change them. Further, there are opportunities to create new industry sectors based around Australian research; particularly in photovoltaic cells, fuel cells and catalysts. This will require new approaches to investment through public–private partnerships and support for small to medium enterprises.

The discussions in the ATSE Workshops (see Appendix B) highlighted these issues and emphasised the pivotal role of Government through consistent and sustained policy initiatives such as challenging targets for reduction of greenhouse gas emissions, targets for the contribution of renewable energy sources such as solar and wind, and application of feed-in tariff schemes for electricity generated in domestic and commercial systems. A clear strategy is essential to the development and application of nanotechnologies in energy systems in Australia and thus the development of a viable nanoindustry sector.

7 Conclusions

The study has raised a number of important issues which need to be addressed by Governments, industry and researchers if nanotechnology is to play a significant role in dealing with Australia's future energy needs. The conclusions arising from the study are:

ENERGY CONCERNS AND AUSTRALIA

1. Three major concerns in meeting future world energy demand are: security and sustainability of energy supply, the link between combustion of fossil fuels and climate change and the availability of technological innovations in energy conversion, transmission and use. There is no single technological bullet to solve the world's projected energy problems. An integrated approach is needed in which various energy technologies make significant contributions.

2. Many techniques are potentially available for energy production and use and thus countries need to make priority decisions about the mix of technologies to ensure security and sustainability in their energy supplies. Ideally these should be low carbon emission solutions to minimise the impacts of rapid climate change.

3. An approach to future energy production and use based on a range of technology options for fossil fuels and renewable energy sources offers substantial social and environmental benefits for Australia. The development of low-emission technologies for fossil fuel combustion would support continuing exports of black coal while new approaches to energy production and use such as solar and wind could lead to new industry sectors based on advanced technology.

4. The discussions in the ATSE Workshops reinforced the need for new technology approaches in Australia in the electricity industry, transport and the use of energy in industry, commercial buildings and dwellings.

NANOTECHNOLOGIES AND ENERGY

5. Nanotechnology is engineering at the molecular (groups of atoms) level. It is the collective term for a range of technologies, techniques and processes that involve the manipulation of matter at the smallest scale (from 1 to 100nm). The potential markets are enormous.

6. Nanotechnologies have the potential to make a contribution to the improvement of current energy systems and to the development of new ones. Initially these contributions are likely to be small but there is potential for major growth and the challenge for each country is to select the area where its R&D can be best directed. A corollary is that the contribution of nanotechnologies to the reduction of greenhouse gases will be small initially but has the potential to grow enormously over the next decades.

OPPORTUNITY AREAS FOR NANOTECHNOLOGIES IN ENERGY IN AUSTRALIA

7. The discussions of current nanotechnology activities in the ATSE Workshops together with further assessment have identified the opportunities for application of nanotechnologies in the energy scene in Australia as:

- short-term (less than five years) – energy conservation, environmental management, catalysts for combustion, photovoltaics;

- medium-term (five to 15 years) – catalysts for conversion of biomass, gas and coal, fuel cells, advanced photovoltaics using engineered nanomaterials; and
- long-term (greater than 15 years) – hydrogen, production, use and storage.

8. There are immediate opportunities in Australia for substantial energy savings using available technology but these can be amplified by the increased application of nanotechnologies in transport and domestic and commercial construction. Research on lightweight nanocomposite structures and nanosensors needs to be strengthened.

9. Research on nanomaterials for membranes for water purification will offer opportunities in Australia for more efficient use of energy both in recirculation of water in power plants and in recycling of water for domestic and industrial needs.

10. The use of nanocatalysts as fuel additives has considerable potential for reduction of greenhouse gas emissions from transport In Australia and research in this area needs to be strengthened.

11. There is a strong effort in Australia on photovoltaics which is the leading area for application of nanotechnologies to renewable energy. Various options are being pursued particularly the use of silicon. However the potential of organic films needs to be explored more actively and other advanced systems using highly engineered materials will emerge in the medium term. Further development is strongly dependent on Government policy on supporting sustained R&D and sustained market development measures such as feed-in tariffs.

12. The substantial stranded reserves of natural gas in Australia offer commercial and strategic opportunities for conversion to liquids for transport fuels. The use of nanostructured catalysts could improve the economic viability of processing and there is a need to strengthen research in this area in Australia.

13. There is a strong effort in the application of nanomaterials in fuel cells which needs to be maintained to ensure that Australia can benefit from potential savings in greenhouse gas emissions in transport and more flexible energy generation sectors.

14. While nanotechnologies may play only a limited role in carbon geosequestration overall, it is important that Australia uses the best available technology in gas separation based on nanomaterials in its future fossil energy production systems.

15. The realisation of a hydrogen economy in Australia is several decades away but there is likely to be a gradual transition from fossil fuels as worldwide pressure for reduction of greenhouse gases increases. It is vital that Australia maintain a strong effort in the application of nanomaterials in production, storage and use of hydrogen to enable participation in international projects and standards developments.

COMMERCIALISATION OF NANOTECHNOLOGIES IN ENERGY IN AUSTRALIA

16. The markets for nanotechnologies in energy systems in Australia are currently small but, based on overseas experience, they are likely to grow rapidly. Through CSIRO and the universities Australia has built up a broad research base on nanotechnologies in energy systems and this must be further developed to support the changes needed to decarbonise

its energy system by reducing dependence on fossil fuels and creating renewable energy systems. Thus the universities need to strengthen their activities in basic research on nanotechnologies and energy, and the training of skilled people through both universities and the TAFE system needs to be enhanced to provide the necessary workforce.

17. A major effort is needed by the Australian Government and industry associations in diffusing new technologies into existing companies to radically change them. Further, there are opportunities to create new industry sectors based around Australian research, particularly photovoltaic cells, fuel cells, and catalysts. This will require new approaches to investment through public–private partnerships and support for small to medium enterprises.

18. The discussions in the ATSE Workshops highlighted these issues and emphasised the pivotal role of Government through consistent and sustained policy initiatives such as challenging targets for reduction of greenhouse gas emissions, targets for the contribution of renewable energy sources such as solar and wind and application of feed-in tariff schemes for electricity generated in domestic and commercial systems. A clear strategy is essential to the development and application of nanotechnologies in energy systems in Australia and thus the development of a viable nanoindustry sector.

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Appendix A: Nanotechnology Workshop Attendees

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Name	Affiliation
Calum Drummond	FTSE , CSIRO
Peter Laver	FTSE, ATSE Vice President
Mike Murray	FTSE
Peter Binks	Nanovic
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Rachel Caruso	University of Melbourne
Paul Webley	Monash University
Andrew Holmes	FTSE, University of Melbourne
Peter Majewski	University of SA
Greg Tamanyan	Novel Laser Technologies
Astighk Tamanyan	Novel Laser Technologies
Udo Bach	Monash University
Paul Donoghue	RIRDC
Vaughan Beck	FTSE, ATSE, Technical Director
Greg Tegart	FTSE
Jason Nielsen	Victoria University
Kim Sweeny	Victoria University
George Simon	Monash University

SYDNEY

Name	Affiliation
Mike Cortie	UTS
Andrew Harris	University of Sydney
Cameron Kepert	University of Sydney
Yiu-Wing Mai	University of Sydney
John Boldeman	FTSE
Adam Jostsons	FTSE
John Sligar	FTSE, Sligar & Associates
Gordon Wallace	University of Wollongong
Phillip Aitchison	Cap-XX
Vaughan Beck	FTSE, ATSE, Technical Director
Greg Tegart	FTSE
Aibing Yu	FTSE, UNSW
Sri Banyopadhyay	Visitor, UNSW
Jin Ooi	Visitor, UNSW

Alain Deryck	Visitor, UNSW
Pin Peng	Visitor, UNSW
Qinghua Zeng	Visitor, UNSW
Xuchuang Jiang	Visitor, UNSW
Runyu Yang	Visitor, UNSW
Lydia Kemal	Visitor, UNSW
Sushil Gupta	UNSW

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Name	Affiliation
John Bell	FTSE, Queensland University of Technology
Joe Da Costa	University of Queensland
Andrew Dicks	University of Queensland
Ken Dredge	FTSE, Tarong Energy
Carla Gerbo	Australian Nanotechnology Alliance
Trevor Gleeson	Stanwell Corporation
Evan Gray	Griffith University
Denisa Jurcakova	University of Queensland
Peter Kambouris	CSIRO Exploration and Mining
Thomas Kohut	Dept of State Development and Trade
Max Lu	FTSE, University of Queensland
Leigh Morpeth	CSIRO
Don Nicklin	FTSE, Niche Consulting Services
Victor Rudolph	University of Queensland
Para Segaram	Miyo Tech
Else Shepherd	FTSE, Miyo Tech
Shi Shu	CSIRO Exploration and Mining
Greg Tegart	FTSE
Alan Twomey	Excel Consulting Group (Qld) Pty Ltd
Peter Vanderaa	Depart of State Development and Trade
James Vuong	Depart of State Development and Trade
John Zhu	University of Queensland

CANBERRA

Name	Affiliation
Jim Williams	FTSE, Australian National University
Chennupati Jagadish	FTSE, Australian National University
Andrew Blakers	FTSE, Australian National University
Natasha Wade	Cooperative Research Centres Assoc.
John Soderbaum	Dept of Resources, Energy & Tourism
Joe Hlubecek	Australian Academy of Science
Greg Tegart	FTSE

Appendix B: Outputs from the ATSE Workshops and Questionnaire

The discussions and the questionnaire covered three areas as are detailed below:

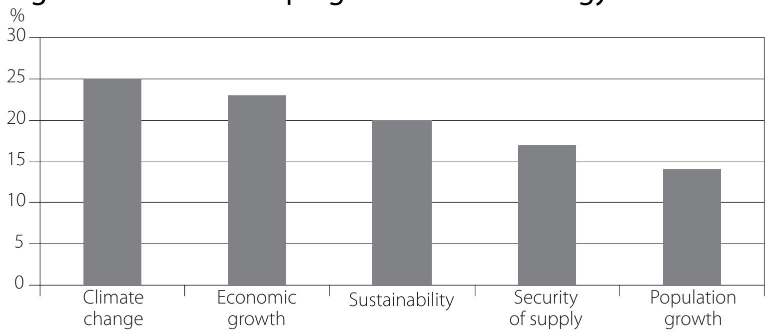
1. THE ENERGY SITUATION IN AUSTRALIA

The discussions in the workshops highlighted the following points:

- climate change – this is seen as a major driver of change in energy technologies with most participants agreeing that continuation of present rates of greenhouse gas emissions could alter the global climate with serious economic, social and environmental consequences.
- electricity generation – a reliable and adequate supply is essential. It is estimated that a $30 billion investment for base-load generating capacity in Australia is required by 2020. This will need to be based on clean coal technology with carbon capture and sequestration. Use of gas for demand loads will increase. Nuclear power will be a minor player. Even with widespread public and political support, it would take 15 years for the first plant to come on line. However it may be an option in the longer term. Wind and biomass will grow but will be only a small fraction of generation capacity, while solar power and photovoltaics offer strong possibilities particularly for smaller cities and rural areas. As the proportion of distributed power sources grows there will need to be a re-think of centralised grid management;
- transport – land and air transport fuels are critical – 75 per cent of oil is used for transport and ¾ of this is for road transport. This pattern is set to continue. This sector is a major producer of greenhouse gas emissions. A looming problem is that indigenous oil supplies are limited and, despite recent developments, self-sufficiency will decline from about 75 per cent in coming years to 45 per cent by 2030. Biofuels offer some relief mainly in bioethanol but sugar production is limited - need development of second generation technology from ligno-cellulose in longer term. Conversion of natural gas from "stranded" gas fields to liquids is an option in medium to long term. New technologies are needed in use of lightweight materials and power sources. Hybrid and electric vehicles with improved batteries are an option in the short term while hydrogen and small fuel cells are a strong option in longer term; and
- energy use – efficiency of use can be improved with potentially large savings in energy and greenhouse gas emissions, perhaps one third. In the short term improved efficiency in industry is possible in many areas while, in the medium term, changes to construction techniques of commercial and domestic buildings offer many opportunities in insulation, sensors for energy control, smart materials etc.

The responses to the questionnaire confirmed the points made in the workshops. The major forces shaping the future of energy in Australia were seen as climate change followed by economic growth and sustainability. Security of supply and population growth were rated lower as shown in Figure B1. The lower rating of security of supply reflects the perceptions that substantial indigenous supplies of petroleum will be available for the next decade and that alternative sources can be obtained from conversion of coal and gas to liquids.

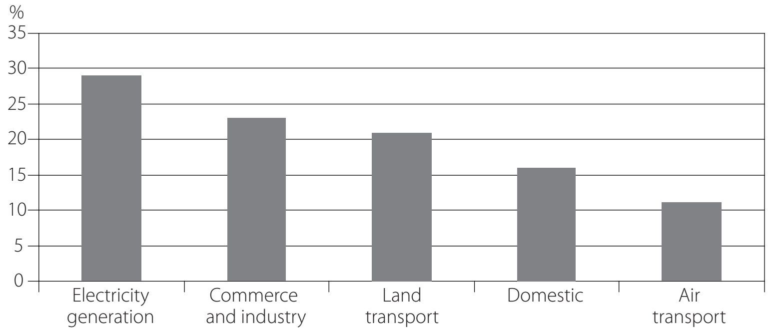
Figure B1: Forces shaping the future of energy in Australia.



Source: ATSE questionnaire

As shown in Figure B2, the most critical sector in future energy patterns was confirmed as electricity generation followed by commerce and industry, and transport, both land and air. This reflects the perception that climate change will increase demand for air conditioning in cities and that building and infrastructure construction, and services/manufacturing activities, will continue strongly in order to cope with an increasing population of perhaps 30 million by 2050 (ATSE 2007).

Figure B2: The critical sectors in future energy patterns in Australia.



Source: ATSE questionnaire

The discussion of the current and future energy scene in Australia in the workshops together with the questionnaire reinforced the need for new technology approaches in the electricity industry, transport and use of energy in industry, commercial buildings and dwellings.

2. NANOTECHNOLOGIES FOR ENERGY TECHNOLOGIES WHICH COULD BE DEVELOPED IN AUSTRALIA

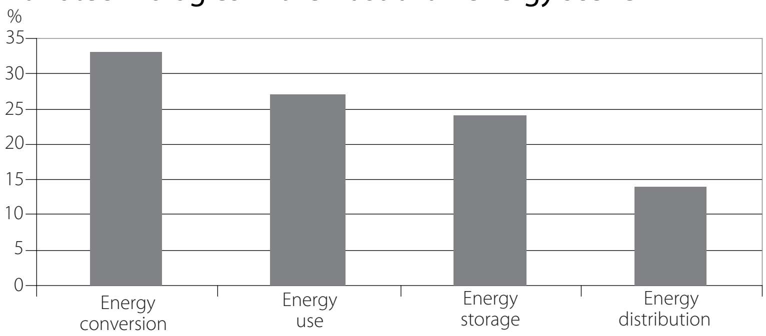
Chapter 2 identified a number of energy technologies that could be developed and used in Australia, where there is activity in most of these areas, particularly in the market leader and rapid follower categories. The Australian Government has provided funding for energy R&D through various mechanisms. CSIRO has a major Energy Transformed Flagship Program with the aim of halving greenhouse gas emissions and doubling the efficiency of new energy systems covering electricity generation, transport and distributed energy applications. Private funding has been invested in establishment of wind power clusters and in commercialisation of solar cells and fuel cells. There is considerable interest in the concept of a Hydrogen Economy in Australia and a Hydrogen Energy Research Cluster has been set up in CSIRO.

Against that background the workshops discussed the extensive research activities in nanotechnologies in Australia and their applications to energy production, transmission, storage and use. In areas of renewable energy the discussions strongly supported the opportunity areas of photovoltaics and energy conservation in the short term, and energy storage and hydrogen production and storage in the longer term. The potential for hybrid vehicles and for weight saving in vehicle materials and design was stressed. Further, because of Australia's major use of coal and natural gas for power generation, there is potential to use nanotechnologies in clean coal technology, including carbon dioxide separation and capture, in the medium term. The production of liquid hydrocarbons from natural gas conversion or from coal conversion in the longer term offers opportunities for process improvement using nanomaterials as catalysts. Environmental applications such as treatment of waste water from steam generators are possible in the short term.

The responses to the questionnaire reinforced the points made in the workshops:

- Most promising areas in the energy scene for application of nanotechnologies in Australia were energy conversion and energy use with energy storage and energy distribution rated lower (Figure B3).

Figure B3: Promising areas for application of nanotechnologies in the Australian energy scene



Source: ATSE questionnaire

Most promising specific areas were considered to be in photovoltaic systems, fuel cells, catalysts, hydrogen production and storage, environmental management and energy conservation. In all of these the development of suitable nanomaterials is the critical factor but then these need to be integrated into operating systems.

The discussions in the workshops reinforced the view that nanotechnologies have a significant role to play in most areas of energy in Australia and also identified a number of opportunity areas.

3. COMMERCIALISATION OF RESEARCH IN AUSTRALIA

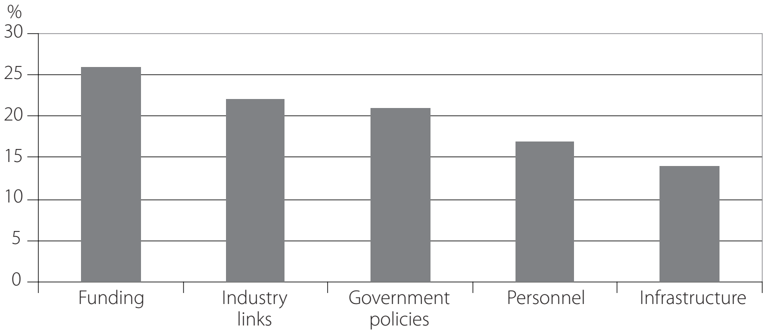
The discussion of commercialisation issues in the workshops highlighted:

- capital raising – the problems of taking research to commercialisation were emphasised and the need for government support to take processes and products to a demonstration stage was emphasised;
- limitations of the size of the Australian market – economies of scale in many new products can only be achieved by manufacturing in overseas markets. This means keeping control of intellectual property in Australia and ensuring that continuing R&D remains in Australia;
- the role of research institutions in innovation – difficulties faced by researchers in translating research into commercialisation were highlighted. Researchers in general are not trained in business skills (this is seen as a priority area by the BCA, 2006b);
- cost of fossil fuels – the low cost of indigenous fossil fuels was seen as a major disincentive to development of new technologies. Carbon pricing is a major issue needing attention; and
- critical role of materials – many of the possible developments in energy technology depend on improved or new materials, especially nanomaterials. These are not necessarily classed in the Energy and Environment sector of the Invest Australia report and thus the current role of nanotechnologies in energy may be underestimated.

The responses to the questionnaires confirmed much of the discussion above. The questions firstly addressed issues of research and development of nanotechnologies in Australia and, secondly, issues associated with their commercialisation. Thus, as Figure B4 shows, the major constraint on R&D was seen as funding followed by industry links and government policies. These two are major components of the innovation system that need attention. Despite concern over funding, both personnel and infrastructure are not seen as major issues. The latter may reflect the stimulus given to research infrastructure by the National Collaborative Research Infrastructure Strategy (NCRIS).

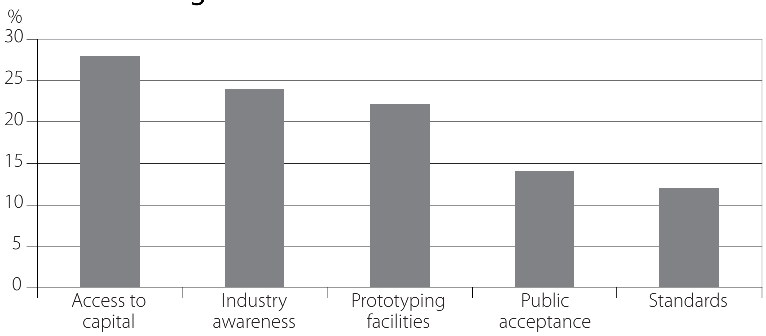
Major constraints on commercialisation were highlighted as access to capital, industry awareness and prototyping facilities as shown in Figure B5. Issues of public acceptance and standards were seen as of lower priority. This may reflect the limited public debate on these latter issues, although they have been discussed in recent major nanotechnology conferences in Australia.

Figure B4: Major Constraints of R&D on Nanotechnologies in Australia



Source: ATSE questionnaire

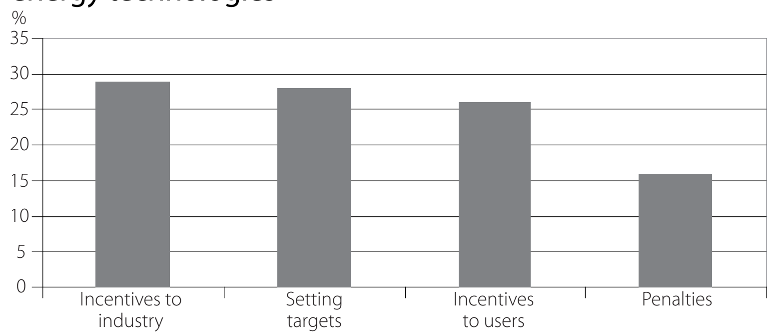
Figure B5: Major constraints in commercialisation of nanotechnologies in Australia



Source: ATSE questionnaire

In considering issues associated with new energy technologies, as Figure B6 shows, the main government actions to stimulate these were considered to be incentives to established industry to innovate, perhaps through public–private partnerships as discussed earlier, coupled with clearly stated and ambitious targets for renewable energy sources. The inconsistency over such targets and lack of strong long-term goals has resulted in uncertainties by investors and has inhibited the development of major local industries, for example, in photovoltaics and in wind turbines.

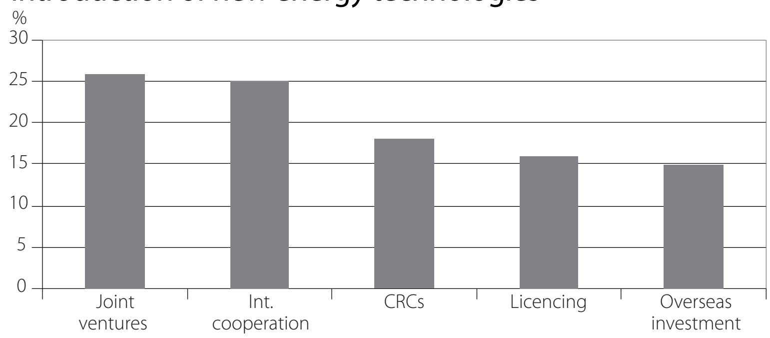
Figure B6: Government actions to stimulate new energy technologies



Source: ATSE questionnaire

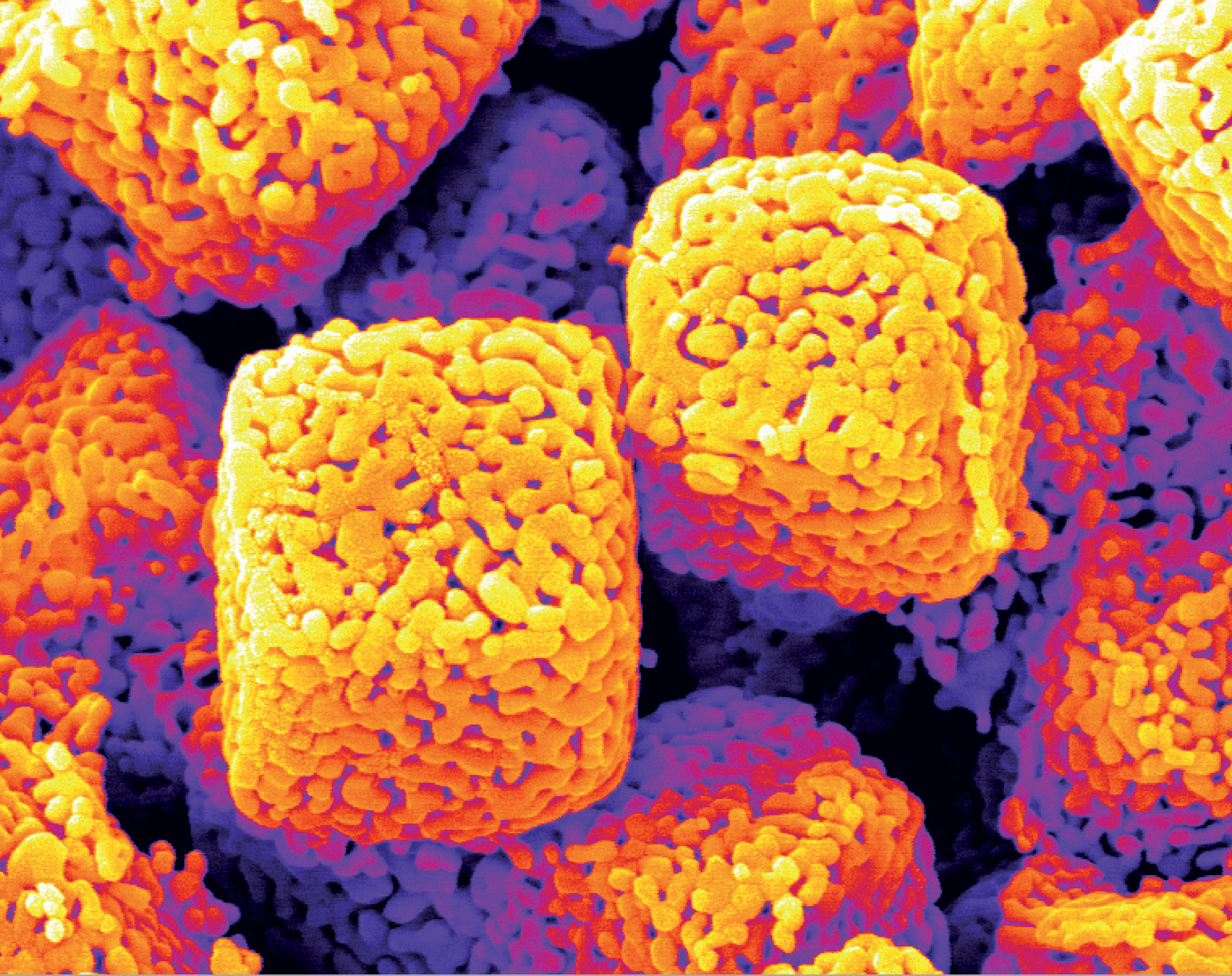
In considering the most effective ways to develop capability in Australian industry in new energy technologies, joint ventures and international cooperation were ranked most highly as shown in Figure B7, perhaps because of the large investments involved and the desire to maintain a strong degree of control. Cooperative Research Centres (CRCs) and licensing were seen as less effective measures.

Figure B7: Most effective way to develop capability for introduction of new energy technologies



Source: ATSE questionnaire

The discussions emphasised the pivotal role of Government through consistent and sustained policy initiatives such as challenging targets for reduction of greenhouse gas emissions, targets for the contribution of renewable energy sources such as solar and wind and application of feed-in tariff schemes for electricity generated in domestic and commercial systems. A clear strategy is essential to the future of the development and application of nanotechnologies in energy systems in Australia and thus the development of a viable nanoindustry sector.



COVER PHOTO: University of Queensland

Energy and Nanotechnologies: Strategy for Australia's Future

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