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Fuel cells, hydrogen and energy supply in Australia

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Abstract

Australia is unique in terms of its geography, population distribution, and energy sources. It has an abundance of fossil fuel in the form of coal, natural gas, coal seam methane (CSM), oil, and a variety renewable energy sources that are under development. Unfortunately, most of the natural gas is located so far away from the main centres of population that it is more economic to ship the energy as LNG to neighboring countries. Electricity generation is the largest consumer of energy in Australia and accounts for around 50% of greenhouse gas emissions as 84% of electricity is produced from coal. Unless these emissions are curbed, there is a risk of increasing temperatures throughout the country and associated climatic instability. To address this, research is underway to develop coal gasification and processes for the capture and sequestration of CO_2. Alternative transport fuels such as biodiesel are being introduced to help reduce emissions from vehicles. The future role of hydrogen is being addressed in a national study commissioned this year by the federal government. Work at the University of Queensland is also addressing full-cycle analysis of hydrogen production, transport, storage, and utilization for both stationary and transport applications. There is a modest but growing amount of university research in fuel cells in Australia, and an increasing interest from industry. Ceramic Fuel Cells Ltd. (CFCL) has a leading position in planar solid oxide fuel cells (SOFCs) technology, which is being developed for a variety of applications, and next year Perth in Western Australia is hosting a trial of buses powered by proton-exchange fuel cells.

Keywords: Fuel cells; Hydrogen; Energy supply; Australia

1. Introduction

The rapid development of fuel-cell technology in recent years, together with a global concern for reducing greenhouse gas emissions is focusing world opinion on options for future hydrogen economies. Australia is unique in terms of its geography, its population distribution and its abundance of natural energy sources. The structure of the economy also has a major impact on its greenhouse-gas emissions profile and its consequent approach to addressing climate change. Energy and greenhouse-gas intensive industries, such as non-ferrous metals and heavy engineering, make a significant contribution to Australia's economy, but the high value that Australia places on traditional energy sources comes at a cost. With a population of less than 20 million, Australia releases more greenhouse-gas emissions per head of population than any other country. Whilst the totals may be small, they are a concern for governments, and for environmental organizations within Australia. The Federal Government has now set environmental sustainability as a key research priority and in 2002 commissioned the first National Hydrogen Study. This paper discusses some of the issues concerning energy supply and demand within the country and the prospects for a future in which hydrogen may play a key role. Consideration is given to issues that relate to greenhouse gas emissions and how the use of hydrogen may help lower emissions. Finally, the interest in fuel-cell technology within Australia is reviewed.

2. Geography

Australia is the sixth largest country in the world with a land area of 7 686 850 km^2 (slightly smaller than the US contiguous 48 states) and its population is estimated to grow by 32% between 1990 and 2020 [1]. This is being driven largely by immigration, fostered by a rich tourism industry in states such as Queensland and New South Wales, and an abundance of natural and mineral resources across many states, which give the country a relatively high standard of living. Australia is the 14th largest world economy, with a

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Table 1
Population statistics [2]

City	Population (millions)	Population density (people per km^2)	
		1986	1996
Sydney	4.085	620	690
Melbourne	3.466	385	412
Brisbane	1.627	186	230
Adelaide	1.096	188	199
Perth	1.381	141	164
Shanghai	7.649		6600
London	6.638		4300
New York	8.008		9300

GDP in 2000/2001 of AUS$ 670 billion (around US$ 361 billion) [1]. Amongst developed nations, the economy is relatively strong but as it grows, so industries and consumers become more energy-intensive.

The population density of Australia as a whole is as low as North America (some 13 people per km^2). Even in the five major cities of Sydney, Melbourne, Brisbane, Adelaide, and Perth the population densities do not exceed 800 km^{-2}, which is very small in global terms (see Table 1). The distribution of population (Fig. 1) has a major impact on energy use—electricity-distribution systems are spread out and reticulated natural gas systems tend to be restricted to metropolitan centres. Transport is clearly a major user of energy, with significant air traffic between states, and road and rail systems within and between urban centres.

Australia is perhaps unique in also having a wide range of climatic zones, long distances between urban centres, and land use patterns that are still undergoing significant change. Agriculture accounts for around 26% of total merchandise exports, valued at just over AUS$ 30 billion in 2000/2001. Agricultural and pastoral properties in Australia cover well over half the land area, of which nearly 90% is used for grazing livestock—particularly cattle and sheep. Unlike most other industrialized countries, land use patterns in Australia are still changing and the land use and forestry sectors are a net source of greenhouse gas emissions. Despite the generally arid to semi-arid landscape, Australian native forests cover about 21% of the continent, mostly being woodland and mallee trees. Australia also has more than 1.3 Mha of forest plantations. Less than 1% of the plantation estate is harvested each year.

3. Energy and hydrogen sources in Australia

3.1. Coal

Australia is rich in energy sources, both in terms of fossil fuels and natural or renewable energy sources. There is an abundance of coal with significant reserves of both black

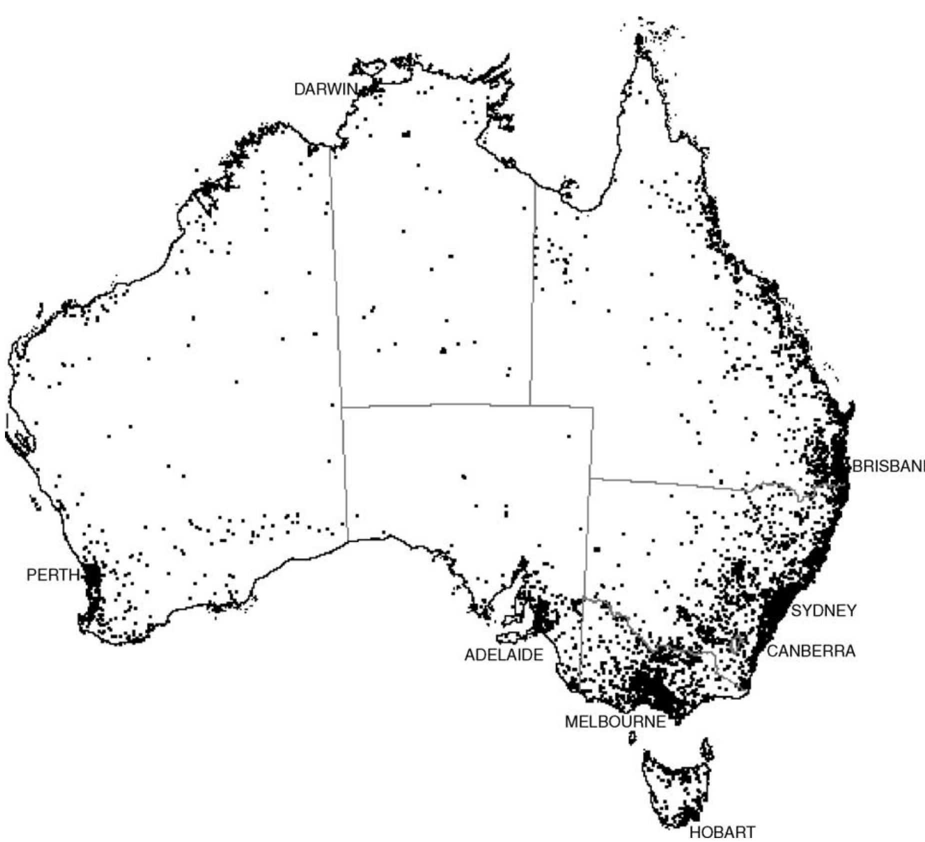

Fig. 1. Population distribution (one dot represents 2000 people).

and brown coal. Estimates of reserves vary widely, with BP figures suggesting a supply of 261 years (compared with a global supply of 216 years) [3]. Many put estimates of Australia's coal much higher, with some over 500 years [4]. In terms of infrastructure, the coal extraction, transportation, and power generation industry in Australia is well established. Coal reserves for both export and domestic use are located within 200 km of the eastern Australian capitals (Brisbane, Sydney, Melbourne, Canberra, Hobart), with almost all within 500 km of major centres.

Coal is important to Australia economically, socially, and environmentally. Black coal is used to generate 84% of Australia's electricity. In addition, around 78% of all mined black coal is exported, amounting to 10% of the country's total exports. The industry also employs around 20 000 directly. On the negative side, electricity generation from black coal accounts for about 30% of total emissions of CO_2, excluding net land-use change.

3.2. Coal seam methane (CSM)

The development of coal seam or coal bed methane within Australia has tremendous potential with inferred resources ranging as high as 532 000 PJ [5]. A large percentage of these reserves occur in the Bowen Basin of Central Queensland and the Sydney Basin in NSW, but substantial resources are also to be found in the Gloucester and Surat basins.

BHP Coal Illawarra operates four underground coal mines located northwest of Wollongong. Three mines, Appin, Tower, and West Cliff produce around 3.5 Mt of coal per year mainly for steel making, and up to the 1990s these mines were producing 250 Mm^3 per year of coal seam methane which was being vented into the atmosphere. In 1994, BHP commissioned a 94 MW power generation plant consisting of 94 gas engines at the Appin and Tower mines to use waste CSM from the mines. In 1997, this was extended to the third mine. The project now achieves a reduction of nearly 3 Mt of CO_2 eq. per year. This makes it one of the largest greenhouse-gas reduction projects in Australia.

Even more significant is the production of CSM in Queensland [6]. Many estimate that reserves could be over 25 000 PJ in this state alone. The first commercial production started in 1996 with gas from the Moura mine feeding into the Wallumba–Gladstone gas pipeline. In 2002, some 25% of the state's gas demand was met by CSM and this year production is expected to be 26.6 PJ, or 30% of the total gas demand in Queensland. Since 1998, some Aus $ 1.4 billion of public money has been raised to fund CSM projects. It is still a fledgling industry but in recent years three developments have helped it to grow [7]. The first was the construction of the 385-MW Swanbank 'E' power station (Queensland) in 2002. This is fuelled with CSM from fields in western Queensland. The second was the award of the Townsville power station supply to the Enertrade methane consortium in February 2003. This is expected to result in AUS$ 500 million investment in energy infrastructure in north and central Queensland. Its main features include the development of a new CSM production field in central Queensland, and the construction of a 391-km pipeline to take the CSM to Townsville. The third major development has been the CSM supply contract between Origin Energy and AGL, the nation's largest energy provider. Origin Energy is now the largest producer of CSM in Australia and supplies in excess of 25 TJ per day or 60% of Queensland CSM sales. The Origin Energy/AGL contract has been a setback to the prospects for constructing a AUS$ 4.6 billion natural gas pipeline between Papua New Guinea and Australia.

New South Wales is also increasing its production of CSM: Sydney Gas has been selling CSM from Camden to AGL since May 2001 and it is developing 100 new gas wells to meet the demands of two 10-year contracts to sell up to 14.5 PJ per year to AGL, the equivalent of 8% of natural gas consumption in New South Wales.

3.3. Oil

Australia has significant petroleum reserves. Proven reserves (i.e., both economic and uneconomic fields at current prices) are estimated to be between 1 and 3.5 billion barrels. This equates to 14 years supply at current production levels, or only 10 years at the current consumption levels [8].

Despite the indigenous reserves, Australia currently imports over 60% of its oil. This comes from a variety of sources, and in 2000–2001 the largest fractions came from the Middle East (18%), and Vietnam (12%). Significant amounts are also imported from Malaysia, Papua New Guinea, and Indonesia. Major oil pipelines are installed between Australian oil fields and refineries or major end-users. The distances are relatively long, with an average pipeline length of 530 km between well and usage ends [9]. The figures for the finite indigenous reserves and imports provide a strong case for Australia moving away from oil-based energy production, and the development of alternative transport fuels. It puts Australia in an undesirable position in terms of imported oil within 20 years, unless new reserves become available, alternatives are found, or major changes in fuel efficiency and use of light personal vehicles emerge.

3.4. Natural gas

In 1961, natural gas was used commercially in Australia for the first time to generate power at Roma in Queensland. In 1969, it was introduced to Adelaide, Brisbane and Melbourne, but it was not until 1976 that natural gas was supplied to Sydney. Estimates of natural gas reserves in Australia vary quite widely. BP [3] estimates reserves at 2.55×10^{12} m^3 and production at a rate of 3.27×10^9 m^3 per year or 874 PJ) which implies a lifetime of 77.9 years, compared with an expected 61.9 years globally. The Australian Gas Association, on the other hand, estimates reserves at 157 343 PJ (commercial and non-commercial), with production at 1231 PJ and consumption at 996 PJ, implying a lifetime of 178 years [10]. Either way, Australia is in an advantageous position with respect to other sources of natural gas. As a result, some 20% of its production (413 PJ, or 7.6 Mt in 2002) is exported as LNG.

Japan has been Australia's major customer for LNG, with some spot cargoes made to South Korea and USA. Most of the natural gas lies off the coast of Western Australia, with over 50% of Australia's reserves being in the Carnarvon basin (Fig. 2). In August 2002, the North West Shelf Project entered into an agreement to supply China with 3 Mt (about 160 PJ) of LNG per year for 25 years. Substantial new natural gas finds by Exxon Mobil in April 2003 [11] could add another fifth to the nation's resources. These have helped underpin a similar large LNG project initiated by ChervronTexaco and Gorgon Joint Venture under the terms of an MOU signed in August 2003. The Gorgon gas field has certified proven reserves of 12.9 trillion cubic feet, and the Gorgon Joint Venture, whose partners also include Exxon Mobil and Shell, aims to bring at least 2 Mt of LNG annually from Western Australia to markets on the west coast of North America. The Venture is due to start in 2008 and extend until 2028.

Western Australia is also the state with the highest internal consumption of natural gas (369.4 PJ in 2001). Victoria is the next highest (251.2 PJ in 2001) with gas from the Otway, Bass, and Gippsland basins providing over 18% of the state's overall energy needs. Indeed, there are significant deposits of natural gas in most of the major populated states and pipelines connect capital cities and many other major industrial and residential centres. In 2002, a natural gas pipeline was laid across the seafloor of Bass strait from Victoria's Gippsland Basin to Tasmania. This connected natural gas to Tasmania for the first time. The total pipeline infrastructure across the country currently amounts to over 20 000 km (Fig. 2). Local distribution networks are also expanding but are still relatively small compared, for example, with the UK. At 30 June 2002, there were 75 449 km of reticulated gas mains in use compared with 64 292 km in 1995.

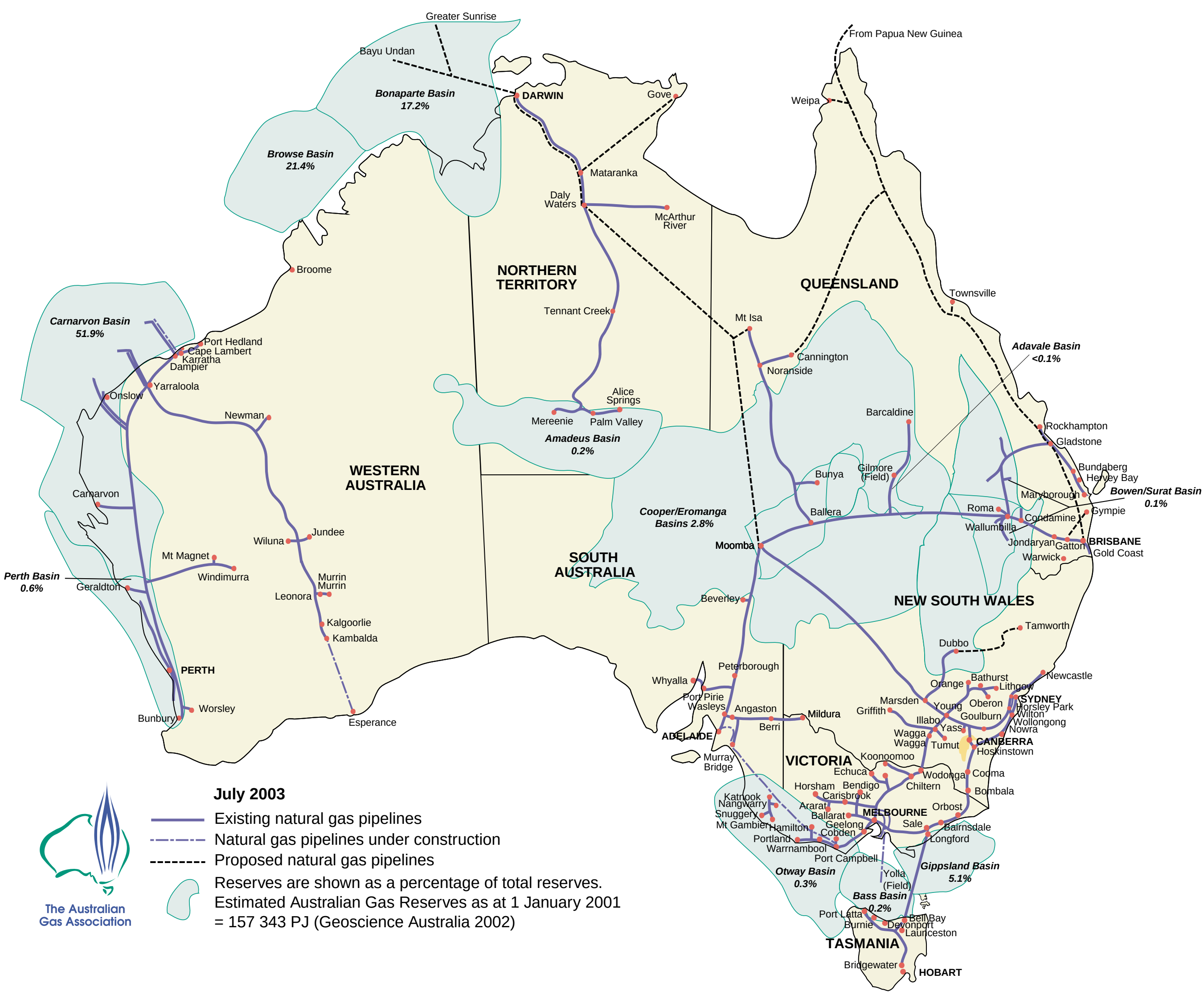

Fig. 2. Australia's natural gas transmission pipelines (courtesy of the Australian Gas Association).

3.5. Electricity

Electricity generation is the largest consumer of energy and, historically, has been one of the fastest-growing sectors. Coal is the principal fuel for electricity generation. In 1998/1999, 84% of electricity was sourced from black and brown coal, while hydro accounted for 9% and natural gas 7%. Whilst coal is likely to remain the main fuel for electricity generation for some years, it is likely that there will be an increased use of natural gas and renewable sources in the longer term [12]. More distributed power generation is also envisaged, particularly in rural areas.

3.6. Renewable energy

Renewable energy currently contributes 5% of Australia's total energy supply and now represents some 10% of Australia's electricity generation. Combustible renewables, which contribute 5.3%, are made up of bagasse used to generate electricity and steam, and wood for home heating. From the 40 Mt of sugar cane harvested annually in Australia, 5.4 Mt of sugar is produced, together with 1.16 Mt of molasses and 6 Mt of bagasse. Already, bagasse is the focus of much research and development since it is a large resource currently under-utilized by the sugar industry. Some bagasse is used to generate electricity (around 250 MW of installed capacity Australia-wide), whilst the rest is either burnt or used as a mulch/fertilizer. At present, most of the bagasse is produced in Queensland, and in 20 sugar mills within the state 163 MW of power is already produced from bagasse. Estimates by the Sugar Research Institute [13] suggest that there is the potential for generation of 1000 MW. In future, bagasse could also be gasified to generate hydrogen, as could landfill gas (currently some 72 MW of installed capacity generating plant is run on landfill gas).

Around 138 Ml of ethanol are also produced each year from molasses (63 Ml) and starch (75 Ml). CSR claim that production could be increased to 360 Ml from molasses for use as an alternative transport fuel [14]. At present, most of the ethanol produced is used for industrial and domestic purposes, with some being exported. There is interest in using ethanol as a renewable fuel, and as a mixture with petrol. Unfortunately, the introduction of blended petrol (E10) fuel has met with political opposition founded on some well publicized mis-information regarding engine damage. Current uncertainty brought about by the lack of Federal policy is also creating resistance to the introduction of ethanol, despite the success of trials in Northern Queensland by the Australian oil company Caltex [15].

Some have estimated that wood could be used to produce electricity for less than the cost of coal fired electricity [13]. The rural location of many of the plantation forests also provides opportunities for decentralized power production. Sawmills produce much useful wood waste but CSIRO has also carried out trials of intensively managed short rotation bioenergy plantations grown on effluent, saline water at Wagga. With rotation times as short as 2–3 years, estimated growth rates for selected eucalyptus are high, at around 15 t ha^{-1} per annum. The Federal Government's 2020 Vision strategy aims to expand the plantation estate of Australia to 3 Mha by 2020, and has noted that a total of 8 Mha of land are available. Wood gasification technology is being developed by CSIRO at the 30 kW scale and a prototype plant incorporating a Capstone microturbine is currently under construction [16].

In 1974, the Snowy Mountains Hydro Power scheme was completed after 25 years of construction. This massive power scheme on average produces some 4500 GWh per year, supplying over 75% of all renewable energy that is available to the eastern mainland grid. In addition, Hydro Tasmania operates 27 hydro-electric power stations in seven catchment areas. These produce an average of 180 MW of power for the state of Tasmania. Unfortunately, Australia has little further large-scale hydroelectric generation potential as most of the commercially favorable sites have already been exploited.

The Roaring Forties, the prevailing westerly winds that circle the earth's high southern latitudes are being harnessed to provide a source of wind energy in Australia. The first small wind farm was established in 1993 at 10 mile Lagoon in Western Australia. Another farm at Huxley Hill on King Island began operating in 1998 with three turbines generating up to 750 kW. Installations have been steadily increasing in number over the past few years with significant wind farms in New South Wales (Crookwell, 1999) and Western Australia (e.g., Nine Mile Beach, 2003). Now Pacific Hydro Ltd. is commissioning Australia's largest wind farm to date at Challicum Hills near Ararat in Victoria. This is expected to produce 52.5 MW from 35 turbines. According to figures from the Australian Wind Energy Association, the present installed capacity of 200 MW in Australia is expected to grow to 2.7 GW by 2010.

Installation of solar heating and solar power (PV) systems are being encouraged throughout Australia with substantial state and federal government grants. In 2002, Australia's production of solar PV systems doubled. The industry now employs over 1000 people and this figure is expected to grow to 6000 by the end of the decade. In 2002, total sales of PV systems amounted to Aus $ 190 million of which Aus $ 100 million represents exports.

Australia has been at the forefront of innovation in solar power and CSIRO, for example, is carrying out work on solar enhanced coal gasification and solar reforming of natural gas [17]. One of the more recent ambitious solar power projects is the planned construction of a solar chimney at Mildura in NSW by EnviroMission. The technology is based on a German concept and will consist of a very tall tower in the center of a translucent canopy. Solar radiation heats the air under the canopy to some 35 °C above ambient and this hot air then rises through the chimney at up to 15 m s^{-1} to create a powerful updraft, which will force the rising air to pass through large turbines placed at the base of the tower. The turbines will be sufficient to generate 200 MW of power.

There are good prospects for the development of wave power generation and a tangible example of this is the Derby Tidal Power Project, in the Kimberley region of Western Australia. It is estimated that the tidal resources of this region alone amount to 300 GW and at a load factor of 0.27 around 700 000 GWh per year is available.

Finally, mention should be made of an important and untapped source of geothermal energy located some 2–5 km below ground. In 2000, Pacific Power drilled some exploratory boreholes in the Hunter Valley region of New South Wales. These confirmed the existence of rocks with temperatures higher than would normally be expected at such depth. This is apparently due to radiogenic heat production in buried granite seams, which means that the granite rock represents a substantial source of energy. As a result of these discoveries, substantial funds are now being spent on exploration for 'hot dry rocks' by Geodynamics Ltd. In April 2003, the company announced that a 3.8 km well had intersected heat-bearing granite near Innamincka in South Australia, with indicative temperatures of 2300 °C, making it the deepest well drilled onshore in Australia and the hottest well drilled anywhere. Geodynamics has an aggressive business plan to build underground heat exchangers and construct multi-MW geothermal power plants.

3.7. Water

Although not an energy source, water is a source of hydrogen and a valuable resource in Australia, which is one of the driest countries in the world. This is particularly so in rural areas which rely on agriculture as the main source of income. Except in coastal areas, hydrogen generation by electrolysis, or other methods of decomposing water, is therefore unlikely to be the preferred option.

4. Energy use and greenhouse gas (GHG) emissions

The total energy consumption in Australia during 2000–2001 was 5060 PJ of which over 28% (1477 PJ) went to electricity generation, 1278 PJ to transport and 1191 to manufacturing industry (Fig. 3). Electricity generation, the largest energy consuming sector, continues to grow particularly through expansion in non-ferrous metals industries and through technological innovations that encourage the use of electrical appliances. Nevertheless, according to ABARE, the annual growth rate in energy consumption in Australia as a whole over the past 30 years has generally declined, from more than 6% in the 1960s to 1.4% in 2000–2001. This is due mainly due to a notable decline in the demand from the iron and steel industry, brought about by a contraction in that sector. Of all the industry sectors, mining is showing the strongest growth in the use of energy, with oil, gas, and LNG usage increasing in this sector since the late 1980s. The other area of buoyant energy consumption is the commercial and service industries sector, which had a growth rate of 3.3% during 2000–2001. This is only slightly less than the average growth rate for this sector over the previous 10 years.

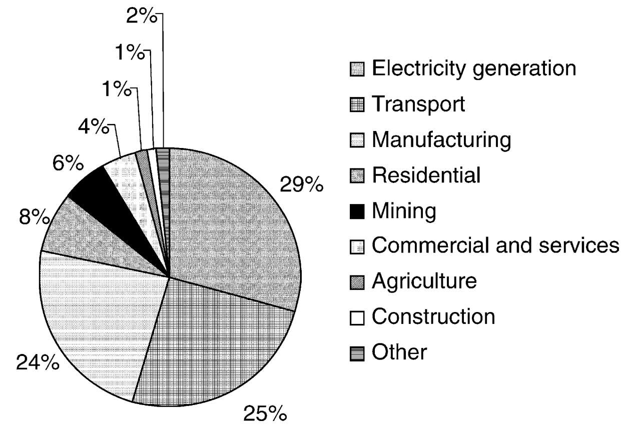

Fig. 3. Energy consumption in Australia by sector.

Given that the energy consumption is growing, albeit slowly, the effect that this has on greenhouse gas emissions is significantly different from many other countries. Currently about 50% of greenhouse gas emissions arise from stationary energy sources, i.e., power stations [18], about 18% from agriculture (methane and NO_x) and about 14% from transport (primarily cars and trucks) [1]. According to CSIRO, coal mining alone is responsible for 7% of these emissions.

Although Australia did not sign up to the Kyoto Protocol to reduce Australia's greenhouse gas emissions to 108% of 1990 levels by 2008–2012, there is widespread agreement that increased CO_2 levels could have a major impact on Australia's climate. At present rates of increase, CSIRO predicts that by 2020 temperature rises of up to 2 °C could occur through most of the continent, and by 2070 temperatures could have risen by 6 °C in the hottest areas. Widespread drying and warming is predicted with the likelihood of increased storm frequency and intensity.

In December 2002, the Australian Academy of Science sponsored a conference to examine the likely impact of greenhouse-gas induced climate change and ways that Australia might adapt to its changed climate. For example, it is widely recognized that the Australian Greenhouse Office has been an effective route to reducing emissions through a series of legislative and economic measures. Nevertheless, easy gains may now be largely exhausted and there is increasing recognition that alternative sources of energy may not offer the means of reducing emissions in the required timeframe (20–40 years).

4.1. Greenhouse gas emissions from coal-fired power generation

A recent study carried out by ACIL Consulting [19] provided an economic examination of how the cost for carbon emissions (carbon tax) could impact in practice on electricity demand and supply. The study showed that the imposition of taxes on electricity supply would only marginally reduce CO_2 emissions at high cost to consumers and to regional economies, thereby concluding that coal will remain Australia's primary fuel for electricity generation. In the time period of the study (to 2015), most emissions reduction would be through the replacement of coal with gas-fired plant.

The problem is that many of Australia's power stations will reach the end of their economic life within the next 20 years, and a switch to natural gas and CSM fired plants through lowering emissions, will lead to more expensive electricity and will still not allow GHG targets, such as laid down in Kyoto, to be met. A strong case can therefore be made for clean coal technologies. COAL 21, an initiative of the Australian Coal Association, was therefore launched in February 2003. It seeks a consensus between major players on steps to be taken on coal, zero-emissions, CO_2 capture, and geo-sequestration, so that government support can be obtained. The outcome of this is that, by December 2003, a National Clean Coal Plan will be released.

4.2. Greenhouse gas emissions from transport

By 2010, under the business as usual scenario, greenhouse gas emissions from Australian transport (both public and private energy end-use emissions) are projected to be 47% higher than 1990 levels. The Bureau of Transport and Regional Economics has recently predicted [20] that the situation by 2020 will be even worse—with emissions by then being 68% higher than 1990 levels.

Clearly, measures need to be taken to curb the threatened increases in emissions from transport. The challenge is being taken up on several fronts, and the first is switching of fuels. Australia now has about 550 000 LPG vehicles which, on a per capita basis, puts the country ahead of Italy, and streets ahead of the US. Interest in biodiesel is also growing and Biodiesel Industries Pty Ltd. (BIA) has constructed the first purpose-built biodiesel production facility in Australia. Located at Maitland, New South Wales, the new production facility was officially opened on 12 March 2003. Numbers of natural gas vehicles are increasing, and all of the new buses in Brisbane, for example, are fuelled with compressed natural gas. As mentioned above, ethanol–petroleum mixtures are being introduced into vehicle fleets with plans for major production facilities well developed [21].

Apart from considering fuels, the design and usage of road vehicles have a profound influence on emissions. Of the current Australian vehicle fleet, passenger cars constitute 9.7 million (80%) of the 12.2 million vehicles on the roads. Road vehicles in Australia compared with Europe are relatively old (average age 10.1 years in 2001) and the fleet is generally ageing [1]. Replacement vehicles can be made more energy efficient although newer cars tend to be bigger. Manufacturers also need to be aware that despite the long distances separating residential centres, most of the driving tends to be in urban areas. More hybrid vehicles are expected on Australian roads [22], and the UltraCommuter vehicle being developed at the University of Queensland is an example of a highly efficient urban commuter vehicle [23].

Reducing greenhouse gas emissions will involve social choices being made, which include consuming less energy and changing consumption patterns. Nevertheless, by using available technologies and exploiting renewable energy sources it is predicted that Australia could cut emissions by 60% by 2050 [24].

5. Production of hydrogen

Hydrogen can be produced from a wide range of source materials, including fossil fuels, biomass, some industrial chemical by-products, and water via electrolysis. The choice for the future will depend on various local factors, including location of resources, available reserves, cost of extraction, cost of transport, and utilization. The techniques used to produce hydrogen will also depend on the allowable conversion efficiency, location, and suitability of local supplies.

Natural gases in Australia are rich in methane and ethane, and range in chemical composition from about 79% methane (the Amadeus–Darwin pipeline) to 91% methane (the Dongara–Perth pipeline), and between 3 and 11% ethane. Nitrogen is present in high concentrations in some pipeline gases (e.g., up to 9% in reticulated gas from the Amadeus basin), and this could cause problems with proton-exchange membrane fuel cells (PEMFCs) through ammonia formation. Nevertheless, processes for the conversion of natural gas to hydrogen are commercially proven and available [25].

Liquid hydrocarbons can also be converted to hydrogen in much the same way as natural gas via a steam reforming or partial oxidation process. Heavy oils can be hydrogenated to lighter fractions which can then be converted by catalytic processes. Hydrogen can also be produced from coal and there are two principal routes—coal gasification, and the use of coal-generated electricity to electrolyse water. The latter is very inefficient and would only be preferred if no other option were available. Coal gasification, on the other hand is relatively efficient, and has been demonstrated commercially. Integrated gasification combined cycle (IGCC) processes have been developed for several years and there are five prototype plants currently in operation with efficiencies close to 50%. The problem is that coal, which has the lowest H:C ratio, produces more CO_2 per mole of H_2 than any other fossil fuel. By employing gasification, however, there is the possibility of achieving high hydrogen purity and low emissions of CO_2 if the latter is captured from the product stream and then sequestered. CSIRO is currently undertaking substantial research in this area. Two active gasification projects are underway, producing 805 000 Nm^3 per day of syngas for hydrogen production, and 20 208 Nm^3 per day

Table 2
Sources of hydrogen in Australia

Fuel	Reserves (years)	Current price (AUS$)	Source to end-user average distance (km)	Notes
Coal	261–500	42.6/t (∼1/GH), black	<500 (∼200 East states)	Extensive infrastructure in place
Natural gas	78–130	∼3/GJ	560 (810 outside Victoria)	Extensive infrastructure in place
Petroleum	10–14	38.3/bbl (∼6.5/GJ)	530	Some infrastructure
Biomass	Limited by available land	Source dependent	100–200	Some infrastructure, potentially inexpensive, renewable

for electricity generation, respectively [26]. In addition, underground coal gasification is being tested at a pilot plant in Queensland with a capacity of 80 000 $Nm^3\,h^{-1}$.

Hydrogen from biomass, be it either waste or from dedicated crop plantations, presents the possibility of large reductions in emissions (with potential zero emissions on a life-cycles basis), due to carbon take-up by growing plants. In terms of hydrogen content, wood is approximately equal to coal, but it contains less carbon (49 wt.% as compared with 85 wt.%) [27]. Biomass also has the prospective benefit of lower NO_x emissions than coal, as it contains less nitrogen. It also has the potential for reducing soil salinity, an important aspect in remote areas of Australia. The major issues with using biomass from dedicated crops are associated with land use and availability. Current estimates [28] indicate that there are over 1 Mha of land that are marginal for agriculture and could be used to produce energy forestry crops, although the economic viability is not yet proven. Hydrogen can be made from biomass via processes that begin with thermochemical gasification, in much the same way as it would be made from coal. The delivered cost is expected to be higher than from natural gas [29]. Alternative biological hydrogen generation methods are the subject of current academic research [30,31].

The characteristics of the main sources of hydrogen for Australia are summarized in Table 2. Note that, apart from biomass, renewable sources have not been included, because their efficiency and costs are difficult to quantify. A recent estimate by Trainer [32] puts the cost of hydrogen via electrolysis in Australia at between 33 and 47 times the cost of hydrogen produced from coal, but several simplifying assumptions were made that may put the costs even higher. The conclusion is that at least in the short term, PV-electrolysis systems do not provide an economic means of hydrogen production in comparison to fossil fuels.

6. Transport of energy and the role of hydrogen

Energy can be transmitted and stored in various forms. Coal has the advantage that it is relatively easy to handle and contain, but the disadvantage of its high carbon content. Liquid fuels such as methanol and oil can be transported by tanker and pipeline. Natural gas has a lower carbon content than both coal and oil, but is less easy to transport over long distances. Hydrogen, may be the cleanest of energy carriers but is the most difficult and costly to transport and store, and therefore is envisaged as a long-term option.

The low cost of electricity produced from coal in Australia has acted as a barrier to the more widespread transmission and distribution of natural gas, which so far is only distributed to customers in the metropolitan areas. Unlike countries such as the UK where the customer base is very broad, in Australia over 90% of natural gas is utilized by industry. Another problem is the sheer distances that separate the major sources of natural gas in Western Australia and Northern Territory to the major centres of population in the eastern states. Bringing natural gas from these remote areas to other parts of the country could be achieved by converting to liquid fuels such as methanol, and proposals for gas-to-liquids processing have been considered for some time. The first tangible outcome of these came from London based GTL Resources who recently confirmed the development of a 1 Mt per annum (3000 t per day) methanol plant on the Burrup Peninsula. The GTL proposal also includes provision for a Fischer–Tropsch plant for synthesizing transport fuel.

Electricity networks, whilst being more mature than gas networks, tend to run along the eastern coast and are fed from power stations close to the mines. The networks do not extend to many areas of the country. In remote regional locations power is usually provided by diesel gensets. In such areas, there is a need for more reliable power supplies that make use of renewable sources such as wind or solar energy.

Thus, for stationary power, coal is likely to continue to dominate as the fuel of choice, providing ways of minimizing the impact of discharged CO_2 can be found. Other fuels such as LPG and Fischer–Tropsch liquids, together with renewable sources, could provide energy in remote areas. For transportation, there is a growing interest in alternative fuels such as biodiesel but the question remains as to what role hydrogen may play in Australia's future.

ACIL Tasman was commissioned by the Federal Government to carry out a National Hydrogen Study 2003. The study has taken the view that since hydrogen is not expected to take a significant share of the energy mix before 2020, forecasting the role of hydrogen would be difficult and a more useful approach would be to discuss of a set of scenarios for possible futures [33]. These will undoubtedly prove useful for setting policy framework, but it is questionable whether such a qualitative approach will help to define transition pathways for the introduction of hydrogen, since these are likely to be governed as much by sound technology development, economic factors, and social choices. To address such issues, detailed models for energy pathways specifically for the Australian context need to be developed and tested.

Some well-to-wheels studies have been carried out by CSIRO [34] and energy pathway studies are now being undertaken at the University of Queensland. These cover both well-to-wheels analysis for transport systems and fuel production, transport, and storage for stationary power systems. These will complement work of a similar nature that has been carried out in the USA [35].

7. Energy systems analysis

A well-to-wheels comparison of alternative fuels for Australian light-duty road vehicles has recently been completed. The fuels considered in this study included unleaded petrol, diesel, LPG, natural gas, hydrogen, electricity, methanol, ethanol, and biodiesel. The relative performance of the alternative fuel pathways was calculated in terms of their full-cycle energy consumption and greenhouse gas emissions. The study led to the following conclusions:

- In general, the best way to utilize an energy feedstock is via as direct a pathway as possible, avoiding any unnecessary energy conversion steps. For the pathways considered, it is preferable *not* to use hydrogen fuel since the energy losses and emissions incurred in its production outweigh the higher efficiency of fuel-cell based powertrains.
- Use of coal as a feedstock for production of vehicle fuels will result in extremely high levels of full-cycle energy consumption and greenhouse emissions.
- Natural gas seems to be a promising transitional energy feedstock for automotive fuels.
- Biofuels do not appear to provide an effective method for reducing greenhouse gas emissions from the light-duty vehicle sector.
- Well-to-wheel pathways based on renewable electricity generation seem to offer the best combination of low full-cycle energy consumption and near-zero greenhouse gas emissions.

As part of an analysis of stationary power systems, modeling of PEMFC systems has been carried out, addressing the requirements for small scale (up to 5 kW_e) remote-area power supplies in the Australian context. For these studies, a complete PEMFC system has been modeled using AspenTech™ and its performance examined when using different natural gas compositions found in Australia. The influence of a natural gas source on reformer efficiency for a particular PEMFC system design is shown in Fig. 4. Such results will provide an information source for small-scale, natural gas, fuel-cell systems, and will help also in the analysis of fuel pathways for stationary systems.

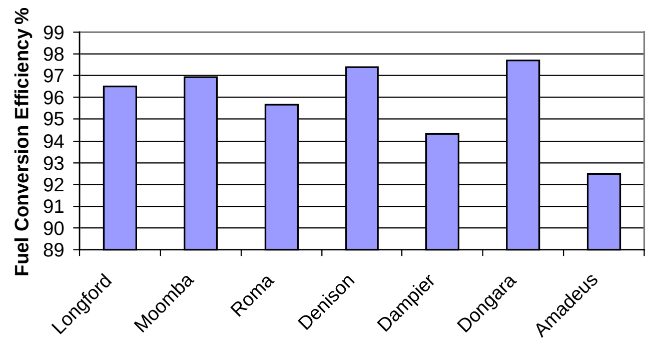

Fig. 4. Influence of source of natural gas on efficiency of fuel processor in PEMFC system.

8. Fuel cells in Australia

There is an interest in fuel cells in Australia which can be traced back at least to the work of Sir Mark Oliphant and John Bockris at Flinders University in the 1970s. Zirconia and yttria, two principle materials used in solid oxide fuel cells (SOFCs), occur in abundance in Western Australia which produces one-third of the world's supply, and also in New South Wales at Peak Hill. In WA, zirconia is manufactured by Australian Fused Materials and by Millennium Chemicals.

8.1. Ceramic Fuel Cells Ltd. (CFCL)

Recognizing the potential of zirconia, CSIRO formed the company Ceramic Fuel Cells Ltd. in 1992 to develop Australian solid oxide fuel cells. Over the past decade, the company has maintained a lead in planar SOFC technology and has designed, built, and operated several different types of stack based on various interconnect technologies in sizes from 100 W to 25 kW. With the various metal–ceramic composite stack designs that were evaluated, thermal cycling proved an elusive goal, as the stress between the mismatch in thermal expansion between the metal interconnect and the ceramic cell led to cell failures and finally stack failure. For this reason, CFCL is now developing a novel all-ceramic stack design. This is characterized by: (i) electrolyte and support cells for operation at 850 °C; (ii) the same thermal characteristics of interconnect plate and electrolyte; (iii) a ceramic seal matched in thermal expansion coefficient to the electrolyte; (iv) compliancy within seal and active areas to take into account height tolerances and the mismatch in the thermal expansion coefficients of coatings in the active area with the seal area. The arrangement of a single circular cell is shown in Fig. 5, and is described in detail elsewhere [36]. Both the cell and interconnect are about 13 mm di-

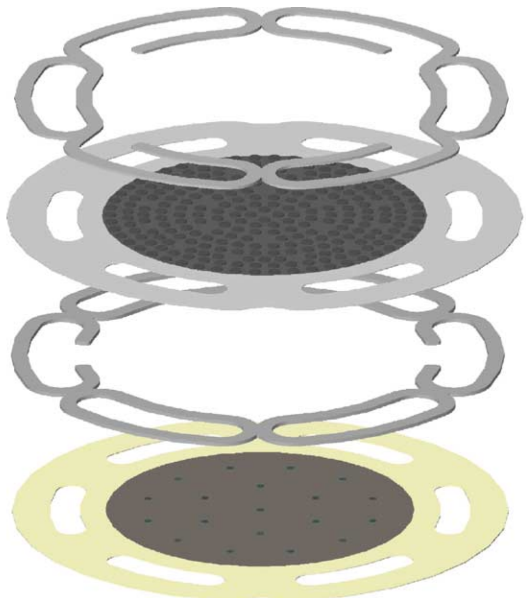

Fig. 5. Disc fuel-cell concept developed by CFCL.

ameter and are fabricated from 10 mol% YSZ containing some alumina, to achieve high strength and toughness. The interconnect has printed conducting layers on either side. Electronic conduction between the two sides is achieved through small holes which are filled with a conducting composite material. Gas-distribution structures are made of cathode material printed on to the cathode side of the cells and anode material on the anode sides. The cell design is commensurate with low-cost fabrication and assembly methods. A multi-layer, fully sintered, repeating unit of 28 pre-fabricated cell assemblies is the building block of complete stacks. The electrochemical output of a 28-cell "Level 1" unit with pre-reformed natural gas ($S/C = 2.25$) at greater than 65% fuel utilization is designed for 150 W. Fourteen such units are assembled to produce a 2 kW stack, the smallest stack size to be used in CFCL systems. Balance-of-plant for natural gas systems has been demonstrated and a large number of test stations are operated by CFCL. The company is now focusing on producing Level 1 units of uniform and consistent properties, and on improving the assembly of 2-kW stacks for a variety of applications.

8.2. Stationary fuel-cell demonstrations and industry development

Interest in stationary fuel-cell systems was shown in Australia by a consortium of companies who funded the installation of a 200-kW phosphoric acid fuel cell (PAFC) plant at the Technology Park in Sydney during 1998. At that time, it was the only such plant in the southern hemisphere [37]. Most recently, there have been proposals for demonstration of imported technology by organizations such as Australia Post and the Engen Institute. Several companies are taking an interest in the developing global fuel-cell industry, as component suppliers and potential system integrators. For example, SE Electronics (WA) is supplying power electronics systems to fuel-cell companies in North America.

8.3. Fuel-cell bus trials

Perth in Western Australia is to take delivery of three fuel-cell buses in 2004 from Evobus. These will be trialled as part of the Clean Urban Transport for Europe (CUTE) program. The buses will be based on the Mercedes Citaro and have been described in detail elsewhere [38]. Unlike most of the other European trials, the Perth bus trials are government led and managed. Hydrogen fuel (provision for up to 50 t per day) will be provided by BP from their Kwinana refinery, and fuel purification will be handled by BOC. The gas will be trucked to the bus depot at Morley in 'torpedo' trailers and it is expected that the fuel supply infrastructure will be in place and commissioned early in 2004. A long process of planning and homologation has taken place to enable this to be achieved. The buses will be housed and maintained by Perth Transit who will be the main operator for the trials. It is planned that the buses will be gradually introduced on to commercial routes after a trial period of 6 months. Eventually, two routes will be serviced by the buses, an central area with a 8–10 km circular route with buses travelling at an average speed of 15 km h^{-1} and an 80 km circular route with speeds ranging from an average of 27 km h^{-1} to a maximum of 80 km h^{-1}. Technical evaluation will be carried out in conjunction with Murdoch University, Perth. The results will be disseminated widely throughout the state and the country as a whole, since funding is being provided by both federal and state governments.

8.4. Fuel cell research

University-based research of fuel cells has been established in Australia for some time. CFCL has supported research in SOFC materials at Victoria University and is now supporting the development of advanced nano-materials for robust SOFCs at the University of Queensland. This forms part of a growing portfolio of work in the nano-materials centre which includes the development of composite membranes for PEMFCs and direct methanol fuel cells (DMFCs), membranes for hydrogen separation, and materials for micro-fuel cells.

Experience of PAFC systems at Murdoch University in Western Australia has led to the evaluation of such systems for remote-area power supplies in collaboration with Industrial Research Ltd. (NZ) [39]. Other university research includes modeling and evaluation of the PEM system (University of Technology, Sydney), and nanocomposite materials research at Monash University.

In addition to research undertaken by CSIRO in hydrogen and fuel cells, the Department of Defense carried out evaluation of fuel cells during the 1980s, using stacks bought from the USA. Although the defense work has ended, CSIRO has maintained an involvement and is now focused on the demonstration and evaluation of PEM systems, with the construction of single cells up to 400 cm^2 area, and stacks up to 1 kW. Test facilities of 0.5 and 3 kW have been set up and these are currently being used to examine systems integration issues, start/stop cycling, lifetime testing, heat and electric load management, and strategies to minimize fuel cleaning.

With interest generated by the National Hydrogen Study, the formation of the Australian Institute of Energy Hydrogen Division, and other recent initiatives, there are good prospects of more hydrogen and fuel cell work being undertaken in Australia.

9. Conclusions

This brief analysis of energy supply shows that Australia faces a dilemma. The country has one of the most cost-effective power supply systems in the world, but it is based on large, remote, base-load coal-fired power plant, which gives a mix of relatively high CO_2 and low efficiencies. To reduce greenhouse gas-emissions significantly in the next 20–40 years requires major changes in the way energy is produced and distributed. As part of developing a national energy strategy, Australia is examining the future role of hydrogen. This is likely to become more important as clean coal technologies are developed, as fuel-for industry, commerce, and residential sectors is decarbonized, and as hybrid and fuel-cell vehicles are introduced into the transport sector.

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References

[1] Year Book Australia, Australian Bureau of Statistics, 2003, (http://www.abs.gov.au).
[2] P.W. Newton, et al., Australia State of the Environment Report (Theme Report), CISRO Publishing on behalf of the Department of Environment and Heritage, Commonwealth of Australia, 2001, ISBN 0 643 067577.
[3] British Petroleum, BP Statistical Review of World Energy, 2002.
[4] R.H. Williams, Toward zero emissions for transportation using fossil fuels, in: Proceedings of the VIII Biennial Conference on Transportation, Energy and Environmental Policy, Monterey, CA, USA, 2001.
[5] AGA, Research Paper No. 2, Coal Seam Methane in Australia: An Overview, The Australian Gas Association, Canberra, Australia, 1996.
[6] J. Draper, Coal Seam Gas in Queensland, NRM Facts—Mines Series, Queensland Government Natural Resources and Mines 2003, Available from http://www.nrm.qld.gov.au.
[7] I. Howarth, Coal-Bed Methane Burning Brightly, The Australian Financial Review, 26 August 2003, http://www.afr.com.
[8] ABARE, Energy Update, 2002 (http://www.abare.gov.au).
[9] APIA Directory Yearbook, The Australian Pipeline Industry Association, 2003.
[10] AGA, Australia's Natural Gas Statistics, The Australian Gas Association, Canberra, Australia, 2003.
[11] N. Wilson, ExxonMobil Makes Biggest Gas Find, The Australian, 25 March 2003.
[12] G. Webb, Review of Future Gas Technology and Infrastructure Options for Australia, The Australian Gas Association, Address to the Beyond Kyoto, Working Party of the Prime Minister's Science, Engineering and Innovation Council, Thursday 19 September 2002.
[13] S. Schuck, Biomass becoming, Australian Energy News No. 7, Australian Department of Industry, Tourism and Resources, 1998, Available online at http://www.industry.gov.au.
[14] B. Kuskopf, CSR ethanol, the potential for growth through renewable fuel, in: Proceedings of the Second Alternative Fuels Conference, Brisbane, IBC Conferences, Australia, 25–26 August 2003.
[15] P. Dunbar, Biofuels: An oil company perspective, in: Proceedings of the Second Alternative Fuels Conference, Brisbane, IBC Conferences, Australia, 25–26 August 2003.
[16] CSIRO, Boost for Small-Scale Electricity Generation Prospects, Onwood Newsletter, vol. 35, Summer 2001–2002.
[17] W. Stein, Solar Thermal Developments in Australia, Presented at the Seminar on Australia and Europe Partnership for Sustainable Energy R&D, Sponsored by CSIRO, 30 June 2002.
[18] C. Riedy, M. Diesendorf, Financial subsidies to the Australian fossil fuel industry, Energy Policy 31 (2003) 125–137.
[19] Electricity Supply Association of Australia, Impact of a Carbon Cost on Australia's Electricity Generation, Generation Directive, ESAA Ltd., Melbourne, Australia, 2002.

[20] S. Stone, Ministerial Opening Address at the Second Australian Alternative Fuels Seminar, Brisbane, 25–26 August 2003, Available from http://www.ibcoz.com.au.

[21] C. Harrison, Dalby Bio-Refinery Ltd., Fuel for the Future, Second Australian Alternative Fuels Seminar, Brisbane, 25–26 August 2003, Available from http://www.ibcoz.com.au.

[22] P.C. Manins, Environmental impact of the new Australian hybrid cars, in: Proceedings of the 15th International Clean Air and Environment Conference, Vic: Clean Air Society of Australia and New Zealand, Sydney, N.S.W., Mitchum, 2000, pp. 117–121.

[23] A. Simpson, G. Walker, M. Greaves, D. Finn, B. Guymer, The ultra-commuter: a viable and desirable solar-powered commuter vehicle, in: Proceedings of the Australasian Universities Power Engineering Conference, AUPEC'02, Melbourne, 2002.

[24] H. Turton, J. Ma, H. Saddler, C. Hamilton, Long-Term Greenhouse Gas Scenarios: A Pilot Study of How Australia can Achieve Deep Cuts in Emissions, Discussion Paper No. 48, The Australian Institute, Canberra, October 2002.

[25] A.L. Dicks, Providing and processing fuel, in: Proceedings of the First International Conference on Fuel Cell Science, Engineering and Technology, Rochester, New York, USA, 21–23 April 2003.

[26] SFA, Gasification Database, SFC Pacific, 2000.

[27] W. Iwasaki, A consideration of economic efficiency of hydrogen production from biomass, Int. J. Hydrogen Energy 28 (2003) 939–944.

[28] Australian Greenhouse Office, Biomass Resources—Renewable Energy Technologies, Canberra, Australia, 2002.

[29] J.M. Ogden, R.H. Williams, Larson, Towards a Hydrogen-Based Transportation System, Princeton Environment Institute, Carbon Mitigation Initiative, 2001.

[30] D.B. Levin, L. Pitt, M. Love, W. Merida, Biohydrogen Production: Prospects and Limitations to Practical Application, University of Victoria, Department of Biology and Institute for Integrated Energy Systems, Victoria, British Columbia, Canada, 2002.

[31] F.R. Hawkes, R. Dinsdale, D.L. Hawkes, I. Hussy, Sustainable fermentative hydrogen production: challenges for process optimisation, Int. J. Hydrogen Energy 27 (2002) 1339–1347.

[32] T. Trainer, Can solar sources meet Australia's electricity and liquid fuel demand? Int. J. Global Energy Issues 19 (1) (2003).

[33] ACIL Tasman, National Hydrogen Study—Interim Report, Produced for The Hydrogen Economy Conference in Broome, WA, 18–21 May 2003.

[34] T. Beer, et al., Comparison of Transport Fuels, Australian Greenhouse Office, Canberra.

[35] C.G. Padro, Hydrogen from Renewable Sources, Presented at The Hydrogen Economy, Broome, Western Australia, 18–21 May 2003.

[36] K. Foger, B. Love, Design and manufacture of CFCL's modular and thermally cyclable stack technology, in: Proceedings of the Eighth International Symposium on Solid Oxide Fuel Cells (SOFC VIII), 203rd Meeting of the Electrochemical Society Inc., Paris, France, 27 April–2 May 2003.

[37] Australian Gas Association, Research Paper No. 11, Fuel Cells—Technologies and Oppurtunities, The Australian Gas Association, Canberra, Australia, 1999.

[38] S. Whitehouse, Perth Hydrogen Bus Trial, Presented at The Hydrogen Economy, Broome, Western Australia, 18–21 May 2003.

[39] M.A. Brown, T.L. Pryor, P. Singh, Comparison of diesel generator, proton exchange membrane fuel cell and alkaline fuel cell system efficiencies for the production of ac power in remote area power supply applications, J. Renew. Energy 3(August (2)) (2001).