Australian Government

Department of Industry
Tourism and Resources

National Hydrogen Study

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A report prepared by ACIL Tasman and Parsons Brinckerhoff for the Department of Industry, Tourism and Resources

For information on this report

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Preface

The national hydrogen study was commissioned on behalf of the Australian Government by the Department of Industry, Tourism and Resources, and its preparation was led by ACIL Tasman.

The study assesses the role of hydrogen in the energy system and makes recommendations that would lay the foundations for Australia's participation in a future hydrogen economy. It builds on the success of the conference, *The Hydrogen Economy – Challenges and Strategies for Australia*, that was held in Broome, Western Australia, in May 2003.

Hydrogen energy is attracting considerable attention from industry, researchers and policy makers around the world. This study explores issues that are especially relevant to Australia, and presents a significant body of knowledge that will assist the development of an informed view of the importance of hydrogen as an energy carrier.

The Government commends the report to all those interested in Australia's energy future.

Contents

Boxes, figures, tables and charts

Acknowledgments

This report would not have been possible without the assistance and valuable contribution of a large number of people, including:

- The members of the High Level Advisory Group (HLAG),
- Lindley Edwards, Managing Director of The Venturebank Limited;
- Simon Whitehouse, Director of Alternative Transport Energy, Department for Planning and Infrastructure;
- Garry Wall, General Manager of the Energy Futures Branch of the Department of Industry, Tourism and Resources;
- Greg Bourne, Regional President BP; and
- Dr Joel Swisher, Rocky Mountain Institute.
- The participants in the stakeholder workshops in Melbourne and Perth; and
- The many national and international participants in the conference *The Hydrogen Economy – Challenges and Strategies for Australia, Including the Tidal Energy Link*, held in Broome from 18-21 May 2003.

While a large number of officials have contributed to this report, including members of the steering group (see Appendix B), the Study Team would particularly like to acknowledge the contributions of: Randall Wilson and Albert Ofei-Mensah from the Department of Industry, Tourism and Resources; Peter McLoughlin, Department of Transport and Regional Services; Dr Adrian Williams and Dr John Wright, CSIRO. The Chief Scientist, Dr Robin Batterham, also provided valuable guidance throughout the project.

The ACIL Tasman Parsons Brinckerhoff team, including Dr John Söderbaum (Project Director), John Daley, Denis Hussey, Greg Martin and Cameron O'Neill from ACIL Tasman, Lane Crockett from Parsons Brinckerhoff, Dr Sukhvinder Badwal of the CSIRO, and Dr Andreas Luzzi of giraSOLAR, welcomed the opportunity to work with the people listed above, and many more, on the National Hydrogen Study.

Overview

Why is hydrogen attracting so much attention?

Access to energy is vital for Australia and world.

Access to adequate supplies of competitively priced energy is a vital precondition for countries to enjoy continued economic growth and for their populations to have improving living standards. Not surprisingly then, global energy consumption continues to grow; Australia is no exception to this trend. Current projections by ABARE show that Australia's consumption of fossil fuels will continue to dominate Australia's primary and final energy consumption in 2020. This consumption of fossil fuels has given Australia among the highest emissions per capita in the world[1].

The two main drivers for the current worldwide interest in hydrogen have their origins in the expected continued strong growth in energy consumption, particularly of fossil fuels. Those drivers are:

Energy security…

- The realisation that fossil fuel supplies are finite and those reserves are increasingly concentrated in regions of the world where there is political or economic instability. In the short to medium-term this exposes energy-importing countries to an increased risk of disruption to their energy supplies. In addition, there is the fear that in the long term there may not be enough energy to meet demand at anywhere near an economically acceptable price.

… and environmental concerns are growing.

- Growing concerns about the environmental implications of energy consumption. These relate both to the impact on local air quality, and the global issue of greenhouse gas emissions.

What does it all mean for Australia?

Australia faces similar pressures to the rest of the world in relation to growing concerns about energy security and greenhouse emissions.

Australia has ample energy resources…

Australia is however fortunate to have significant reserves of fossil fuels (particularly coal and gas) as well as having substantial renewable energy resources in this country. Consequently, Australia is in a better position than many other countries that have little or no energy resources of their own and are thus far more at risk of disruptions to supply.

… but is a significant greenhouse gas emitter.

On the other hand, Australia is among the highest per capita emitters of greenhouse gases in the world. Indeed, the consistent view of the stakeholders

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[1] The reason for this is more to do with the energy intensive nature of Australia's industry sector and a strong reliance on fossil fuels (particularly coal) for power generation, rather than any inherent inefficiency in the way energy is used.

consulted during the course of this Study was that environmental concerns (greenhouse and local air quality) were the primary driver for hydrogen in Australia.

Hydrogen could help Australia reduce its emissions profile.

The government has said that Australia will position itself to maintain a strong and internationally competitive economy with a lower emissions signature. It aims to do this by encouraging cost-effective low-emission technologies to enhance our competitive advantages[2]. Hydrogen has the potential to be one such technology.

Hydrogen is beginning to enter the energy mix in a number of countries, primarily as a result of demonstration projects. Australia has joined this group through the hydrogen bus trial in Perth. At present hydrogen represents a minute share of energy consumption, but it is likely to grow, provided hydrogen technologies can overcome the relative efficiency and cost barriers they face. The history of innovation suggests that this will eventually happen.

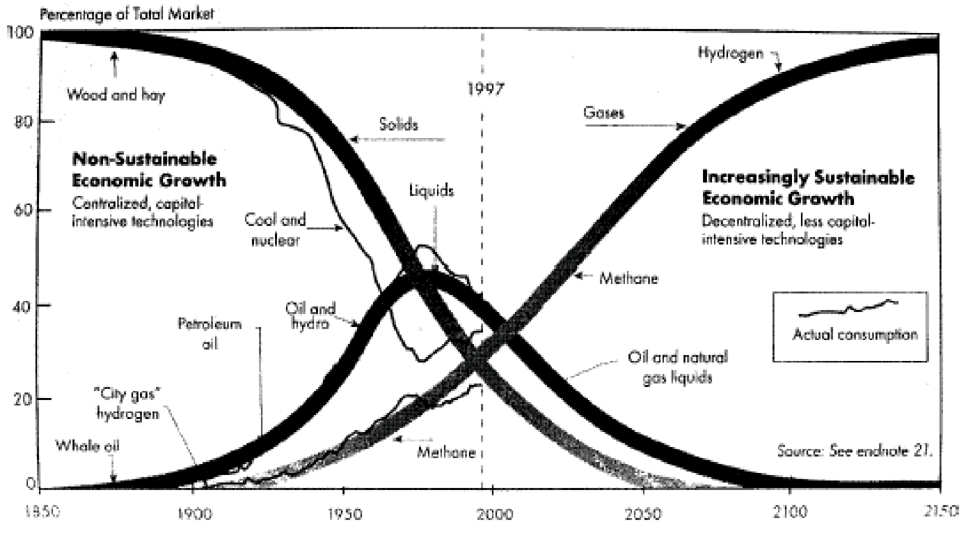
The Stone Age did not end because the world ran out of rocks.

Figure 1 illustrates how the global energy use has changed in the past and how those trends might continue into the future. It shows that the carbon content of fuels has progressively declined over time. Further, it suggests that by 2100 hydrogen would have a dominant share of the energy market.

It is worth noting that changes in energy use patterns do not always occur because of shortfalls in a particular form of energy. Often it is just that something better or cheaper has come along. Hydrogen could well be that something better.

[2] Joint Media Release by the Minister for the Environment and Heritage, Dr David Kemp, and the Minister for Foreign Affairs, Alexander Downer, 15 August 2002.

Figure 1 **Energy systems in transition**

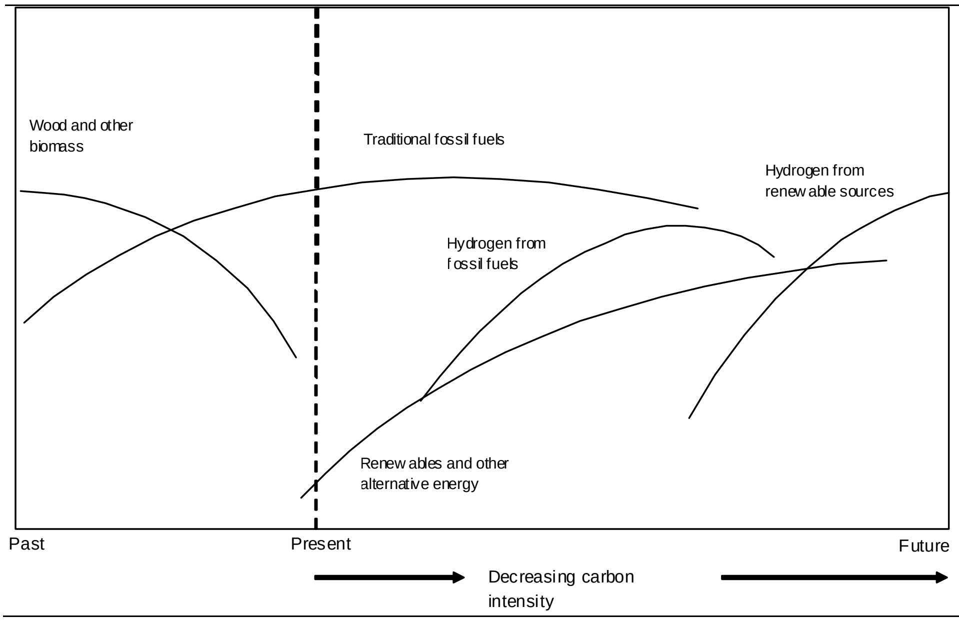


Source: Jiqiang Zhang, "The Prospect of Hydrogen Economy - A Strategic Decision for Every Nation" Undated presentation

A transition to hydrogen would continue an established trend,

Hydrogen can provide the mechanism for utilising fossil fuel resources while reducing emissions. It also can act as an energy storage mechanism and carrier for renewable energy sources. Figure 2 is a stylised representation of hydrogen as a bridge between a carbon economy and a hydrogen economy based on renewable energy with an interim phase where hydrogen is sourced from fossil fuels.

Figure 2 **Hydrogen - more than just a bridge**



Source: ACIL Tasman

...but the timing is uncertain.

There is a growing consensus that the hydrogen economy will eventuate. The major uncertainty is how long a transition might take and particularly when it might start.

A recent major development with relevance for world economies in general, and Australia in particular, is the substantial investment in hydrogen R&D now being made by industry and governments, including the United States, Japan and Europe. This money is being spent on things like product development and the beginnings of infrastructure in order to bring forward the hydrogen economy. There is little doubt that this investment increases the possibility of a hydrogen economy arriving sooner rather than later, primarily through the success of R&D in driving down the costs of using hydrogen.

What might a hydrogen economy look like in Australia?

Let's look forward to 2100.

Jump forward in time – perhaps 100 years, but maybe much less. Scientific research and innovation has successfully developed efficient and cost competitive hydrogen production, storage and transportation mechanisms. Consumer products using fuel cells are the norm. Portable appliances use fuel cells exclusively and batteries have gone the way of vinyl records.

Hydrogen is the fuel of choice.

Hydrogen has become accepted as a clean, safe and sustainable form of energy. Indeed, it is the consumer's fuel of choice. Emissions are a fraction of what they are today notwithstanding continuing population and economic growth. The world, including Australia, has made the transition to a hydrogen economy.

Cities and towns are filled with vehicles conveying people and goods, but there would be important differences – and much for the better. These vehicles would be hydrogen powered, emitting only water vapour and would drive past with only a gentle hum. These vehicles are far more energy-efficient than today's and cost less to use. That efficiency has made the hydrogen fuel tank and fuel cell motor compact and affordable.

Many of these vehicles would refuel at common refuelling stations where hydrogen supplies are received by pipeline from centralised production facilities. Others would fill their hydrogen tanks from home or workplace refuelling stations that would generate their hydrogen from either small-scale natural gas reformers or renewable energy powered electrolysis plants, possibly photovoltaics. Futuristic perhaps – but these technologies, albeit currently costly, are available already.

In this future world – which may be much closer than many expect – home owners have the choice of buying electricity from the grid or supplying their own energy needs with a dedicated fuel cell that provides electricity and thermal energy for heating or cooling. That fuel cell will utilise either hydrogen or natural gas reticulated by pipeline. The latter would be reformed to hydrogen on site. Some consumers may even plug their cars into a socket and use them to provide additional power overnight. Others may even plug them in when they get to work and be paid to provide some of their employer's power and cooling needs during peak hours when the power is most needed.

That hydrogen will come from a mix of sources, including fossil fuels....

In this future hydrogen economy, Australia would still have central electricity generating stations utilising coal and natural gas. However, these will ultimately emit only water vapour. Australia's vast coal reserves would remain a long term, secure and cost-effective source of energy, but power plants would gasify that coal and capture and sequester the CO_2 in geological formations or convert it to useful and environmentally safe solid products. Some of the hydrogen produced would be burnt in high efficiency gas turbines to provide electricity, and some would be piped to customers for use in vehicles and distributed generation plants. A 'critical mass' market for hydrogen vehicles and distributed fuel cell generators will necessarily have developed previously, since it is unlikely that large scale, centrally sourced systems would be financially viable otherwise. However, they are likely to reduce costs significantly and, from that point, greatly accelerate the emergence of this new energy delivery system.

... and renewable energy.

Throughout the country renewable energy would be increasingly used to produce both power and hydrogen. Not only does hydrogen provide an energy storage medium to balance the time variations in direct renewable power output and load variations, but also in some areas it is less costly to transmit than electricity. By now hydrogen distribution infrastructure and end-use markets would largely be in place.

Tasmania would exploit its significant wind resources to contribute to hydrogen supply. In South Australia, the substantial geothermal resources deep underground in the north of the State could be tapped to meet part of its hydrogen demand. Western Australia could utilise a mixture of solar and tidal energy to supply hydrogen throughout the State. Those energy resources could fuel continuing industrial and export development and provide a means to exploit the vast resources of the Kimberley region.

Australia could be a world leader in hydrogen.

This vision of the future would have Australia among the world leaders in hydrogen technology. Australian renewable energy/hydrogen hybrid power supply systems, developed to address local needs, could be exported all over the world. Our fossil fuel resources would continue to sustain major export industries, but in many instances coal exports would now be converted to hydrogen at their destination and flue gases would be sequestered. 'Hydrogen economy' power plants and related sequestration infrastructure could be founded on international technological R&D in which Australian input and collaboration played an important and influential role.

There are opportunities there for the taking…

In short, there is opportunity, in this future, for hydrogen to meet Australia's own and much of the world's energy needs for a very long time, underpinning a secure economic future for the people of this country. In that world there would be few of the environmental problems currently associated with energy production and distribution — and anxiety about key concerns, like greenhouse emissions and air quality would be greatly diminished.

…should we choose to grasp them.

Those opportunities should not be missed, either by inadvertently putting obstacles in its way, or by failing to take the necessary actions now that may be needed to ensure any future hydrogen economy that emerges has characteristics which benefit, rather than detract from, Australia's economic and environmental interests.

How might hydrogen enter the energy mix?

The above section paints a picture of what Australia might look like in a hundred years time in a future where the hydrogen economy is a global fait accompli. But how might that transition happen?

Scenarios are a useful tool for thinking about the future.

The study team has outlined three "what if" scenarios of possible hydrogen futures. The scenarios take a very long-range (out to 2050) look out into the future and speculate about how that future might turn out given a number of assumptions about global developments. It is important to realise that these are not forecasts of hydrogen consumption, but rather word pictures of possible futures.

The scenarios must be long-range since these are the time frames that are generally accepted as being associated with any transition to a hydrogen economy. Obviously, there is always a great deal of uncertainty about how the future might unfold and the further one looks ahead the greater that uncertainty becomes.

The scenarios can be categorised as relating to high, medium and low hydrogen penetration in the energy mix. Each scenario contains a set of assumptions about what the application for hydrogen might be and the time frame in which it might emerge. The scenarios draw on previous studies and stakeholder discussions about how a transition to a hydrogen economy might occur.

Three assumed end uses for hydrogen.

The scenarios assume that the main end uses for hydrogen in Australia in the period to 2050 will be:

- road transport;
- distributed heat and power generation; and

- portable electrical appliances (for example, portable computers and mobile phones).

While these end uses are likely to dominate, there is a strong likelihood that other uses will emerge over the 50-year period covered by the scenarios. For example, recent reports have suggested that there could be a market for hydrogen powered fuel cells in power back-up systems.

Hydrogen costs are still high,

The most important factor affecting the development of a hydrogen economy is the relative cost of using hydrogen as an energy source compared to conventional fuels. Currently that cost comparison does not favour hydrogen. However, technology is constantly developing and there is an expectation that the relative cost of hydrogen will fall. What is less clear is the time frame for that to happen.

...but they will decline.

It is however possible to identify conditions that should favour the emergence of a hydrogen economy. Hydrogen may be a more important fuel in the future if one or more of the following are true:

- rates of economic growth are generally high;
- there is a high level of environmental consciousness and, specifically, high motivation to curb greenhouse emissions – manifested by public policy settings that drive changes in end-user behaviour and;
- rates of technological progress and innovation are high and outcomes favour hydrogen; and
- higher prices for conventional energy improve the relative cost competitiveness of hydrogen.

The Study Team calculated hydrogen demand in 2030 and 2050 (see Table 1). Demand from the transport sector is the largest component of total demand in all scenarios.

Table 1 **Calculated Australian hydrogen demand by scenario and conventional energy equivalents**

	2030			2050		
	Scenario			Scenario		
Possible demand	1	2	3	1	2	3
Million m^3 H_2	18,002	10,800	6,611	42,050	25,206	11,797
Energy equivalents						
• Million m^3 natural gas	5,254	3,152	1,929	12,272	7,356	3,443
• kilo tonnes black coal	6,943	4,165	2,550	16,217	9,721	4,550
• kilo tonnes brown coal	13,500	8,099	4,958	31,533	18,902	8,847
• GWh of electricity	54,004	32,398	19,832	126,143	75,614	35,389

Source: ACIL Tasman estimates

By comparison, the amounts of total production of these energy forms in Australia in 2001/2002 were: 33,173 million m^3 for natural gas; 273,000 kilo tonnes for black coal; 67,000 kilo tonnes for brown coal; and 201,000 GWh of electricity.

The portable market could be very important.

Demand for use in portable appliances is relatively insignificant in energy terms, but may be highly important in other ways. Demand from this sector is likely to be the first to emerge and while the energy demand for each fuel cell is very small, the potential size of the market could lead to substantial cash flows for fuel cell manufacturers. This income could fund further R&D accelerating further improvements in efficiency and cost reductions. In addition, the potential benefits in terms of achieving public acceptance of fuel cells are considerable. Australia's elaborately transformed manufacturing sector is relatively small, capturing the opportunities associated with the emergence of this new market will therefore be a key challenge.

Does Australia need to do anything?

Doing nothing is not the best option.

Some argue that Australia does not need to play an active role in hydrogen related R&D and could delay adapting to a global shift to a hydrogen economy. The study team concludes that this is not the preferred approach. The reasons are straightforward:

- Australia is part of the global economy and there are potentially significant costs associated with adopting an isolationist approach to developments in the rest of the world in general, and our major trading partners in particular;
- many of our trading partners are increasing their activities in the hydrogen area, including launching collaborative R&D efforts and participation in these would provide valuable opportunities;
- Australia's strong interest in protecting our environment.
- in addition, there is a strong risk that the rest of the world might penalise an actual or perceived poor environmental record;
- there is an opportunity through innovation, or being a fast follower, to capture new markets. This could generate significant new industrial development and the ability to influence global standards;
- Australia has competitive advantages in the areas of R&D and access to the primary means of producing hydrogen and every effort should be made to capitalise on these.

What should Australia do?

The rest of the world is stepping up its hydrogen efforts.

Globally, there is a dramatic increase in activity related to hydrogen. While the nature of that activity varies from country to country, there are also strong common themes emerging, namely:

- improving the efficiency and reducing the cost of fuels cells;
- reducing the cost of producing hydrogen;
- pursuing opportunities for carbon sequestration;
- funding demonstration projects (particularly in the transport sector);
- work on uniform codes and standards; and
- forming public/private partnerships.

In recognition of the commonality of interest among countries investing in hydrogen R&D, the promotion of international collaboration in relation to the above themes is an overarching theme.

Australia should do the same.

Australia stands to gain considerably by responding to these same challenges. To do so it must do three things:

1. Establish a policy framework;
2. Encourage collaboration and partnerships; and
3. Lay the groundwork for a possible transition.

Establishing the policy framework

Need a policy statement to set the scene.

There is a consensus among stakeholders that a clear and unambiguous policy signal from governments that hydrogen was included in their thinking about Australia's future energy mix would send a powerful message to stakeholders.

Recommendation One – An Australian vision for hydrogen

The Study Team supports that view and recommends that Australia adopt a vision for hydrogen. The proposed vision explicitly recognises hydrogen's potential contribution to Australia's energy mix, and the potential environmental benefits of hydrogen use. It also commits Australia to playing an active role in the development of hydrogen and related enabling technologies. The suggested form of words is shown in Box 1.

Box 1 **An Australian vision for hydrogen**

Australia recognises the potential of hydrogen to contribute to a more environmentally friendly and sustainable energy mix. Australia will play an active role in the national and international development of hydrogen technologies and related enabling technologies. In doing so, Australia will focus on areas where it has resource, scientific, technical or other advantages.

The vision does not specify any targets for hydrogen use. The market will determine how and when hydrogen will enter the energy mix, recognising that there are a range of energy options available to Australia. The expected emergence of a market for fuel cells in portable appliances is a good example of how this will occur without the need for any government mandates. The key issue is to promote and encourage adaptation to developments that are arising as a result of policy and technological change.

It is up to industry to capture opportunities…

Where there is a role for governments, is in aiding industry to capture the opportunities that will emerge by ensuring that any barriers to doing so are removed or reduced. Given that the use of hydrogen as an energy form is very much in its infancy at this time, it is difficult to be precise about what those barriers might be. However, possible examples include policies and regulations in relation to:

…but governments can help by removing barriers.

- mandates either for or against particular energy forms. For example, a policy that precluded new coal fired power stations would rule out an important option for providing the hydrogen needed for a transition to a hydrogen economy;
- access to the electricity grid for hydrogen fuelled distributed generation facilities;
- the use of at-home refuelling facilities for transport;
- the dual use of hydrogen fuelled cars for private transport or power generation when parked; or
- the taxation treatment of transformed fuels.

Recommendation Two – Capturing the opportunities

Given the uncertainty over what might constitute a barrier in the future this Report recommends that governments commit themselves to reviewing any policies or regulations that are identified by the industry or research sectors as posing a barrier to hydrogen. In doing so, the bias should be towards removing or reducing that barrier.

Australia's portfolio of strategies must be flexible.

Undoubtedly over time a portfolio of policies and programs relating to hydrogen will emerge. However, the high levels of uncertainty that apply to many aspects of the use of hydrogen as an energy source suggests that there should be a regular review process to ensure that any strategies adopted remain appropriate.

Recommendation Three – Flexible strategies and periodic reviews

The Study Team recommends that hydrogen policies and measures should be reviewed every two to three years, possibly by the Productivity Commission, to ensure that they remain appropriate to the circumstances prevailing at the time.

As a corollary to this any policies and programs adopted should be sufficiently flexible to adapt to new circumstances and developments, both in Australia and overseas.

Encouraging collaboration and partnerships

As mentioned above, the recognition of the commonality of interest among countries investing in hydrogen R&D is leading to increased international collaboration. Furthermore, substantial increases in funding for hydrogen R&D by overseas governments and private firms are accompanying that growth in collaboration.

International collaboration can stretch Australia's R&D dollars.

The growth in overseas investment provides potential new funding sources for Australian researchers. International collaboration on hydrogen R&D is an excellent mechanism for maximising the efficiency of the funds available for R&D in this country. In this context, Australia is already participating in the international hydrogen bus trial currently under way in Perth and there are a growing number of other international collaborative opportunities that Australia could participate in. Examples include the US initiative for an International Partnership for the Hydrogen Economy (IPHE) and the IEA Implementing Agreement on Hydrogen.

Recommendation Four – International collaboration

This Report recommends that Australia should seek to participate in bilateral or multilateral hydrogen R&D programs.

In line with the recommended vision for hydrogen, particular attention should be placed on ensuring that the subjects for cooperation take into account Australia's competitive advantages.

Clearly increasing the level of participation in bilateral or multilateral collaborative R&D programs will not be without some additional cost. That additional cost should be recognised when applications for R&D funding are being considered.

Building links within Australia is also vital.

There is considerable hydrogen related R&D under way throughout Australia, but there is a need to better disseminate the nature and results of that research. The lack of communication between Australian researchers and industry has been identified as an important impediment to hydrogen.

Improving linkages between researchers and industry can help ensure that successful R&D outcomes are more quickly commercialised. Such linkages can also assist researchers to prioritise their research. It is important to try to create those linkages at as early a stage as possible. The Perth hydrogen bus trial is a good example of a project that includes stakeholders from a wide range of backgrounds.

Recommendation Five – Encouraging a private sector role

The private sector should be encouraged to play a key role in broadening and deepening collaboration in relation to hydrogen. Government programs and initiatives such as international collaboration should aim to foster the development of strategic relationships, alliances and joint ventures through which Australian businesses can build knowledge and expertise in the field of hydrogen.

While there are a considerable number of hydrogen researchers in Australia, the hydrogen industry has only a small number of participants in Australia. As with any emerging industry sector there is therefore a lack of a champion for the industry.

Australia needs a hydrogen champion.

The collective view of participants in the stakeholder workshops and the Broome conference was that a Group should be to set up to represent the industry's concerns to government and to help implement the recommendations arising from this report.

A champion could have many roles.

The Study Team supports this view and believes that other tasks for an Australian Hydrogen Group should include:

- providing a forum for networking to foster and enhance collaboration between researchers, industry and governments;
- monitoring overseas hydrogen R&D projects and identifying opportunities for Australian participation in these;
- coordinating bilateral and multilateral activities on hydrogen;
- commissioning technology road maps;
- being responsible for informing government decision makers and the broader community on issues relating to hydrogen;
- working to identify and assess any additional barriers that might arise and thus inhibit private sector investment and interest in hydrogen and recommending measures to overcome these; and
- helping promote the adoption of global codes and standards relating to hydrogen, and ensuring that Australia's codes and standards conform with international standards unless the former are anti-competitive or have the potential to stultify innovation.

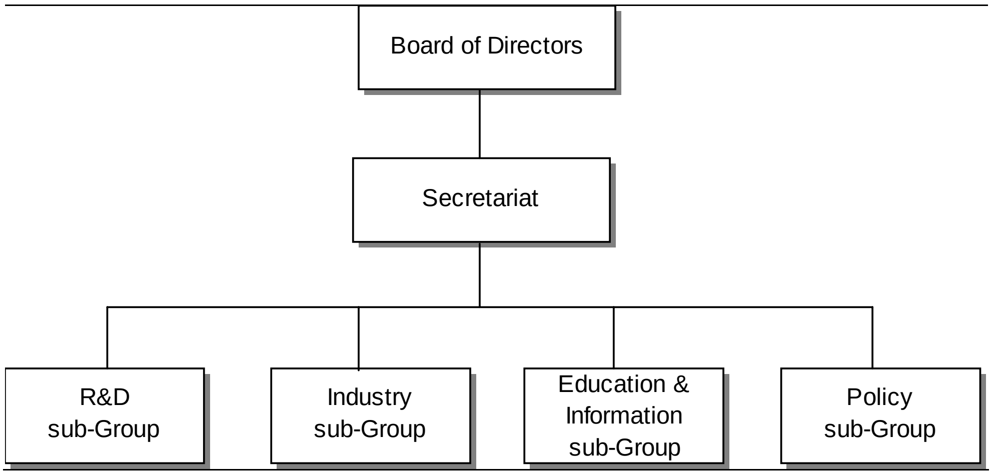
A champion must be representative.

It will be important that the Australian Hydrogen Group represents the interests of all stakeholders in a manner that both is, and is seen to be, independent of any particular interests. Obviously most parties who are working in this area, and who should properly be involved in an Australian Hydrogen Group, will have their own interests to promote. Maintaining the Group's independence will therefore depend upon maintaining a balanced membership structure and an open and transparent decision making process. One possible structure for the Australian Hydrogen Group is shown in Figure 3.

The suggested Board of Directors should be independent, multi-disciplinary and representative. There would clearly be some overlap between the interests and memberships of the sub-Groups, and any others that might be suggested.

Indeed, that would be desirable since it would increase networking opportunities and improve collaboration.

Figure 3 **Possible structure for an Australian Hydrogen Group**



Source: ACIL Tasman

A strong, well-resourced secretariat is vital.

The success or failure of groups of this kind is very dependent upon having an effective secretariat. This in turn requires that it be adequately funded and staffed. Given the emerging nature of the hydrogen industry in Australia it is unrealistic to expect that the industry will have the ability to fully support the Group's secretariat, at least initially. As one of the members of the proposed Group, the government should contribute to its operations and recognise that at least initially it may need to provide a larger share of the funding.

The members of the secretariat will have a mix of skills. They could consist of a mixture of directly employed staff and persons seconded from various organisations. Ideally they should be co-located.

The Australian Hydrogen Group will need time to prove itself…

The Group will need adequate time to demonstrate its value to its members and government support for the secretariat should be provided for long enough to allow it to do so. That period should be at least three and preferably four years. Support arrangements should be reviewed at the end of two years.

…but ultimately it should become self supporting.

In time, as the hydrogen industry grows and develops, there will be a sufficient number of stakeholders for the industry itself to progressively take on more of the responsibility for funding the secretariat.

Recommendation Six – An Australian Hydrogen Group

We recommend that the government work with industry and research sectors to establish an Australian Hydrogen Group. The Group's participants should be drawn from Australian science and public policy establishments and the private sector, throughout the country. The government should provide support for the secretariat of the Group.

The Study Team is aware of the CSIRO's proposal for a National Hydrogen Centre[3]. The Centre is intended to deliver at least some of the tasks that the study team has identified as being within the remit of the Australian Hydrogen Group. The National Hydrogen Centre proposal is still being developed and it would be premature to commit funds to any other group until the membership, structure and roles of the National Hydrogen Centre are resolved.

It would certainly be inefficient to create two new hydrogen bodies. We commend the initiative shown by the CSIRO and recommend that all parties work together to ensure that their proposal is developed in a way that ensures it can fulfil all the roles listed above.

Consumers and producers need to build confidence in hydrogen.

An important barrier to hydrogen is what is often referred to as the "chicken and egg problem". Namely, without supply chain infrastructure in place consumers cannot be confident that any demand that they might have for hydrogen will be satisfied. Conversely, potential suppliers of hydrogen have little incentive to put in place the supply infrastructure in the absence of a clear demand for their product.

Problems of this nature are not unique to hydrogen. For example, the development of Australia's natural gas resources has often been delayed until long-term supply contracts, that reduce the risk of investment in the supply infrastructure, are in place, whether it is a liquefaction plant or a transmission pipeline.

Governments today are generally reducing their role in the provision of supply infrastructure. Nonetheless, there are public good issues that need to be considered. Two obvious examples in this case are energy security and environmental issues. There are a number of things that governments can do to help build market confidence. They include:

- ensuring that the public have access to the information they require to inform their choices;
- promoting public confidence in the safety of hydrogen as an energy option by working to ensure that internationally accepted codes and standards are developed and adopted;
- encouraging hydrogen utilisation demonstration programs; and
- where appropriate, entering into public-private partnerships to help reduce the perceived risk of hydrogen infrastructure provision.

The first two of these would be among the tasks covered by the proposed Australian Hydrogen Group. The third will be important in the short to

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3 There may also be other groups that come forward with proposals of a similar kind.

medium term. The use of public-private partnerships will assume greater importance in the medium to long term.

Recommendation Seven – Promoting market confidence

To help promote market confidence the government should adopt measures aimed at encouraging the early adoption of hydrogen related technology by consumers, including by:

- providing funding assistance for demonstration projects; and
- creating public-private partnerships, particularly for infrastructure provision.

Laying the groundwork for a possible transition

We should adopt national codes and standards...

As has already been pointed out there is considerable uncertainty surrounding the nature and timing of a possible transition to a hydrogen economy. However, there are a number of things that can still be done now. This includes ensuring that the appropriate codes and standards are put in place.

...that are in accord with international ones.

Ideally those codes and standards should be those that are being developed and adopted internationally. However, Australia should play an active role in that process to ensure that the codes and standards are not detrimental to Australia realising its ambitions to exploit its renewable and fossil resources for hydrogen production or to utilise hydrogen in any particular way.

Again, the proposed Australian Hydrogen Group would have an important role to play in this process.

Recommendation Eight – Codes and standards

Australia should play an active role in the formulation of international codes and standards relating to hydrogen.

The discussion in this Report identified a wide range of different research directions. It is unlikely that Australian researchers are positioned to advance all of these. The question then is how to assign research priorities.

Technology road maps can help define research priorities.

Technology road maps can be a powerful tool for helping to identify research priorities and funding needs. To be most effective road maps should focus on those areas of hydrogen research that capitalise on Australia's competitive advantages. Examples of such areas might include:

- integration of renewable energy resources (for example wind, solar, tidal energy) and hydrogen production;
- fuel cell technologies; and
- utilisation of fossil fuel resources for hydrogen production, in particular coal gasification and distributed gas reformation.

Recommendation Nine – Technology road maps

To assist in better targeting available R&D funding, technology road maps should be commissioned for areas of hydrogen R&D identified as capitalising on Australia's competitive advantages.

Technology road maps will also help in determining what level of funding is appropriate.

What is the timetable for action?

There needs to be a timetable for action.

One of the difficulties with hydrogen is that it can be argued that it is still so far in the future that there is no need to do anything now. Conversely, it can also be argued that the time available can be put to good use in ensuring that any transition that does take place does so with the least possible disruption. The Study Team supports the latter argument and furthermore believes that there are significant opportunities for Australian industry and taking early action will help ensure that those opportunities are captured.

All the recommendations have an important role to play. Some are one-off actions and others have an ongoing nature. In terms of priorities we believe that they can be grouped into three categories.

1. Things to do immediately:
- adopt a vision for hydrogen; and
- create an Australian Hydrogen Group.
2. Things to do over the coming year:
- boost bilateral and multilateral collaboration; and
- commission technology road maps.
3. Things that are ongoing:
- increase the role of industry;
- review strategies to ensure they remain appropriate;
- reduce or remove the impact of any identified impediments;
- work to build confidence; and
- work towards the adoption of international codes and standards.

How far will this take Australia?

The recommendations in this report will not guarantee any of the benefits foreseen. However, every journey begins with a single step and implementing the above recommendations will mean that Australia has taken that first step on a path that could lead to a very different future.

There is no way to be sure what that future might look like. It could be something like the world described earlier in this overview or it might be quite different from anything imaginable here and now.

What the Study Team *is* sure of, is that the prospect of a Hydrogen Age is real and the evidence of its onset – in technology and commercial terms – is already available. It is conceivable that this will be a transition analogous to the one that took place during the industrial revolution. There have of course been many such events. The advent of the Information Age is a more recent example.

The Study Team believes that the recommendations in this report will help ensure that Australia will be among the group of leading nations as the transition occurs. One only has to imagine what life would have been like today if the industrial revolution or the Information Age had not been embraced, to recognise the importance of positioning Australia for a transition to a hydrogen economy.

1 Introduction

There is growing interest in the use of hydrogen as an energy source.

Around the world a growing number of countries are seriously considering the implications of a shift towards a hydrogen economy[4]. There is little doubt that any country that switched to a hydrogen economy would experience enormous changes and face numerous challenges. However, there are also many potential opportunities and benefits that could flow from such a change.

The Australian government decided to conduct the National Hydrogen Study (the Study) to assist governments and other stakeholders to better understand the complex issues surrounding a possible transition to a hydrogen economy and assess the respective roles for each. In particular, the Study is designed to help parties to assess whether the general optimism for hydrogen as a future energy source is justified. The Study is designed to assess all the above from the point of view of Australia's specific circumstances.

Key drivers include the environment and energy security.

There are a many reasons why the use of hydrogen in the energy mix is attracting growing interest. They include:

- Growing concerns about the environmental impact of energy consumption, both in terms of global effects such as greenhouse gas emissions and local impacts such as air quality. These concerns are in turn leading to pressure for the use of more environmentally friendly forms of energy;
- Recognition that reserves of conventional fuels are finite, and that for some fuels, reserve to production ratios are approaching the 20-40 year time frames that most believe would be involved in a possible transition to a hydrogen economy; and
- A growing realisation that the transition issues associated with a shift to a hydrogen economy will be both challenging and complex. A wide range of policy, regulatory, technical, economic, financial, investment and environmental questions need to be addressed. Thinking about these now and starting to put in place the appropriate frameworks and strategies would help to ensure that any eventual transition would be as smooth as possible.

The Broome Conference[5] participants discussed the drivers for a hydrogen economy in Australia. The general view was that environmental concerns were

4 The term "hydrogen economy" is generally used in discussing any transition to the greater use of hydrogen as a source of energy. Clearly any transition would take place slowly and over a long time frame and the term should not be interpreted as suggesting that any transition is likely to be either quick or complete.

5 The conference, The Hydrogen Economy, Challenges and Strategies for Australia, Including the Tidal Energy Link, was held in Broome, Western Australia from 18 to 21 May 2003.

probably the key driver in this country[6]. While energy security was also regarded as an important driver, participants believed that Australia's abundant reserves of coal, gas and renewable energy resources meant that this driver was ranked below the environmental one. Nevertheless, in the longer-term, as finite energy resources declined, energy security would be likely to grow in importance as a driver.

Doing nothing is not an option.

Some may question whether or not Australia needs to play an active role in the current global focus on issues relating to the hydrogen economy. An alternative would be to wait for others to develop the necessary technology and then purchase it. The clear conclusion of the participants in the consultative process was that the latter approach was not a viable one. Reasons for this included:

- Australia is part of the global economy and there are potentially significant cost penalties associated with following a different path from that pursued by the rest of the world;
- There is a strong risk that the rest of the world might penalise what might be perceived as a poor environmental record; and
- There is an opportunity to capture a first mover advantage, both in terms of setting the global standards and capturing new markets. Equally, Australia is unlikely to be able to commit the level of investment being made by others, suggesting that priorities need to be established for Australian investment.
- A significant investment in hydrogen R&D is already being made and additional investment has been foreshadowed: a do-nothing approach would mean scaling back these investments.

The National Hydrogen Study has been prepared in a number of phases. One of the objectives of the Study has been to seek to involve as many stakeholders in the process as possible. To this end there have been a number of opportunities for interested parties to provide input into the Study. These include both formal consultations and via the publication on the ACIL Tasman web site of various reports over the course of the project. In addition the Study benefited from a High Level Advisory Group which provided guidance through the course of the study

The formal consultative mechanisms are listed in Appendix B.

The Study has four main steps: the Issues Paper,

The first stage of the Study was the preparation on an Issues Paper. That document outlined the state of play for hydrogen and explored the implications for Australia of a possible transition to a hydrogen economy.

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[6] The drivers for the growing interest in the hydrogen economy tend to be the same throughout the world although the relative priorities assigned these drivers will vary from country to country.

The Issues Paper examined the opportunities and impediments associated with such a transition across the entire supply chain, namely:

- Production;
- Transportation and distribution;
- Storage; and
- End-use.

The Issues Paper considered the impacts on all stakeholders, including those actively involved in the hydrogen industry today as well as those that are involved in industries that could be regarded as competitors to hydrogen, such as the existing fossil fuel industry.

stakeholder workshops,...

The Study also included two stakeholder workshops, held in Melbourne and Perth. The workshops were used to help ensure that the lists of opportunities and impediments developed by the study team were as comprehensive and complete as possible. They also helped to prioritise these lists and assisted the study team to begin to develop strategies for what needs to be done if impediments are to be overcome and opportunities capitalised on. The information in the Issues Paper and the feedback from the stakeholder workshops formed the basis for an Interim Report.

A key outcome of the workshops was broad agreement that Australia should adopt a vision for hydrogen. A suggested form of words developed in consultation with workshop participants, the high level advisory group (HLAG), and other interested parties is shown in Box 2

Box 2 **An Australian vision for hydrogen**

Australia recognises the potential of hydrogen to contribute to a more environmentally friendly and sustainable energy mix. Australia will continue to play an active role in the national and international development of hydrogen technologies and related enabling technologies. In doing so, Australia will focus on areas where it has resource, scientific, technical or other advantages.

the Broome conference,...

The objective of the Interim Report was to brief the participants in the Broome Conference and to help inform their discussions in the workshops that were held as part of the Conference.

Both the Issues Paper and the Interim Report were published on the National Hydrogen Study web site hosted by ACIL Tasman, and interested parties were given the opportunity to provide comments on those documents.

and the Final Report.

The results of the research done for the Issues Paper, and the outcomes of the Broome conference and the stakeholder workshops, were considered and incorporated as appropriate into this Final Report.

2 Hydrogen demand scenarios

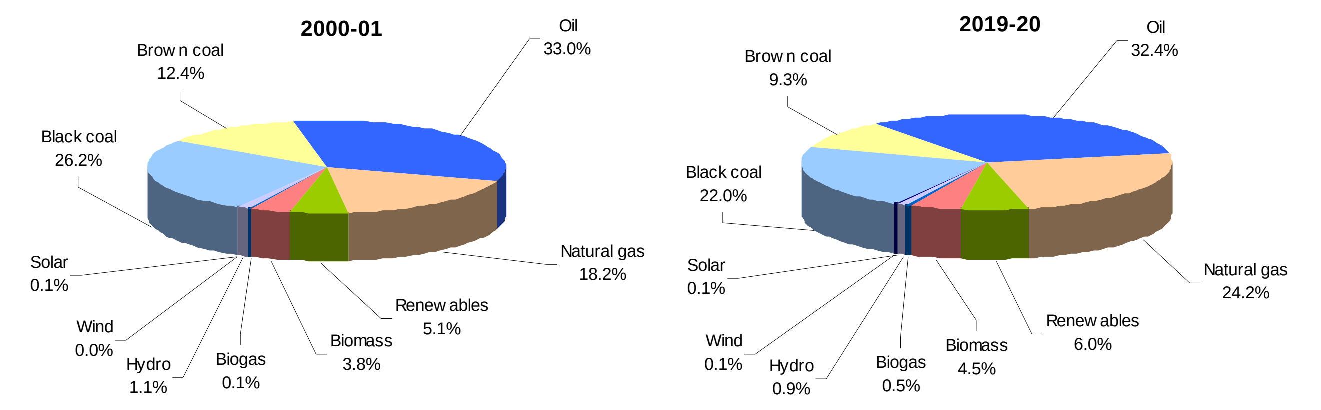
2.1 Australia's energy outlook

Australia's energy demand to grow strongly

ABARE projects Australia's total energy consumption to increase by an average of 2.1 per cent a year out to 2020. Growth is expected to vary between 5 % for the Northern Territory to 1.3 % for Tasmania.

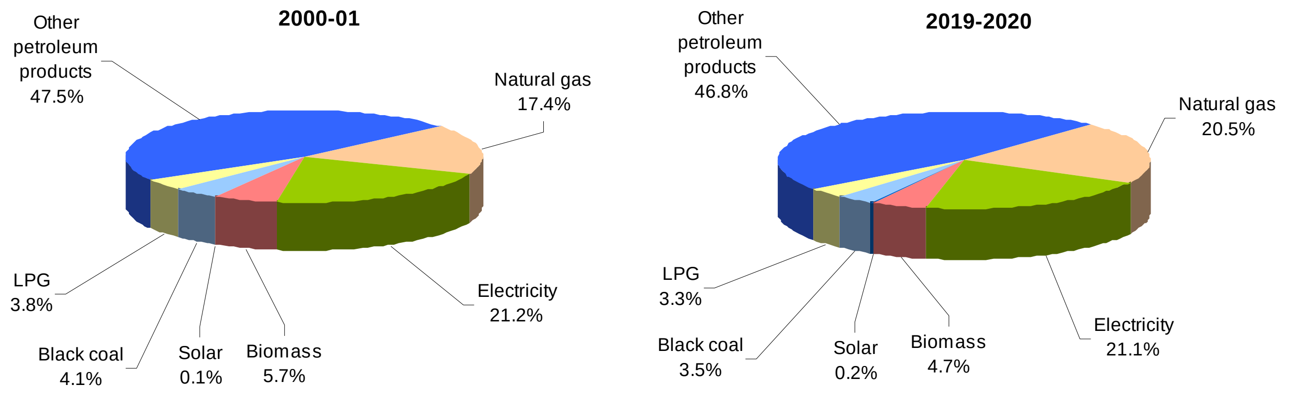
Fossil fuels will continue to supply the majority of Australia's domestic energy needs, with oil's share remaining relatively constant throughout the projection period. However, coal's share of primary energy consumption will fall from 38.6 % in 2001 to 31.3 per cent by 2020. Natural gas consumption will increase by 7 per cent by 2020. Biomass and renewable energy consumption will grow slightly at the expense of coal, as shown in Figure 4.

Figure 4 **ABARE data and projections of Australia's primary energy consumption by fuel, 2000-01 and 2019-2020**



Data source: ABARE, Australian Energy Projections to 2019-2020

Figure 5 **ABARE data and projections of Australia's final energy consumption by fuel, 2000-01 and 2019-2020**



Data source: ABARE, Australian Energy Projections to 2019-2020

Oil will dominate final consumption ...

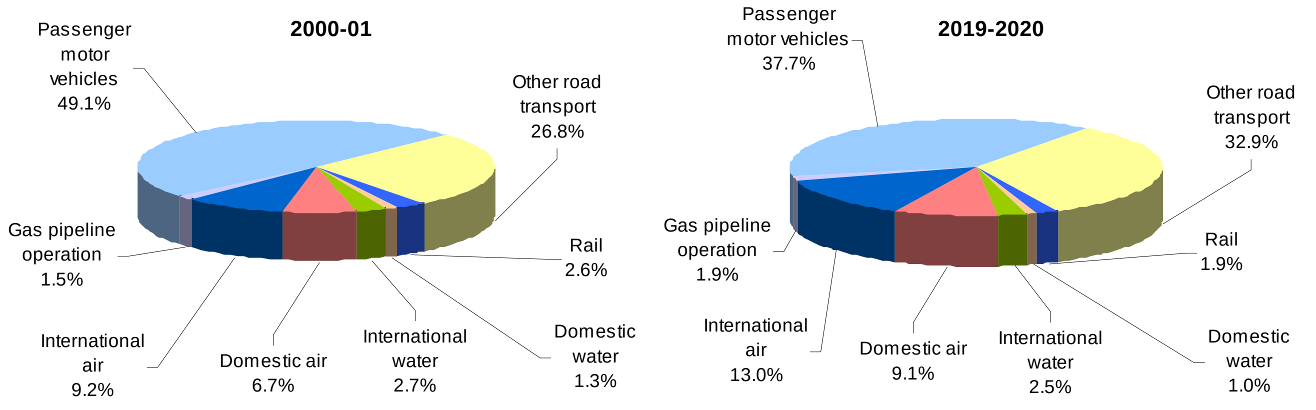
Figure 5 displays the fuel share of final energy consumption in 2000-01 and 2019-20. Petroleum products remain the dominant source of final energy consumption in 2020 despite their share falling from 47.5 per cent to 46.8 per cent. The share of natural gas in final energy consumption increases the most over projection period.

... mainly for transport.

Natural gas demand will grow in the industry sector...

The transport sector, in particular road transport, is the largest consumer of final energy followed by the manufacturing sector. ABARE forecasts that both sectors will increase energy consumption in line with total energy consumption. Road transport accounts for most of the final energy consumption by the transport sector, as shown in Figure 6. ABARE projects that other road transport (trucks, buses etc) will grow from 26.8 per cent to 32.9 per cent of Australia's transport final energy consumption during the period 2001 to 2020. The share of energy consumption by small passenger vehicles is projected to fall.

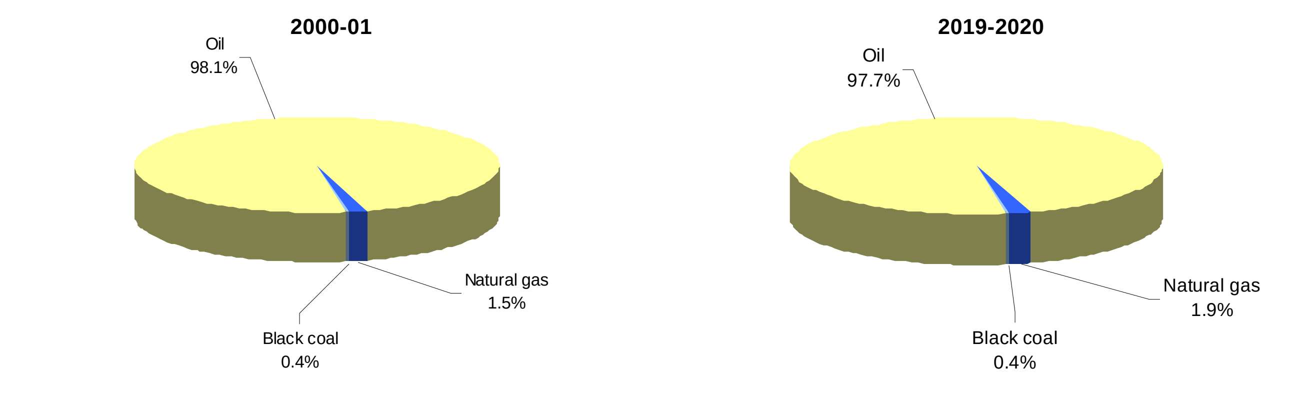
Figure 6 **ABARE projections of transport sub-sector final energy consumption, 2000-01 to 2019-20**



Data source: Data source: ABARE, Australian Energy Projections to 2019-2020

Almost all of the transport sector's energy consumption is petroleum fuel and transport is projected to account for the majority of the total increase in petroleum fuel consumption out to 2020. Figure 7 illustrates the dominant share of oil in the supply of primary energy to the transport sector, a situation that ABARE projects will vary only slightly from 2001 to 2020.

Figure 7 **ABARE projections of transport sector primary energy consumption by fuel type, 2000-01 to 2019-20**



Data source: Data source: Data source: ABARE, Australian Energy Projections to 2019-2020

The manufacturing sector is a significant end-use consumer of natural gas and the fuel share of natural gas in this sector is projected to increase, accounting for a large proportion of the total increase in natural gas.

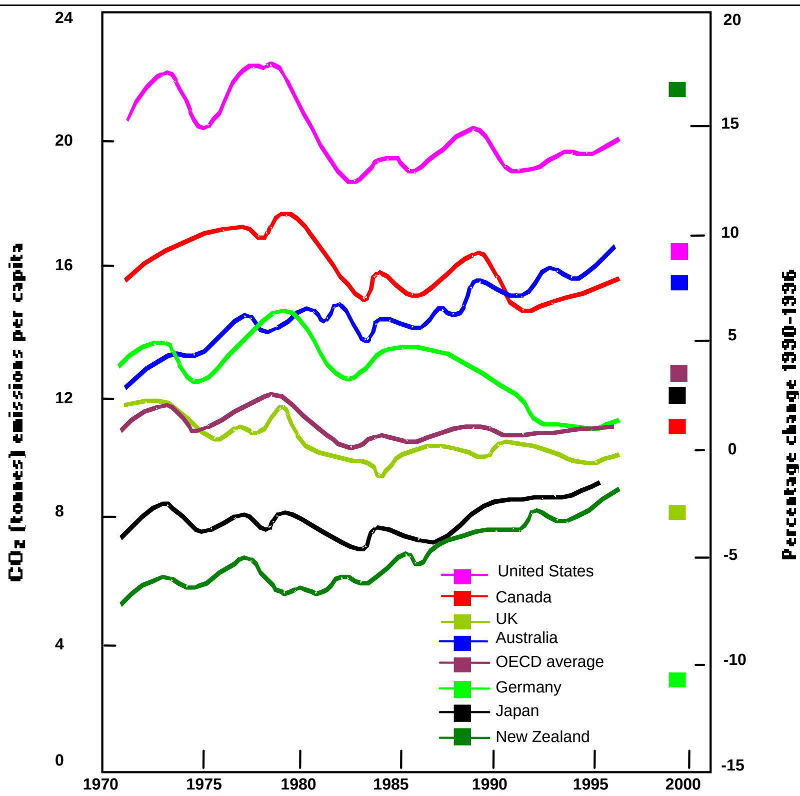
... and in the power sector.

Energy use in the iron and steel sector is projected to increase strongly, driven largely by growth in the WA reduced iron sector. Electricity generation is expected to increase in line with national average energy consumption growth retaining a share of final energy consumption of around 20 per cent.

According to ABARE, electricity generation is projected to grow by 2.2 per cent per year out to 2020, with coal set to continue to account for over 67 per cent of the fuel mix used for generation.

Australia's heavy reliance on fossil fuels to meet its primary and final energy needs has resulted in it having one of the highest rates of emissions per capita in the world, as shown in Figure 8.

Figure 8 **Emissions per capita for selected countries 1970-1998.**



Data source: State of the environment report

2.1.1 Energy supply

Energy supplies are ample and cheap.

A key determinant of Australia's projected primary and final energy consumption patterns is the abundance of cheap and readily available fossil fuels. Our natural endowment of coal, gas and oil has supported the development of Australia as an energy intensive economy, supporting a range of energy intensive industries.

Australia is a net exporter of black coal, LNG and LPG and is self-sufficient in natural gas and brown coal, but we are a net importer of crude oil and other refinery feedstock. Australia imports crude oil from Indonesia, Vietnam, Saudi Arabia and other Asian countries including significant amounts of petroleum products from Singapore.

Table 2 **Key oil data for Australia – million metric tons oil equivalent (mmtoe)**

	1980	1985	1990	1995	1999	2005	2010	2015
Production	21.3	27.7	28.5	28.0	25.7	30.4	29.4	29.3
Imports	14.5	8.8	14.3	20.8	28.3	32.9	38.9	44.8
Exports	-3.3	-8.2	-9.2	-13.0	-16.7	-22.2	-24.4	-27.7
Bunkers	-1.1	-0.7	-0.6	-0.8	-0.8	-0.9	-0.9	-0.9
Net imports	10.0	-0.1	4.5	7.0	10.8	9.8	13.6	16.2
Total supply	31.4	27.6	32.9	35.0	36.6	40.2	43.0	45.6
Import dependence (%)	32.0		13.6	20.0	29.6	24.3	31.6	35.6

Source: IEA, ABARE, historic data and projections

Table 2 sets out key oil statistics for Australia and highlights the projected increasing dependence on imports.

ABARE projects that Australia's net imports of crude oil will grow at an average 3.8 per cent per year to 2020, outstripping annual average growth in domestic crude oil production of 1 per cent over the same period. By 2019-20 it is forecast that Australia's imports of crude oil will be greater than domestic production, accounting for 51 per cent of domestic consumption. Australia's increasing reliance on imported oil could result in greater risk exposure to potentially volatile oil prices and possible disruptions to international supply.

2.2 The potential role for hydrogen

This section discusses three possible scenarios for hydrogen penetration into our energy mix and considers the environmental, infrastructure and economic implications of each of these.

2.2.1 Why scenarios?

There is uncertainty about how the future will look.

A key objective of the National Hydrogen Study is to provide an informed assessment of the strategic steps that government, industry and other stakeholders would need to consider if Australia is to make greater use of hydrogen to meet its future energy needs. This is by definition a forward-looking exercise. To carry out this task we need to have some ideas about how a future world might look.

There is little to draw on from the major global and domestic energy projections about the potential for hydrogen uptake in the energy mix explicitly. All the major forecasts predict a continuation in the dominant share of primary and final energy consumption taken by fossil fuels – particularly in transport. This is not surprising since most forecasts only go out to 2020 and few experts expect hydrogen to begin to capture a significant share of the energy mix much before then. The IEA predicts that fuel-cell vehicles will not penetrate the fleet to a significant degree before 2030[7].

Any analysis about the implications of a hydrogen economy is necessarily concerned with the long term. Obviously, there is a great deal of uncertainty about how the future might unfold and this uncertainty is exacerbated by the long time frames that are generally accepted as being associated with any transition to the greater use of hydrogen

Scenarios help us think about possible futures.

The Study has used scenario or 'what if' analysis to create a picture of potential hydrogen energy utilisation in the Australian economy by 2050 under a range of different circumstances.

The task is primarily to determine how the future might look in terms of global and domestic energy use, with particular reference to hydrogen, and what signposts exist now, and might exist in the future, to help anticipate what path Australia is on. In addition, it is important to have a feel of the implications that the use of hydrogen fuel may have for Australia. We need to understand what such a transition might imply and whether or not it is a desirable goal, or indeed an attainable one.

Rather than try to develop a single projection of future energy consumption and fuel use, this report proposes a set of scenarios that reflect a range of possible futures. This 'what if?' approach to the analysis should aid the development of both responsive and pre-emptive strategies for a number of potential outcomes. The scenarios are a tool to assist the subsequent analysis of economic and environmental factors, infrastructure requirements and formulation of recommendations for strategies and policies.

2.2.2 Developing the scenarios

Clearly there are many factors, including economic, technological, social and demographic, that could be varied to differentiate between the scenarios. However, to incorporate all of these explicitly, would increase substantially the level of complexity. Also, incorporating that level of detail might create a false impression of precision.

Instead the focus is on the key variables that might drive Australia towards particular future outcomes. The aim is to create a simple, transparent and internally consistent picture for each of the scenarios, using selected key descriptors.

[7] *World Energy Outlook, 2002*. International Energy Agency

At the broadest level, the scenarios can be simply categorised as relating to high, medium and low hydrogen penetration in the energy mix. Each scenario contains a set of assumptions about where hydrogen will be used and by when.

Three possible end uses for hydrogen.

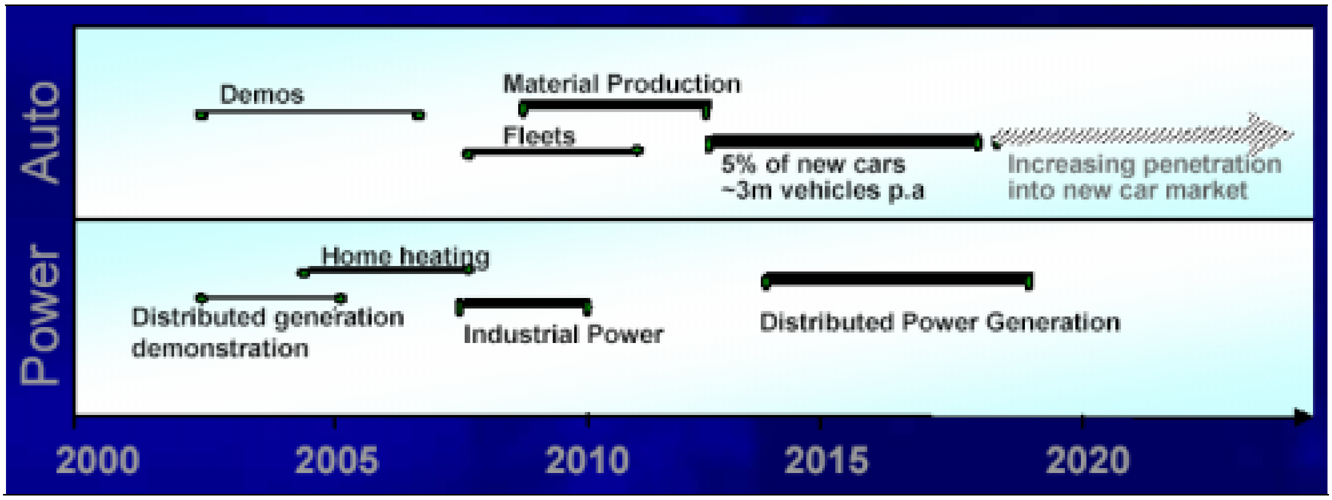
It is assumed that the main potential end uses for hydrogen for Australia in the period to 2050 will be[8]:

- Road transport;
- Portable electrical appliances (for example portable computers and mobile phones); and
- Distributed generation.

The scenarios draw from other projections.

Existing projections and discussions for the timing of commercial hydrogen applications and the transition to a hydrogen economy have been used as a guide in developing the scenarios. One scenario, presented to an IEA Renewable Energy Working Party Seminar in March 2003, provides possible timelines for the emergence of market applications in the transport and distributed power generation sectors (see Figure 9).

Figure 9 **Indicative timing range for hydrogen market applications**



Data source: "Towards a Hydrogen Economy", a presentation to IEA Renewable Energy Working Party Seminar by BP Cleaner Energies, 3rd March, 2003

The US position on the possible transition path is shown in Figure 10. This Figure shows how technology might evolve across the entire supply chain. Figure 12 in section 4 shows Japan's thinking on the possible timing for a hydrogen transition.

8 It is worth noting that given the 50-year outlook period there is a real likelihood that other uses might emerge.

Figure 10 **Overview of the transition to a US hydrogen economy**

Hydrogen Industry Segments	2000	2010 – 2020 – 2030	2030 – 2040
Public Policy Framework	Security Climate H_2 safety	Outreach and acceptance →	Public confidence in hydrogen as an energy carrier
Production Process	Reforming of natural gas/biomass	Gasification of coal Electrolysis using renewable and nuclear Thermo-chemical splitting of water using nuclear	Biophotocatalysis Photolytics to split water
Delivery	Pipelines Trucks, rail, barges	Onsite 'distributed' facilities	Integrated central distributed networks
Storage Technologies	Pressurized tanks (gases and liquids)	Solid state (hydrides) → Mature technologies for mass production Solid state (carbon, glass structures)	
Conversion Technologies	Combustion	Fuel cells Advanced combustion } Mature technologies for mass production	
End-use Energy Markets	Fuel refining Space shuttle Portable power	Stationary distributed power Bus fleets Government fleets Commercial fleets Distributed CHP Market introduction of personal vehicles	Utility systems

Data source: *A National Vision of America's Transition to a Hydrogen Economy - to 2030 and beyond*, US Department of Energy 2002

Key drivers for the scenarios

Possibly the most important factor affecting the development of a hydrogen economy is the cost to the user / consumer of hydrogen fuel, and associated end-use products, relative to conventional fuels and products – for example, petroleum products in conventional road transport vehicles.

Four key drivers for greater use of hydrogen.

There are many factors that will determine whether or not a hydrogen economy develops. However, hydrogen may be a more important fuel in the future if one or more of the following are true:

- Rates of economic growth are generally high;
- There is a high level of environmental consciousness and, specifically, high motivation to curb greenhouse emissions – manifested both in consumer behaviour and public policy settings;
- Rates of technological progress and innovation are high. R&D and innovation are biased towards outcomes favouring hydrogen; and
- Higher prices for conventional energy mean that alternative fuels, including hydrogen, improve their relative cost competitiveness.

Different paths could lead to the same end point.

Each of the scenarios proposed below could result from distinctly different paths involving markedly different trends for these drivers. Importantly, the economic implications of a hydrogen economy could differ markedly depending on what eventuates and what the key drivers are.

For example, the economic implications of the emergence of a hydrogen economy driven by high market-determined oil prices might be quite different to that resulting from government mandates and policies driven by a desire to reduce emissions. Similarly, a world in which high hydrogen penetration was driven by rapid technological progress that enabled hydrogen and the vehicles and appliances using it to be supplied cheaply and safely almost irrespective of oil prices could look very different again.

The three scenarios described below (high, medium and low penetration rates for hydrogen) provide three possible outcomes and a possible path for arriving at each outcome. However, they do not purport to represent the full range of possible end points, or all possible ways of getting there.

2.2.3 The scenario descriptions

Scenario 1 (High)

Scenario 1 is positive for hydrogen.

Scenario 1 postulates that Australian and world economic growth will be strong and relatively consistent. Those high levels of growth will lead to rapidly growing energy demand that could lead to higher prices for conventional fuels.

Rapid growth in energy consumption could also increase concerns about the environmental impact of that consumption. This will not only tend to channel increased amounts of R&D funding[9] into work on cleaner fuels such as hydrogen, but will also lead to greater pressure to reduce the emissions associated with energy use. Scenario 1 postulates that the increased R&D funding leads to significant technological breakthroughs and innovation that are ultimately successful in supplying the market with hydrogen fuelled products that are competitive both in terms of price and performance with incumbent technologies.

Average personal incomes will be higher in real terms allowing consumers greater opportunity to purchase (possibly more expensive, at least initially) hydrogen powered consumer products. Increased environmental consciousness could lead to greater consumer demand for low emission products, possible government mandates to adopt alternative, lower emission energy technologies and policies that increase the relative cost of traditional fuels.

9 Note that funds for R&D are likely to be more readily available in a buoyant economic climate.

Governments are more likely to promote hydrogen usage through the introduction of hydrogen fuel cell buses in urban public transport fleets Australia wide.

Fuel cells for portable power could emerge first.

Fuel cell powered portable appliances could emerge on the market within the next two to three years and gain a relatively significant market share by 2010. The fuel cell, while expensive, will operate significantly longer without "recharging" than conventional batteries. This will outweigh the fact that re-fuelling appliances may, at least initially, not be as convenient.

Over time portable appliances will become cheaper, lighter, and more efficient and therefore capture an increasing share of the market. This in turn will drive increased investment in R&D as well as hydrogen production and supply infrastructure. By 2050, hydrogen fuel cells replace conventional batteries as the dominant energy source for portable appliances.

Commercial and fleet vehicles are early adopters of fuel cell technology.

Demonstration fuel cell vehicles, mainly buses and trucks, progressively become more common. Fuel cell vehicles are commercially available by around 2020. Initial market penetration is limited due to the large (and expensive) infrastructure requirements associated with producing, storing and distributing the hydrogen fuel. Consequently, commercial and fleet vehicles are the first fuel cell vehicles to appear on the roads in any significant numbers. By 2030 perhaps 20% of service stations are equipped to supply hydrogen, enabling passenger and other vehicles to re-fuel in urban centres. This provides the impetus for fuel cell vehicles to increase their share of the national road transport market out to 2050.

Fuel cells face competition from electricity generation from Australia's abundant fossil fuel sources. The use of fuel cells for distributed generation emerges to a limited extent by 2030 helped both by government policies that increase the relative cost of fossil fuels and reductions in the cost of distributed generation systems driven by technology developments.

Scenario 2 (Medium)

Scenario 2 sees slower, more hesitant growth in hydrogen use.

Scenario 2 is characterised by economic and energy consumption growth that broadly follows past trends. The increased energy consumption worldwide places mild upward pressure on conventional energy prices reflecting some concerns regarding the adequacy of fossil fuel reserves to supply future demand.

Strong R&D funding results in the production of hydrogen-fuelled products that begin to be accepted by consumers on cost and performance grounds. Increased environmental consciousness supports government mandates to adopt alternative, lower emission energy technologies, and policies that serve to increase the cost of traditional fuels. Governments actively promote hydrogen usage through the gradual uptake of hydrogen fuel cell buses in urban public transport fleets throughout Australia.

Hydrogen fuel cell powered appliances (lap tops, mobile phones, etc) are commercially available between 2005-2010 but are slow to be accepted by consumers due to their higher cost. The hydrogen fuel cell continues to face competition from cheaper, conventional batteries – it is assumed that through time the latter can be made smaller, cheaper and longer lasting. Real incomes increase only moderately, inhibiting to some extent the consumer's capacity to purchase the more expensive hydrogen powered appliances.

Fuel cell products remain relatively costly and their performance is worse than conventional alternatives.

Hydrogen fuel cell powered vehicle use extends beyond demonstration programs by 2030 but growth is initially slow due to the higher cost and relatively poor performance of smaller vehicles and the lack of widespread infrastructure required for refuelling. Use is initially restricted to public bus and government fleet vehicles, but later includes small passenger vehicles and light commercial vehicles, as successive models of these vehicles become cheaper and perform better and refuelling infrastructure becomes more widespread.

Fuel cells for distributed generation are very slow to be adopted, facing stiff competition from cheap electricity generated using abundant fossil fuel sources. Their use emerges only to a very limited extent by 2030.

Scenario 3 (Low)

Scenario 3 sees only limited amounts of hydrogen in the energy mix.

Scenario 3 assumes that Australian and world growth rates are consistently lower and energy demand growth follows suit. Traded energy prices are low and at the prevailing consumption rates, it is perceived that energy resources and reserves will be more than adequate to cater for future demand without any increase in real prices.

The amount of public and private funding available for R&D is limited. Many fuel cell companies are unable to operate in this environment and the industry consolidates considerably. The reduced size of the industry inhibits the rate of progress and reduces the frequency and impact of technological breakthroughs. The performance and cost of fuel cell products improves only slowly. This delays the appearance of many products on the market and extends the time taken to 'catch up' with incumbent products in terms of cost and performance. However, governments continue to actively promote hydrogen usage through the purchase of hydrogen fuel cell buses for urban public transport fleets.

Fuel cell products remain costly and perform less well.

Fuel cell powered appliances are commercially available by 2010 but are considerably more expensive than conventional battery-powered appliances.

This inhibits their penetration and the demand for hydrogen remains limited. Consumers are reluctant to adopt a range of products that remain more expensive and are potentially inconvenient to refuel.

Fuel cell vehicle manufacturers are unable to produce hydrogen-powered vehicles that are cheap, powerful and small enough. Thus they are unable to capture market share from conventional vehicles[10].

Out to 2030, public transport (buses) is the main area of use in the transport sector. Government initiatives and mandates remain the key driver in most states. Later in the projection period there is some uptake of hydrogen fuel cell vehicles in the passenger and light commercial vehicle markets but the limited fuel production, storage, and distribution networks sees refuelling difficulties remaining an impediment up to 2050.

2.2.4 The scenario implications

Indicative sectoral penetration rates have been assumed for each scenario. These penetration rates are not forecasts but merely attempts to provide a numerical basis for the quantitative analysis of the economic and environmental implications of possible scenarios for hydrogen usage.

The three scenarios and the various penetration rates were derived from ACIL Tasman research, discussions with the High Level Advisory Group (HLAG) and feedback from the Melbourne and Perth Workshops.

Note that the scenarios and their outcomes are intended to be indicative only.

Road transport

Buses and fleets first to use hydrogen in transport sector.

All the scenarios assume that buses in capital cities and urban areas will be the initial entry point for hydrogen-fuelled vehicles. The growth in their use will follow on from demonstration projects, such as the bus trials currently under way in Europe, the US, and Western Australia.

Scenario 1 sees the most aggressive hydrogen penetration into the transport sector. By 2030, hydrogen fuels all buses and 20 per cent of other vehicles in all areas. By 2050, hydrogen accounts for a 30 per cent share of Australia's total road transport fuel consumption.

In Scenario 2, all buses and 10 per cent of other vehicles, in all areas, will be fuelled by hydrogen by 2030. By 2050, hydrogen accounts for 15 % of road vehicle fuel consumption.

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10 It is also possible that technology improvements may favour hybrid vehicles and these may become an option for consumers.

For scenario 3, it is assumed that by 2030 re-fuelling infrastructure is still only available in capital cities and urban areas. Nonetheless, by this time, all urban buses are fuelled by hydrogen, accounting for about 1 per cent of total fuel consumption by road vehicles. By 2050 it is assumed that buses in all areas are fuelled by hydrogen and a limited number of other vehicles (passenger vehicles, light commercials and trucks) in all areas are fuelled by hydrogen.

Distributed generation

The IEA's 2002 World Energy Outlook suggested that hydrogen fuel cell plants could account for between 1 and 2 per cent of incremental electricity generation capacity between 2000 and 2030. The scenarios assume that most of these capacity additions are for distributed generation.

Fuel cells are most likely to be used for distributed generation.

Currently, distributed generation accounts for approximately 10 per cent of Australia's total generation capacity[11]. The breakdown of existing generation capacity by plant and fuel type is shown in Table 3.

Table 3 **Distributed generation capacity by plant and fuel type 2000/01**

Plant type	Fuel type	Capacity (MW)	Capacity (% of total non-grid)
Hydro		316.1	7.3%
Steam	Coal	0	
	Natural gas	164.5	3.8%
	Waste gas	60	1.4%
Gas turbine	Gas	844.5	19.4%
Combined cycle gas turbine	Gas	351.5	8.1%
Reciprocating engine	Gas	40	0.9%
	Waste methane	101.8	2.3%
	Oil	24.51	0.6%
Cogeneration	Natural gas	841.3	19.4%
	Bagasse	241.1	4.9%
	Coal	241.1	4.9%
	Waste gas	153	3.5%
	Oil	91.8	2.1%
	Renewable	15.3	0.4%
Renewable generation		910	21%
Total		4342.5	100%

Source: Electricity Supply Association of Australia, Australian Cogeneration Association

However, hydrogen is unlikely to be a competitive fuel alternative for most of the existing generation shown in the above table. It is hard to see how the economics of converting an existing natural gas fuelled distributed generation

[11] *Electricity Australia 2002*, ESAA

plant to one that used natural gas to generate hydrogen which was then used in a fuel cell, could be competitive with the status quo.

Gas customers are potential users of fuel cells for distributed generation.

It is perhaps more likely that the entry point will be existing customers of natural gas networks installing new generation units that integrate a natural gas reformer and fuel cell and possible heat recovery as well. Initially at least customers for such equipment are more likely to be individual residential consumers or commercial businesses that could use both the power and the heat generated from a fuel cell. Apart from competitive unit and fuel costs, other drivers for the penetration of such units might include the ability to sell power (or standby capacity) back to the grid, a desire to be independent of the electricity grid, and improved reliability.

Appliances

Portable appliances could be the first mass market for fuel cells.

Many analysts suggest that portable appliances such as lap top computers, personal digital assistants (PDAs), mobile telephones, etc. may be the first mass market for fuel cell technology[12]. In recent months there have been press reports that several major companies are currently working on fuel cell powered versions of such appliances.

One reason why this sector may be the first to emerge is that there is a consumer demand for a better alternative to the battery for powering portable appliances. Namely a product that will allow longer operation between recharges, be quicker to recharge and not require access to the electricity grid[13]. Fuel cells have the potential to address all these problems.

Another reason why this sector might be the first to see significant numbers of fuel cells entering the market is that the alternative technology (batteries) is a relatively high cost one. Hence price differentials might be smaller or even favourable to fuel cells. It also worth noting that portable appliances operate on DC power and there is therefore no need for costly inverters.

The creation of a fuel cell market could have important benefits.

This market sector is not a major source of energy demand so the impact on Australia's energy mix will not be significant. However, the real value from the penetration of hydrogen into this sector would be in:

- a much increased consumer awareness of hydrogen as a source of energy;
- an acceptance of fuel cells as a means of supplying power (including their safety); and

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12 For example, according to the 5 March 2002 edition of Japan's largest financial daily, the Nihon Keizai Shimbun, the Casio computer company of Japan, has developed micro fuel cell technology and hopes to commercialise it as early as 2004.

13 It is worth noting that all these properties would be attractive to the military and if the technology emerges they could very well be early adopters and provide the market demand to help achieve economies of scale.

- the creation of a true market for hydrogen technology that could provide the cash flow that would help drive further R&D and ultimately continued improvements in the competitiveness of hydrogen as a source of energy.

Table 4 and Table 5 list the assumed sectoral penetration rates for hydrogen fuel cell products in 2030 and 2050 respectively for each of the three scenarios. For example, in Table 4 the assumed 50% penetration rate for the appliance sector under scenario 1 means that 50% of all portable appliances use hydrogen as an energy source.

Table 4 **Hydrogen penetration rates - 2030**

2030	Scenario		
Sector	**1**	**2**	**3**
Appliances (laptops, mobile phones)	50%	20%	5%
Road transport	20%	10%	1%
Commercial/residential distributed generation	5%	3%	1%

Table 5 **Hydrogen penetration rates - 2050**

2050	Scenario		
Sector	**1**	**2**	**3**
Appliances (laptops, mobile phones)	100%	40%	10%
Road transport	30%	15%	5%
Commercial/residential distributed generation	15%	10%	3%

The Study Team have applied the above penetration rates to projections of sectoral energy consumption out to 2050 to yield estimates of hydrogen demand for each of the scenarios. The sectoral energy projections were derived from ACIL Tasman spreadsheet modelling. The time frame is long in modelling terms, which means that the precision of the long-term estimates becomes increasingly unreliable. Key inputs were ABS population projections and ABARE economic growth projections. Baseline information for the break-up of kilometres travelled and fuel consumption by passenger vehicles and buses was derived from the ABS, commercial and residential electricity consumption from ABARE, and mobile phone and laptop usage from the Australian Communications Authority (ACA).

Table 6 shows the calculated hydrogen demand by market segment and total in 2030 and 2050.

Table 6 **Calculated hydrogen demand by scenario (million m^3)**

	2030			2050		
	Scenario			Scenario		
Market segment	**1**	**2**	**3**	**1**	**2**	**3**
Appliances	26	10	3	56	22	6
Transport	15,034	9,025	6,020	29,585	16,912	9,309
Distributed generation	2,942	1,765	588	12,409	8,272	2,482
Total	18,002	10,800	6,611	42,050	25,206	11,797

Source: ACIL Tasman estimates

In all scenarios the transport sector has the largest demand for hydrogen, whereas the demand from the portable appliance sector is minimal even in the most optimistic scenario.

3 Hydrogen supply options

At present, some 500 billion cubic metres[14] of hydrogen are produced worldwide each year. In energy equivalent terms this is about 1.5% of the world's energy consumption. Almost all of this hydrogen is produced from fossil fuels, primarily natural gas, with chemical production and renewable energy sources accounting for the rest (about 1% of the total)[15].

3.1 Hydrogen production options

There are several options for manufacturing hydrogen. However, they all have two points in common. First, they all require some form of feedstock from which to extract hydrogen, be it water, gas or coal. Second there must be some form of energy input in order to breakdown the feedstock and release the hydrogen. Different production options do however have widely varying environmental implications.

The ultimate success of the various production technologies will be determined by the market; based on consumer needs, the availability of appropriate feedstocks and energy supplies, the environmental performance, and the efficiency and cost of the various production options. These variables will change over time and the mix of production methods at any point in time will vary accordingly.

3.1.1 Fossil fuel reformation

Fossil fuels such as coal, crude oil and natural gas and many hydrocarbon derivatives from the processing of these fossil fuels can serve as a feedstock in hydrogen production systems.

There are two highly mature process routes by which fossil fuels are reformed to lighter hydrocarbon fuels, mostly synthesis gas (a mixture of hydrogen and carbon monoxide). They are steam-reformation and partial-oxidation. Both processes have advanced over the past 50-100 years to become the current best practise industry standard for large-scale production.

At its simplest level, the steam reformation process is based on heating up hydrocarbons, steam and in some instances air or oxygen, which are then combined in a reactor. During this process, the water molecule and the raw

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14 Unless otherwise indicated all references to cubic metres should be interpreted as being to normal cubic metres. A normal cubic metre is the volume of dry gas that occupies a volume of 1 m^3 at a temperature of 273 K and an absolute pressure of 101.3 kPa.

15 "Hydrogen Today & Tomorrow", IEA Greenhouse Gas R&D Program, 1999.

material are split, and the result is H_2, CO and CO_2. In other words, the hydrogen gas comes from both the steam and the hydrocarbon compound.

Another method is to heat up hydrocarbons without air until they split into hydrogen and carbon.

Gasification of coal

Gasification of coal is the oldest method of producing hydrogen. This technique was the source of the "city gas" that was originally supplied to many cities in Australia before natural gas became available. This gas contains up to 60% hydrogen, but also large amounts of CO. To make it, the coal is typically heated up to 900ºC where it turns into a gaseous form, it is then mixed with steam and in the presence of a catalyst a mixture of H_2, CO and CO_2 is produced.

There are other methods of gasifying coal. However broadly speaking they all turn coal, treated with steam and oxygen at high temperatures, into H_2, CO and CO_2.

In addition, sulphur and nitrogen compounds are released during the process, which like the CO and CO_2, must be handled in an environmentally friendly way.

Steam reformation of methane

Steam reforming of natural gas is currently the cheapest way to produce hydrogen, and accounts for about half of the world's hydrogen production. Steam, at a temperature of 700-1000 ºC, is mixed under pressure with methane in a reactor in the presence of a catalyst. The reaction that takes place is:

$$CH_4 + H_2O = CO + 3H_2$$

Followed by the "shift reaction":

$$CO + H_2O = CO_2 + H_2$$

Note that the natural gas is used to power the reaction as well as taking part in the reaction process.

3.1.2 Electrolysis of water

Hydrogen production via electrolysis of water is another well-established technology. Though various low-, medium- and high-temperature processes have been developed over the years, the chlorine-alkaline solution process dominates the commercial world of electrolysis.

Hydrogen production via electrolysis is generally restricted to applications requiring high-purity hydrogen such as the electronics manufacturing industry and space exploration programs. The reaction that occurs is:

$$2H_2O + energy = 2H_2 + O_2$$

Electrolysis can be used for distributed hydrogen production (thus removing the need for a transportation / distribution infrastructure). The process is indifferent to the source of electricity used and can be used with a range of current and future electricity generation technologies (coal, gas, nuclear, renewable). Conversion of renewable energy (solar, wind, photovoltaic, geothermal, tidal, hydro, etc.) to electricity followed by electrolysis of water to generate hydrogen offers a totally sustainable energy cycle[16].

3.1.3 Other production processes

There are also several other production processes that are somewhat less advanced than the ones discussed above. Nonetheless, they have a number of potential benefits, including the lack of greenhouse emissions and the utilisation of renewable resources that are plentiful in Australia. Consequently, there is considerable interest in them and several research groups are investigating them.

Solar hydrogen

One approach is the direct production of hydrogen using solar energy and photosensitive materials designed to produce the chemical energy needed to split water into its component parts.

Another option is the thermal decomposition of water using a thermal solar power plant. By heating water to over 2,000ºC, it is broken down into hydrogen and oxygen.

Production from biomass

Hydrogen can also be produced by thermal gasification of biomass such as forestry by-products, straw, municipal solid waste and sewage. The amount of hydrogen (by weight) in biomass is about a quarter of that in natural gas. The processes involved in producing hydrogen from biomass are similar to those used in producing hydrogen from fossil fuels.

The biomass is heated to a high temperature and breaks down to a gas consisting mainly of H_2, CO and CH_4 (methane). Steam is then introduced to

[16] Since many of the renewable technologies produce intermittent power, hydrogen storage can be used as the medium for load levelling and making electricity available 24 hours a day.

reform CH_4 to H_2 and CO. CO is then put through the shift process to attain a higher level of hydrogen. As with fossil fuel reformation the process produces CO_2, however it is considered greenhouse neutral, as it does not increase the CO_2 concentration in the atmosphere.

3.2 Current R&D directions in hydrogen production

Improved efficiency is a key target for R&D.

The bulk of the research effort in relation to hydrogen production is directed at improving the efficiency of the process.

Fossil Fuel Reformation

Thermal partial oxidation of fossil fuels (eg, coal, biomass, heavy oil, or natural gas) using a controlled supply of oxygen rather than in air has the advantage of avoiding the problem of NOx formation and the additional cost of N_2 separation. However, a cheap source of oxygen is required, as the cryogenic route for oxygen separation is expensive. Alternative separation technologies attracting substantial attention are based on ceramic or polymer membranes

Other areas of R&D into fossil fuel reformation include:

- Small-scale steam-reformation for gaseous and liquid hydrocarbon fuels;
- Coal-gasification and sequestration for 'zero-emission' electricity and hydrogen co-production; and
- Gasification as well as fast-pyrolysis of biomass feedstock.

Small-Scale Reformers

Drawing on the experience gained from the world's mature, large-scale steam-reformation industry, various R&D groups are now working toward the construction of commercially viable steam-reformation equipment that operates on the much smaller scale needed for distributed hydrogen production[17].

Natural gas, LPG and methanol are seen as the most promising fuel feedstocks for these small-scale reformers.

'Zero-Emission' Coal Gasification

Development of cost effective and proven technologies for the long-term safe disposal of CO_2 would have a major impact on the emissions associated with hydrogen production. Large scale hydrogen production either by reforming of

[17] Odgen J. (2002): Review of small stationary reformers for hydrogen production, IEA-H2 report.

natural gas or gasification of coal, or small-scale production at distributed sites via electrolysis of water using electricity generated from[18] burning fossil fuels could become a greenhouse gas emissions free process.

Zero emission power is attracting increased R&D funding.

Consequently, R&D into large-scale, 'zero-emission' coal gasification technology route for the co-production of electricity and hydrogen has gained significant momentum over the past few years[19]. Mineral carbonation for the storage of carbon dioxide in a solid rather than gaseous form is also gaining R&D attention.[20,21]

Power generation using coal gasification combined with geological sequestration is expected to be able to reduce greenhouse gas emissions by about 80 per cent, compared with electricity generation without sequestration, but with an efficiency penalty of about 7 per cent.

FutureGen is a public-private partnership to develop 'zero emission' power.

Box 3 describes the US FutureGen project, which aims to produce 'zero-emission' electricity. A similar project, COAL21, is currently under development in Australia. This is discussed in more detail in section 3.5.

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18 IEA, "Putting the carbon back in the ground", p.21

19 Nawaz M. and Ruby J. (2001): Zero Emission Coal Alliance project conceptual design and economics. International Coal Technology and Coal Utilization Conference, Clearwater Florida.

20 Lackner K., Butt D. and Wendt C. (1998): The need for carbon dioxide disposal: A threat and an opportunity, 23rd International Conference on Coal Utilization and Fuel Systems, Clearwater Florida.

21 O'Connor W., Dahlin D., Nilsen D., Rush G., Walters R. and Turner P. (2000): CO_2 storage in solid form: A study of direct mineral carbonation, Proceedings of the 5th International Conference on Greenhouse Gas Control Technologies, Cairns, Australia, August.

Box 3 **The US FutureGen project**

In February 2003 the United States announced an ambitious new international effort to advance carbon capture and storage technology as a way to reduce greenhouse emissions.

The project is a $1 billion, public-private effort to construct the world's first fossil fuel, low-pollution power plant. The plant, known as FutureGen, will serve as a prototype for new carbon sequestration technologies and produce both electricity and hydrogen. The FutureGen initiative will comprise a coal gasification plant with an additional water shift reactor, to produce hydrogen and CO_2. About one million tonnes of CO_2 (at least 90% of throughput) will then be separated by membrane technology and sequestered geologically. The hydrogen will be burned in a 275 MWe generating plant and later in fuel cells.

Other common air pollutants such as sulfur dioxide and nitrogen oxides would be cleaned from the coal gases and converted to useable products such as fertilisers and soil enhancers. Mercury pollutants would also be removed.

The objective of FutureGen is to help turn coal from an environmentally challenging energy resource, into an environmentally benign one. The prototype power plant will serve as the test bed for demonstrating the best technologies the world has to offer.

The project is designed to show that by 2020 electricity can be generated in such a plant with only a 10% cost premium and that hydrogen can be produced at US$3.80 per GJ, equivalent to petrol at 12.7 US cents per litre.

Biomass Gasification and Pyrolysis

Fossil fuel reformation still faces R&D challenges...

The following science and technology challenges are examples of key areas for on-going fundamental R&D efforts related to fossil fuel reformation (including biomass):

- catalyst developments;
- small-scale tubular and plate reformers;
- sorbent enhanced reforming;
- ion transport membrane reforming;
- plasma reformers;
- microchannel reformers;
- thermocracking of methane;
- radiant flash pyrolysis; and
- cyclone reactor pyrolysis.

...including improving gas cleaning and separation technologies.

A range of technologies need to be developed for separating and purifying hydrogen from other gases especially if production is from fossil fuels via reforming or partial oxidation. Although some technologies exist for large-scale plants, they are either too expensive or not effective for end-use applications such as small production units for distributed hydrogen, for example, at homes, service stations, or on-board vehicles.

Electrolysis of water

Electrolysis faces similar challenges.

Industrial electrolysis systems have hydrogen production capacities of up to 5 tons per hour and net system efficiencies of between 75% and 85%. Such systems operate with a net power consumption of around 40 – 45 kWh per kg of hydrogen produced. Current R&D efforts are aimed at improving net system efficiencies of commercial electrolysis toward 90% and beyond.

The following science and technology challenges are examples of emerging key areas for on-going fundamental R&D efforts related to electrolysis:

- catalyst developments;
- electrode surface area optimisation with nano-technology techniques;
- electronic charge carrier transport and surface reaction kinetics of doped metal oxides;
- fluid-dynamic optimisation;
- doped high-temperature ceramic membrane materials;
- surface modification of proton exchange membranes (polysulphone);
- steam electrolysis (yttrium ceramic);
- high-pressure electrolysis;
- thermochemical cycles (adiabatic “UT-3” (Ca, Fe & Br) & sulphur iodine);
- high-temperature reactor developments (molten salt, alkali metal, gas-cooled, etc.).

Biological and photolytic systems

Several innovative production methods are emerging.

In recent times, increased attention has been focused on photolytic and biological means of hydrogen production. For example, solar thermal processes, photo-electrolysis, photo-catalytic and photo-biological processes.

Biological production of hydrogen using micro-algal photosynthesis is a process whereby hydrogen is derived from organic matter and water by micro-organisms such as algae and cyano-bacteria[22,23]. The most common examples of organic feedstock include biomass crops, agricultural as well as animal wastes, and soils. The natural micro-algal hydrogen metabolism has to be genetically engineered in order to achieve significant, “natural over-production” of hydrogen.

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[22] Zaborsky O. – Editor (1998): BioHydrogen, Plenum Press, ISBN 0-306-46057-2.

[23] Miyaka J., Matsunaga T. and SanPietro A. - Editors (2002): BioHydrogen II, Pergamon-Elsevier Science, ISBN 0-08—43947-0.

Many small-scale projects have successfully demonstrated the ability of these technologies to produce hydrogen. However, the R&D is still in its infancy and production costs remain significant. Nonetheless, the body of knowledge in this area of research is increasing rapidly.

Key areas for on-going fundamental R&D efforts related to biological hydrogen production systems include:

- studies of genetic mechanisms and biochemical pathways of hydrogen metabolism;
- hydrogen metabolism investigations of micro-algae in daylight and darkness;
- maximisation of photosynthetic efficiencies;
- improvement of oxygen tolerance of algae;
- hydrogen fermentation processes;
- recycling of algal cells after hydrogen evolution process; and
- development of bioreactor systems that operate under visible light.

Distributed hydrogen production

Inexpensive distributed hydrogen production is a key aim.

Efficient and inexpensive distributed hydrogen production at service stations, homes or other demand centres would reduce the need for hydrogen transportation and distribution infrastructure and could assist with the early introduction of the hydrogen economy.

Two key enabling technologies that need to be developed for this to occur are:

1. Small and compact reformers with integrated gas cleaning systems for on-site, on-demand hydrogen production using a range of fuels (eg. natural gas, methanol, ethanol, LPG, diesel).
2. Low maintenance, highly efficient systems (over 85-90%) which can operate at current densities well above 10,000A/m^2 (small footprint, low cost), and show very low degradation during operation are required. Solid state electrochemical systems offer several advantages over conventional acid or alkali based electrolysers. High-pressure operation would also reduce the downstream cost of compressing hydrogen for storage. High temperature electrolysers integrated with solar energy have the potential to reduce the electricity demand for hydrogen production by embedding energy in the form of heat into the electrolysis process.

Reversible fuel cells

Reversible fuel cells have the potential to reduce overall system costs. Particularly if they are integrated with renewable energy sources such as wind, solar, geothermal and tidal. They could be used to generate hydrogen when renewable energy is available and utilise hydrogen to produce power when the renewable energy is not available. Special materials (eg. catalytic electrodes) need to be developed, as existing fuel cells will not operate in reverse mode.

3.3 Cost of hydrogen production

For industry, the cost of production is perhaps the most important consideration. Table 7 summarises the key points for the most common hydrogen production methods and provides an approximate manufactured cost. It is worth noting that estimated production costs quoted in the literature vary significantly. The assumptions made and the point at which the cost is quoted can lead to large variations in the numbers quoted. For example, does the cost include gas separation, compression, transportation, and so on.

Table 7 **Summary of common hydrogen production methods**

Production Process	Summary	Current Usage	Approximate Manufactured Cost ($/GJ)	Used in Australia?
Steam-methane reforming	There are three steps involved in this process: steam reforming, water gas shift reaction and hydrogen purification.	Reagent in the petrochemical industry	8*	Yes
Partial oxidation of hydrocarbons	The hydrocarbon feedstock is oxidised to produce CO2 and hydrogen.	Chemical processes such as oil refining	18-25**	Yes
Gasification of Coal, Biomass or Wastes	The hydrocarbon feedstock is gasified at high temperature to produce a syngas, which is then processed and purified to obtain hydrogen.	Chemical processes such as ammonia production	10-11***	Yes
Water electrolysis	Electricity is passed through an aqueous electrolyte, breaking down water into its constituents, hydrogen and oxygen.	Insulator and cooling gas in high power alternators	29-42*	Yes, minor scale (eg power industry point of use)

Notes:

* Dincer, I. Technical, environmental and exegetic aspects of hydrogen energy systems. International Journal of Hydrogen Energy, Vol. 27, pp 265-285.

** AEA Technology. The feasibility, costs and markets for hydrogen production – Final Report. Prepared for British Energy, September 2002.

*** Gray, D. and Tomlinson, G. Hydrogen from coal, Mitretek Technical Paper 2002-31, July 2002.

In addition, this is a field where considerable research is still under way and improvements in technology are occurring with reasonable frequency. Cost estimates can therefore quickly become outdated. The costs quoted in this report are not immune to the above difficulties. At the end of the day, those considering investment in the technology, either for R&D or commercialisation will need to be well informed about current and likely future cost paths.

The costs of natural gas and reformer operation are relatively low, consequently steam reformation of methane is currently the cheapest, and hence the most common, means of hydrogen production.

Electrolysis of water is at the opposite end of the cost spectrum. Not only is the capital cost of electrolysis plant high, relative to the hydrogen output capacity, but also the energy input (electricity) must itself first be generated (and paid for). Electricity can be generated by using conventional fuel sources (such as oil, gas, coal) or renewable energy sources (for example wind, bagasse, hydro, tidal, or solar). In a recent report ABARE projected the average cost of a wide range of renewable energy sources in 2010 and 2020[24]. Those projections are shown in Table 8.

[24] Christopher Short and Andrew Dickson, "Excluding Technologies from the Mandatory Renewable Energy Target", ABARE e Report 03.12

Table 8 **Projected average cost of energy from different technologies**

	2000		2010		2020	
	Rank	$/MWh	Rank	$/MWh	Rank	$/MWh
Technology						
Hydro — large, existing	1	10.95	1	10.95	1	10.95
Biomass into coal capacity	2	23.14	2	23.14	2	23.14
Bagasse, new (with wood waste)	3	32.93	3	29.71	4	29.71
Landfill gas	4	35.59	5	35.59	7	35.59
Municipal waste water	5	36.31	6	36.31	5	34.17
Wet waste	6	37.28	7	37.28	8	37.28
Hydro — large (Qld)	7	39.87	8	39.87	9	39.87
Hydro — small, various states	8	40.11	13	48.25	13	48.25
Bagasse, new	9	42.17	10	42.17	11	42.17
Municipal solid waste	10	43.60	11	43.60	10	41.03
Hydro — large (Tas)	11	48.23	12	48.23	12	48.23
Wind (Tasmania)	12	51.88	4	33.4	3	28.12
Wind (other states)	13	64.85	9	41.75	6	35.15
Forest residue and wood waste	14	74.49	14	63.62	14	58.51
Hydro — large (NSW)	15	77.79	15	77.79	15	77.79
Hydro — large (Vic)	16	81.52	16	81.52	16	81.52
Energy crops	17	98.91	17	95.02	17	92.30
Bagasse, existing	18	112.46	19	112.46	19	112.46
Black liquor	19	139.67	21	138.67	21	138.67
Crop waste	20	141.08	20	133.3	20	130.58
Solar thermal	21	169.54	18	101.06	18	97.41
Photovoltaics, remote areas	22	641.73	22	244.55	23	219.9
Photovoltaics, grid connected	23	784.34	23	254.26	22	206.27

Data source: ABARE

ABARE did not include tidal power in its projections. However a recent UK report found that the cost of power from tidal barrages was expected to remain at some $120/MWh beyond 2020[25]. Similarly, the cost of tidal stream power was expected to remain between $80 and $150/MWh. The cost of wave power was projected to fall from $80-$200/MWh to $50-70/MWh.

Electricity from renewables is in most cases still more expensive than power sourced from conventional energy sources. However, some argue that this disadvantage can be offset if external costs such as the environmental impact of fossil fuel emissions are included in the cost of the latter. Certainly, if carbon dioxide sequestration from fossil fuel usage was required then the cost of that process would increase the price of conventional power, perhaps by as much as $20 - $50/MWh[26], although this could be conservative.[27]

25 Assessment of Technological Options to Address Climate Change – A Report for the Prime Minister's Strategy Unit, ICCEPT, December 20, 2002.

26 Assuming a $50/tonne CO_2 sequestration cost. Actual cost will depend upon fuel used and efficiency of the power plant.

The US President has stated his belief that technology offers great promise to significantly reduce greenhouse gas emissions. Extensive R&D work is under way aimed at bringing down the cost of sequestration in Australia and the US.[28] The US National Energy Technology Laboratory has a specific carbon sequestration program (see Box 4).

3.3.1 Cost trends

This section examines the cost trends for the two main hydrogen production processes used today, namely steam-methane reformation and water electrolysis[29]. The cost potential of hydrogen production from future large-scale coal-gasification is also briefly discussed.

Steam-Methane Reformation (SMR)

Table 7 reports the cost of SMR as $8/GJ. Another reference quotes the cost as about $10/GJ[30]. The latter costs are ex-refinery and are based on natural gas fuel costs of between $5 and $6/GJ and a hydrogen production capacity of around 150 tons per day[31].

Gas cost is 60-65% of SMR cost

The cost of the natural gas feedstock typically represents almost two thirds of the hydrogen production costs, hence the cost of bulk production of hydrogen from natural gas are likely to follow movements in the market price of natural gas.

Sequestration costs of $50 per tonne of CO_2 would increase the current hydrogen production costs from SMR by about $2.9/GJ. However, this would be an underestimate if the CO_2 sequestration costs are of the order of $67- $100, as suggested earlier.

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27 The IEA Greenhouse Gas R&D Programme puts the cost at US$40 to US$60 per tonne CO2. See "Putting the carbon back in the ground", IEA, February 2001

28 See http://www.netl.doe.gov/coalpower/sequestration/pubs/presentations/nacbmforum_jan03.pdf for an outline of the US Department of Energy Carbon Sequestration Program

29 Information from the following reference was used extensively for this section. "Survey of the economics of hydrogen technologies" by C. Padro & V. Putsche, Technical Report 570-27079, NREL (1999).

30 Steinberg M. and Cheng H. (1989): Modern and prospective technologies for hydrogen production from fossil fuels, Upton, NY, USA, Brookhaven National Laboratory.

31 Note that the purity of the hydrogen gas produced is typically around 99% this is too low for many applications, such as PEM fuel cells. Purification would add to costs.

Box 4 National Energy Technology Laboratory: Sequestration program vision and goals

Vision Statement

Possess the scientific understanding of carbon sequestration options and provide cost-effective, environmentally sound technology options that ultimately lead to a reduction in greenhouse gas intensity and stabilisation of overall atmospheric concentrations of CO2.

Overarching Goals

- By 2006 develop instrumentation and measurement protocols for direct sequestration in geologic formations and for in-direct sequestration in forests and soils that enable the implementation of wide-scale carbon accounting and trading schemes
- By 2008, begin demonstration of large-scale carbon storage options (> 1 MMTCO2/year) for value-added (enhanced oil recovery, enhanced coalbed methane recovery, enhanced gas recovery) and non-value added (depleted oil/gas reservoirs and saline aquifers)
- By 2008, develop to the point of commercial deployment systems for advanced indirect sequestration of GHGs that protect human and ecosystem health and cost no more than $10 per metric ton of carbon sequestered, net of any value-added benefits
- By 2010 develop instrumentation and protocols to accurately measure, monitor, and verify both carbon storage and the protection of human and ecosystem health for carbon sequestration in terrestrial ecosystems and geologic reservoirs. MMV systems should represent no more that 10% of the total sequestration system cost.
- By 2012, develop to the point of commercial deployment systems for direct capture and sequestration of GHG emissions from fossil fuel conversion processes that protect human and ecosystem health and result in less than a 10% increase in the cost of energy services, net of any value-added benefits.
- By 2015, develop to the point of commercial deployment systems for direct capture and sequestration of GHG and criteria pollutant emissions from fossil fuel conversion processes that result in near-zero emissions and approach a no net cost increase for energy services, net of any value-added benefits.
- Enable sequestration deployments to contribute to the President’s Global Climate Change Initiative goal of an 18% reduction in the GHG intensity of the United States economy by 2012.
- Provide a portfolio of commercial ready sequestration systems and also one to three breakthrough technologies that have progressed to the pilot test stage for the 2012 assessment under the Global Climate Change Initiative

On-site production can reduce delivered cost.

By comparison, the costs of on-site hydrogen production using emerging small-scale SMR technology, which produce some 0.25 – 2.5 tons per day, has been estimated at around $20 - $42/GJ, assuming natural gas costs of $5 per GJ[32]. This approach is understood to offer the lowest delivered hydrogen costs in the near- to mid-term future.[33]

Water Electrolysis

Table 7 reports the cost of hydrogen from electrolysis as being between $29-42/GJ. Another reference reports that, based on electricity costs of around $0.06 per kWh, and depending on the choice of technology[34], the current production costs from water electrolysis are about $42 – 58 per GJ at a hydrogen production capacity of about 5 tons per day[35].

Electricity costs are 75-85% of cost of electrolysis.

The cost of electricity is the main cost factor for hydrogen production from water electrolysis. Typically, electricity cost makes up between 75% and 80% of the total production cost. The current market value of the oxygen by-product from the electrolysis process equates to between $3 to $5/GJ of hydrogen produced. This is of course dependent upon having a market for the oxygen at or near the electrolysis site.

The electrolytic conversion efficiency of an advanced medium-scale unit (production capacity of between 2 and 20 kg/day) is similar to that of a large-scale unit. Given that distributed production of hydrogen via water electrolysis eliminates the need for hydrogen transport and distribution infrastructure, this technology has the potential to become economically competitive in certain niche markets, such as refuelling private fuel cell vehicles, particularly where natural gas is not readily available.

Low-cost electricity such as off-peak power is required to increase the adoption of small-scale electrolysers (production < 2 kilograms per day) in the market. Industries are working toward a cost goal of about $2,900 for a 2-kg-per-day "personal fuel appliance" water electrolyser[36].

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32 Odgen J. (2002): Review of small stationary reformers for hydrogen production, IEA-H2 report.

33 Distributed hydrogen production has the advantage of avoiding transmission and distribution costs and, potentially, storage costs as well.

34 Basye L. and Swaminathan S. (1997): Hydrogen production costs – A survey, MD, USA, Sentech Inc., 1997.

35 The purity level of hydrogen produced from water electrolysis is very high, typically in excess of 99.99%.

36 Fairlie M. and Scott P. (2002): Filling-up with hydrogen 2000, US Hydrogen Program Review Meeting, NREL/CP-610-32405.

Coal Gasification

Existing coal gasification processes are quoted as being capable of generating hydrogen at costs of between \$20 and \$30/GJ of hydrogen[37]. These costs are for hydrogen production capacities of between 500 – 650 tons per day and coal feedstock costs of some \$3.30 to \$4.20 per GJ[38]. The purity of hydrogen produced from today's coal gasification processes is typically about 97%.

Coal gasification costs could drop significantly.

The 2020 vision for the US FutureGen project sees the potential for hydrogen production costs from new 'zero-emission' coal technologies of around US\$3.80 per GJ (approximately A\$6.33/GJ)[39,40].

The Australian Coal Association's COAL21 initiative is also aimed at realising the potential of technologies such as coal gasification to reduce greenhouse emissions. This is discussed further in section 3.5.

3.4 Other supply costs

Production is of course just one component of the hydrogen supply chain. The sections that follow examine the costs associated with the other elements of the supply chain.

3.4.1 Distribution and storage

Hydrogen can be transported by truck or pipeline.

Providing hydrogen to the end-user, or consumer, can be done in a variety of ways. These include bulk transportation and distribution of hydrogen for immediate use, or alternatively, transportation of other energy sources for local conversion to hydrogen.

The most common method of hydrogen supply in the short term is likely to be the road tanker, since initial demand for hydrogen is likely to be relatively small and geographically dispersed. This method is currently widely utilised around the world and will be used in Australia in the Perth Fuel Cell Bus Trial.

Larger quantities of hydrogen could be supplied by road tankers transporting liquefied hydrogen, or pipeline delivery of gaseous hydrogen. Hydrogen can

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37 Fahrni R. (2002): Hydrogen production – An overview of hydrogen production methods and costs today, Master Thesis, Swiss Federal Institute of Technology (ETH), Zürich.

38 Australian black coal for power generation sells for between \$0.80 and \$1.70/GJ. This would give a hydrogen price of between \$5 and \$10/GJ (not including CO_2 sequestration costs).

39 FutureGen Project Factsheet (2003), US Department of Energy.

40 Nawaz M. and Ruby J. (2001): Zero Emission Coal Alliance project conceptual design and economics. International Coal Technology and Coal Utilization Conference, Clearwater Florida.

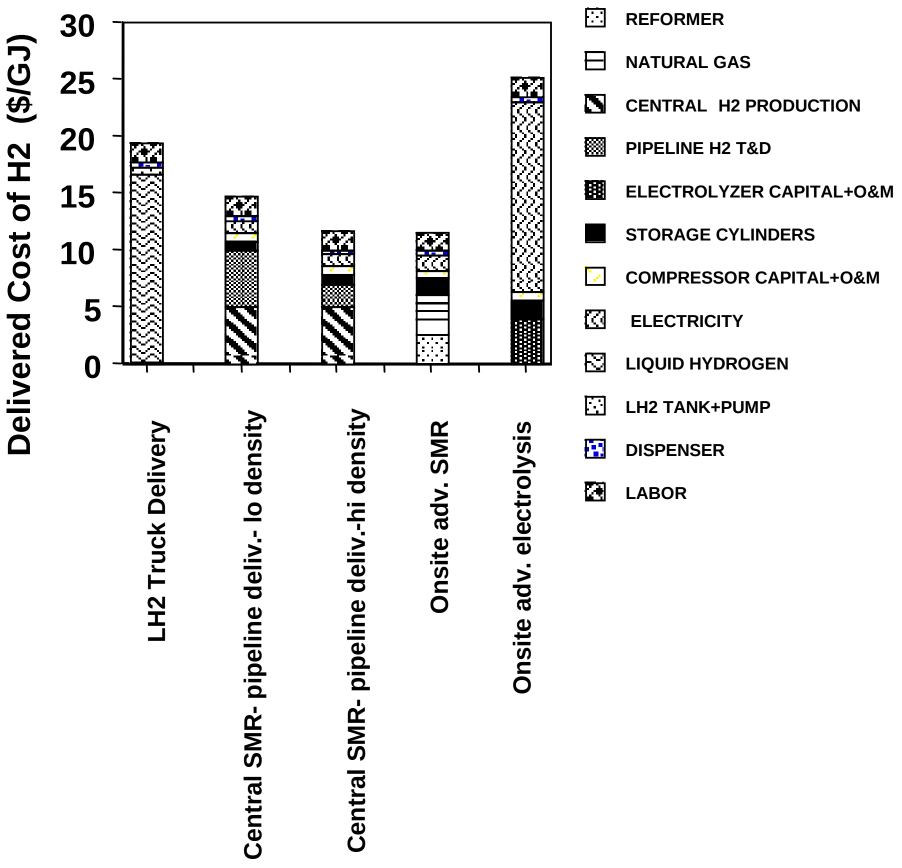
also be produced at the point of use by electrolysis of water or by the reformation of a fossil fuel, such as natural gas.

A comparative cost assessment suggests that high throughput delivery of hydrogen by pipeline can almost compete on a cost basis with on-site steam reformation of natural gas at a refuelling site, as shown in Figure 11. Note that the costs are given in US dollars.

However, the cost of transporting hydrogen remains high.

There is clearly some way to go before hydrogen delivered by any of the above means can compete with the cost of natural gas on a delivered energy basis. At current exchange rates the assumed cost of natural gas in Figure 11 is equivalent to about $5/GJ, which is similar to the delivered cost to an industrial consumer in Australia. This is significantly below the cheapest option shown for hydrogen, namely $19/GJ for advanced on-site steam methane reforming.

Figure 11 **Indicative delivered cost of hydrogen as a transportation fuel (US$/GJ)**



Data source: Courtesy of J Ogden from: Prospects for Building a Hydrogen Energy Infrastructure, Annual Review Energy Environment. 1999. 24:227-79

Three key criteria for hydrogen storage.

Much of the R&D related to hydrogen storage has focussed on identifying a means to store hydrogen in a sufficiently concentrated form in order to make it practical to use in hydrogen energy systems. The design and operation of a hydrogen storage system aims to satisfy four key criteria. The first priority is safety, the others three key criteria are applicability, economics and reliability.

1. **Applicability** comprises issues such as storage convenience, hydrogen storage capacity, rapid delivery (kinetics), integrity of storage medium and components, operation and versatility of storage system, and simple system integration compatibility.
2. **Economics** is dominated by the need to reduce investment costs for materials, manufacture and infrastructure needs. Operation and maintenance costs are the main recurring cost factors to be considered.

3. **Reliability** can be ensured through choice of materials, quality control during manufacture, long-term operational tests, and on-going life-cycle considerations.

The following five hydrogen storage mechanisms are subject to ongoing R&D:

- compressed gaseous storage (CH2);
- cryogenic liquid storage (LH2);
- metallic storage (metal hydrides and alanates);
- carbon storage (carbon-based nano-materials); and
- liquid storage (chemical hydrides).

No current storage mechanism fully satisfies the three requirements discussed above[41] - each of them has specific advantages and disadvantages. Existing R&D programs are aimed at improving performance across the full range of criteria listed above.

3.4.2 End use

Supply infrastructure will emerge to meet demand.

The end use infrastructure implications will vary depending upon the particular end-use sector being considered. In most cases the supply infrastructure will simply emerge in order to meet the demand. That demand will in turn grow when the products available can compete on price and performance.

Appliances

For appliances the infrastructure requirements will be analogous to those that apply to battery supplies now. Instead of buying a battery the consumer will buy a supply of hydrogen or methanol fuel. Instead of a battery manufacturer there will be a manufacturer of the particular fuel and the storage device for it.

The fuel cell component of the power unit will of course need to be manufactured and installed in the appliance. This is likely to be done in the location where the appliance itself is manufactured.

Vehicles

Fuel cell vehicles will be sold in much the same way that current vehicles are. There is likely to be a mix of imported and locally manufactured vehicles with the former dominating early on, but the latter gaining market share if the market grows.

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[41] Here the Study assumes that safety is paramount and takes precedence over all other requirements.

There will need to be a significant investment in retooling to make the new vehicles. Refuelling infrastructure will also need to be put in place. There are a number of possible ways this could occur including:

- One approach would be distributed production of hydrogen from natural gas at refuelling sites (eg existing service stations, home refuelling stations, or, as suggested by some, fuel cell vehicle sales companies);
- An alternative approach would be the centralised production of hydrogen (say by coal gasification) and the distribution of hydrogen by pipeline or tanker to service stations; or
- Distributed hydrogen production using renewable energy.

Distributed generation

The situation for this end use will be much the same as for vehicles. As with vehicles, there are already products available on the market for consumers to buy. As these progressively improve in terms of cost and performance their up-take is likely to grow.

It is probable that the availability of cheap grid based electricity in Australia will, initially at least, limit the scope for fuel cells to enter the market for distributed generation. However as costs fall buyers are likely to increase in number, most likely in the residential and commercial sectors, at least initially. Another possibility is that the cost of grid based power increases, for example if carbon capture and sequestration becomes commonplace.

Supply infrastructure is likely to follow a similar pattern to that discussed above for vehicles.

3.5 Implications for Australia

In Australia, the two most common hydrogen production methods are steam reformation of methane and electrolysis of water. Australia is well endowed with the resources needed to continue to make hydrogen by these means. It is likely that production from coal gasification might join that portfolio of production methods.

COAL21 is likely to focus on coal gasification and CO_2 sequestration.

Of course hydrogen production via steam reformation of gas or coal gasification would still lead to significant greenhouse emissions unless the CO_2 produced is captured and sequestered. This is indeed the focus of the proposed COAL21 project sponsored by the Australian Coal Association.

COAL21 is a program aimed at fully realising the potential of advanced technologies to reduce or eliminate greenhouse gas emissions associated with the use of coal, while at the same time maintaining Australia's competitive advantage of low cost electricity from coal.

The key objectives of COAL21 include to:

- create a National Action Plan to scope, develop, demonstrate and implement near-zero emissions coal-based electricity generation that will achieve major reductions in greenhouse gas emissions over time and maintain Australia's low cost electricity advantage. The National Action Plan is scheduled to be implemented in 2004.
- use the Plan to inform governments and industry as an input to policy development.
- Facilitate the demonstration, commercialisation and early uptake of technologies identified in the Plan.
- Promote relevant Australian RD&D so that it can both build upon and make a unique contribution to international RD&D in the area.

Discussions with the Australian Coal Association have highlighted a number of areas where there are synergies between the National Hydrogen Study and COAL21. These are discussed in Box 5.

Box 5 **Possible linkages between COAL21 and the National Hydrogen Study**

There are a number of areas where there may be useful linkages between COAL21 and the National Hydrogen Study. Two obvious ones are:

- The COAL21 Action Plan for new coal-based generating capacity will be based on a number of different scenarios for electricity demand projections, emission reduction goals, and technology cost-reduction curves to 2030. COAL21 should include similar scenarios for the production of hydrogen for non-electric power applications. Targets for this “excess hydrogen production capacity” could be draw on the National Hydrogen Study’s scenario analysis of what Australia’s demand for hydrogen for non-electricity applications could be by 2030 and 2050. The COAL21 process should also include consideration of the non- electricity hydrogen demand when developing its roadmap and action plan.
- If the COAL21 process results in the construction of a coal gasification IGCC plant this would generate a stream of hydrogen gas that could be used by Australian hydrogen researchers for work in a range of areas (eg hydrogen gas purification, fuel cell testing, large scale storage, etc.). The COAL21 roadmap and action plan should include scope for cooperative activity of this kind.

In the longer term, any transition to the greater use of hydrogen in Australia’s energy mix is likely to increasingly utilise Australia’s considerable renewable energy resources to produce hydrogen. These include hydropower, wind, tidal, biomass and solar energy. This means of producing hydrogen has no associated greenhouse emissions.

However, on the basis of current conversion efficiencies and costs, using renewable energy to produce hydrogen still faces some serious cost barriers.

What might be more likely in the medium term is that hydrogen could be used as a storage medium for renewable energy that might otherwise not be able to find a buyer. However, the cost of the conversion to, and storage of, the hydrogen would ultimately need to be recovered and this would be a considerable hurdle. Table 9 provides indicative energy costs in Australia. Note that the costs quoted are at the point of production.

Table 9 **Indicative costs of different Australian energy sources**

Fuel	Current Usage	$/GJ (at point of production)
Hydrogen	Reagent in chemical processes and insulator and cooling gas in high power alternators	8-58
Natural Gas	Industrial, commercial and domestic fuel	5
Coal	Industrial and power plant fuel	1-3
Petrol	Liquid fuel for transportation	10*
Electricity	Energy for various applications	10**

Data source: ACIL Tasman

Notes: * Ex-refinery price before tax. ** Assumes a spot price of $36/MWh. In 2000-01 large business electricity prices were between $60 and $100/MWh, while smaller businesses paid $100 -$170/MWh.

Table 9 shows that hydrogen is still a relatively high cost source of energy. Adding storage and transport costs further accentuates the cost differential.

4 International policy initiatives

Hydrogen is attracting growing interest worldwide.

As noted above, there is growing interest worldwide in the potential to use hydrogen as an energy source. This is reflected in a significant growth in public and private sector funding allocated to this topic and an increasing number of bilateral agreements for collaborative research and development into hydrogen technologies. This chapter examines these developments in more detail for a selected number of countries.

4.1 Japan

Japan's hydrogen effort is focussed on R&D for commercialising and popularising fuel cells, fuel cell vehicles and hydrogen infrastructure. Japan is a technologically advanced country and a world leader in the automobile and electronics industries. Accordingly, Japan's hydrogen R&D focus is primarily aimed at achieving the technological advances to enable high performance and cost effective fuel cells to penetrate the market. In particular the use of fuel cells in vehicle and stationary energy markets.

Japan has set some ambitious targets.

The Japanese Government has set some ambitious targets for the penetration of hydrogen fuel cells in these markets by 2010 and 2020. Those targets are shown in Table 10.

Table 10 **Japan's targets for fuel cell sales**

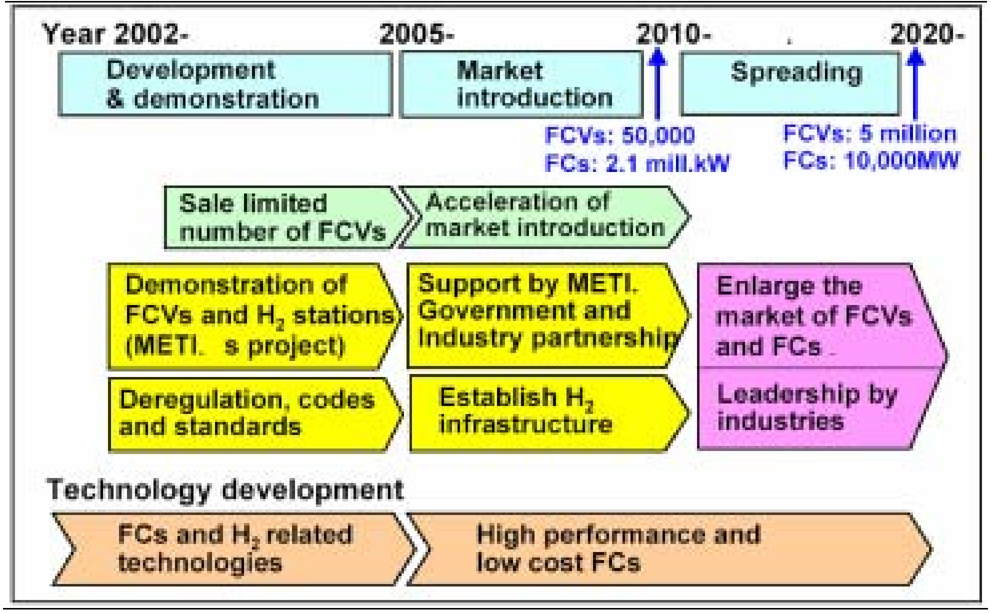
Year	In transport	In stationary energy applications
	(Number of vehicles)	(Capacity (MW))
2010	50,000	2,100
2020	5 million	10,000

Source: Japan NEDO, 2003

Figure 12 depicts the Hydrogen Energy Systems Society of Japan's[42] views on the underlying steps required to achieve these targets. There are technical and cost goals for fuel cell performance, efficiency and operating lifetime, the cost of the hydrogen, and the development and acceptance of the fuel infrastructure.

42 The Hydrogen Energy Systems Society of Japan (HESS) was established in July 1973, to promote hydrogen energy systems. Headquartered at Yokohama University, HESS is a leading centre for hydrogen energy research in Japan.

Figure 12 **Timeframe for implementation of Japan's hydrogen targets**



Data source: Hydrogen Energy Systems Society of Japan

A public-private cooperative venture has been created to help achieve the milestones shown in Figure 12. The partnership brings together the Policy Study Group for Fuel Cell Commercialisation, a government research group established in December 1999, and the Fuel Cell Commercialisation Conference of Japan (FCCJ), a voluntary industry organisation established in March 2001.

The major Japanese hydrogen and fuel cell initiative is the National Hydrogen Program (WE-NET)[43]. This program commenced in 1993, and is due to be completed in 2003. The total R&D budget for this program was 22 billion yen ($US 183 million at $US 1 = 120 yen). The new hydrogen project plan will commence in 2003. Its objectives are set out in Box 6. The requested budget in FY 2003 for the project is 30.7 billion yen ($US 256 million at $US 1 = 120 yen) to be spent over FY 2003-FY2007. The amount to be spent in FY 2003 alone is $US 37.5 million.

[43] World Energy - Network

Box 6 **Japan's forthcoming hydrogen plan**

Objectives

- To support market introduction of hydrogen fuelled fuel cell vehicles from 2005
- To establish hydrogen infrastructure for vehicles
- To contribute to the global environment and to secure energy sources

Project term

- FY 2003-FY2007 (5 years)

Total budget:

- 30.7 billion yen (US$ 256 million)

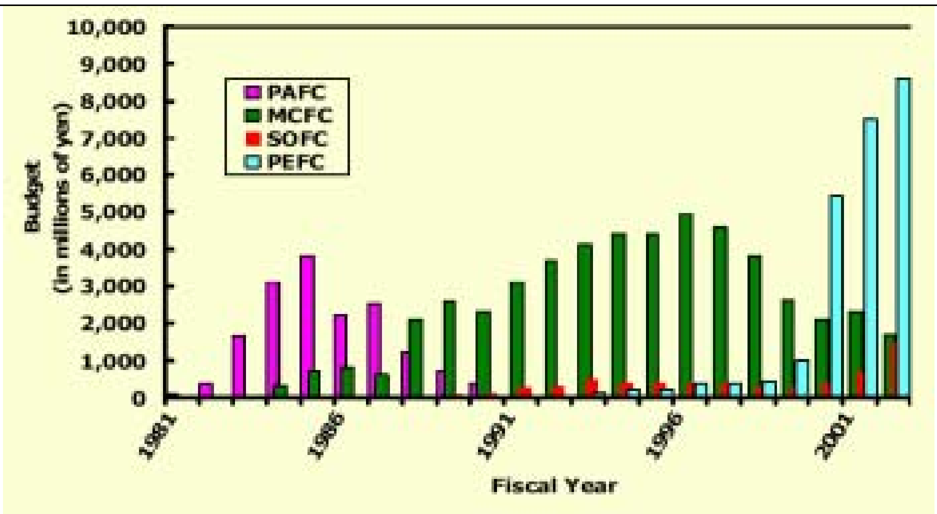
R&D priorities

- Validation and evaluation for safety of hydrogen to enact regulation, code and standards
- Establish hydrogen infrastructure and develop related technologies (Compressors, 70 MP hydrogen cylinders)
- Micro fuel cell systems for electronic devices

Data source: Hydrogen Energy Systems Society of Japan

Expenditure on fuel cell R&D in Japan since 1980 is shown in Figure 13. Research has tended to concentrate on one type of fuel cell technology at any one time.

Figure 13 **Expenditure on Japan's fuel cell projects**



Data source: Japan NEDO, 2003

Over the last twenty years there have been research projects concentrating on proton exchange membrane fuel cells (PEFC), the phosphoric acid fuel cell

(PAFC), the solid oxide fuel cell (SOFC) and on the molten carbonate fuel cell (MCFC).

In December 2002 the Japanese Government launched a demonstration program with five fuel cell vehicles.

4.2 The United States

The US President's State of the Union focussed attention on hydrogen…

The US has recently been an outspoken advocate of the transition to hydrogen as a replacement for fossil fuels on the grounds of energy security and the environment (see Box 7). The overall US hydrogen strategy can be broadly summarised as:

- The public promotion of the benefits of hydrogen fuel to garner public acceptance;
- Domestic R&D into transport and stationary fuel cell applications; and
- International cooperation to leverage off international developments.

Box 7 **State of the Union Address 28 January 2003**

"Tonight I am proposing $1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles."

"A simple chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car producing only water, not exhaust fumes. With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom so that the first car driven by a child born today could be powered by hydrogen, and pollution-free. Join me in this important innovation to make our air significantly cleaner, and our country much less dependent on foreign sources of energy."

— President Bush, State of the Union Address, January 28, 2003

… and led to a significant increase in funding.

The US Government has pledged $1.7 billion over the next five years to develop hydrogen-powered fuel cells, hydrogen infrastructure and advanced automotive technologies. The initiative aims to develop the technology for mass production of clean hydrogen powered automobiles and the infrastructure to support them by 2020, such that America can lead the world in hydrogen-powered automobiles. For the FY 2003/04, The US DOE has placed a $US 272.8 million budget request to continue funding of the "FreedomCAR" project, the US hydrogen fuel cell vehicle initiative[44].

44 FreedomCAR (Cooperative Automotive Research) is a public/private partnership between the US Department of Energy and General Motors, Ford and Daimler Chrysler.

The US R&D efforts can be broadly characterised as being directed towards the cost competitive production, storage, distribution and delivery of hydrogen. For example:

- Reducing the costs of producing high performance fuel cells;
- Reducing the delivered cost of the hydrogen fuel itself. The goal is to bring down the cost of the hydrogen so that it is equivalent to a price of US$1.50 for a gallon of petrol by 2010 (before tax). This is equivalent to approximately A$0.66/litre;
- Building the hydrogen infrastructure needed to enable convenient and affordable refuelling; and
- Developing higher energy density hydrogen storage systems.

The effort also includes the development of codes and standards that will help ensure the safe handling and operation of hydrogen-fuelled vehicles.

The US hydrogen vision envisages the emergence of a transportation system powered by hydrogen derived from a variety of domestic sources, as well as stationary fuel cell applications.

Another key US initiative is the FutureGen project. This project is a public-private effort to construct the world's first pollution-free fossil fuel power plant. The project has been described in more detail in Box 3 on page 26.

International collaboration plays a key role in the US efforts.

Part of the US Hydrogen strategy is to leverage off international efforts where possible, to complement domestic efforts. For example, at the recent International Energy Agency Ministerial Meeting, the US proposed an international partnership for the hydrogen economy (IPHE) to establish cooperative and collaborative efforts in hydrogen production, storage, transport, and end use technologies.

In June 2003 the US and the European signed the Fuel Cell Annex to the US-EU Non-Nuclear Energy Cooperation Agreement. This is discussed in greater detail in section 4.7.

4.3 Iceland

Over 70 per cent[45] of Iceland's primary energy requirements are met by hydro and geothermal electricity. This energy mix sets a favourable backdrop for hydrogen, as zero-emission electricity could be used to produce hydrogen fuel via electrolysis.

Iceland wants to become the first hydrogen economy.

The Iceland Government's vision is to create the world's first hydrogen economy[46]. Because the majority of the country's stationary energy is derived from renewable and environmentally friendly sources, the initial focus of Iceland's efforts are being directed at the transport sector.

Two thirds of Iceland's current oil consumption is used by the industry sector (including the fishing industry). The rest is used for ground transportation. Fishing accounts for 65 percent of Iceland's exports, and the nation relies on low oil prices to supply fish to the world market at a competitive price. If oil prices go up, while fish prices remain relatively unchanged, exports and national income fall.

Public-private partnership will again play a role…

The initiative to achieve a hydrogen economy involves cooperative R&D through various public/private partnerships. The most significant, Icelandic New Energy (INE) was established as a joint venture to promote the use of hydrogen as a fuel for transport. INE is jointly owned by the Iceland Government and academic institutions (51%), Shell Hydrogen (16%), Norsk Hydro (16%) and Daimler Chrysler (16%). The principal work being undertaken by INE is demonstration projects for buses, cars and fishing vessels.

…with a focus on the transport sector.

A demonstration project for passenger buses is already under way in Iceland (the ECTOS project 2001-2005). The four-year ECTOS project is divided into two key components:

- The first two years were spent on preparation, establishing infrastructure, maintenance facilities, and conducting economic/social research, etc;
- The second period sees the public demonstration of three fuel cell buses and the associated commercial infrastructure.

As part of the ECTOS project, the world's first hydrogen refuelling station for buses was opened in Reykjavik in early 2003.

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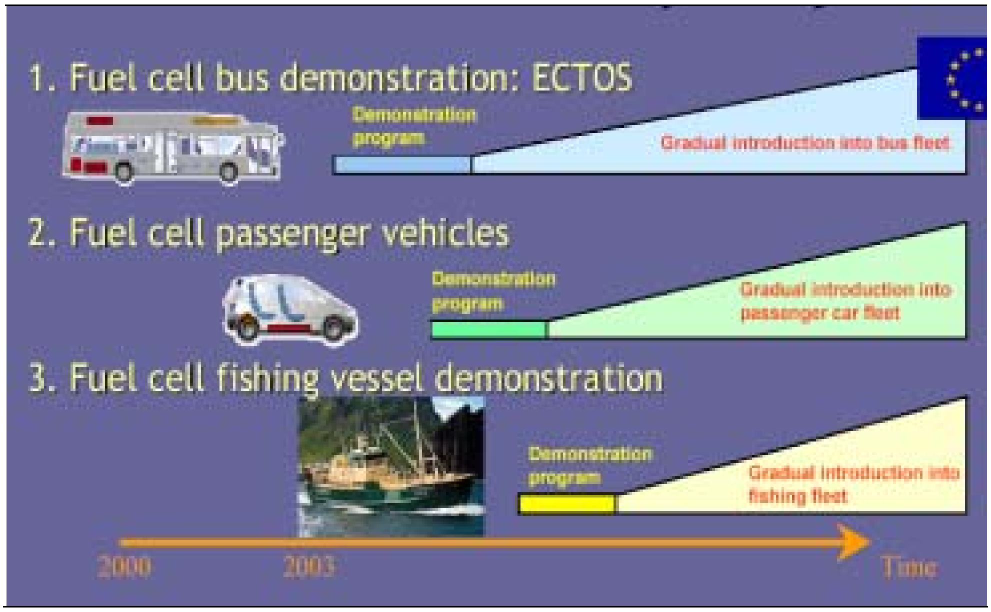
45 INE publication to the IEA Hydrogen Workshop, 2003

46 The country has completed major shifts in its energy supply mix in the past. In 1950 Iceland moved all of its heating and electricity production from oil- and coal-fired power plants to geothermal and hydroelectric power plants.

Demonstration programs for cars and fishing vessels are projected to follow. The time frames for the transport demonstration initiatives are shown in Figure 14.

Figure 14 **Iceland's timeframe for demonstration and introduction to market of hydrogen products**



Data source: Icelandic New Energy presentation to IEA Hydrogen workshop, 2003

4.4 The European Union (EU)

The EU has been at the forefront of hydrogen R&D.

Many EU countries have been among the most active worldwide in developing the technologies and concepts that would underlie any transition hydrogen economy. The EU is seeking to promote greater cooperation, pooling of resources and harmonisation of efforts. The goals are the reduction of negative environmental impacts of energy use and improved security of energy supply.

The long-term EU vision is to have in place an energy supply system based on renewable energies and fuel cells with hydrogen and electricity as prominent energy carriers within 20-30 years.

The main EU R&D initiative is the European Research Area (ERA). ERA funding for hydrogen and fuel cell research projects was 2.5 million and 30 million euros respectively in 2001-02.

The most significant programs are:

- The European Integrated Hydrogen Project (EIHP 1 and 2): a study of the regulations and standards aspects relating to hydrogen energy and fuel cells in Europe, harmonisation of standards in the EU;
- The CUTE and ECTOS projects. The production, commissioning and operation of 30 Citaro type Daimler Chrysler fuel cell buses with hydrogen stored under pressure, in 10 European cities, from 2003 onwards. The EU has contributed 21 million Euros to this project.
- HYNET: the setting up of a European information network on hydrogen
- ELEDRIVE: thematic network on electric vehicles including hybrid and fuel cell vehicles;

There are two European associations

- The European Fuel Cell Group (EFCG)
- European Hydrogen Association (EHA) – a federation of existing national associations

4.5 Canada

Canada has a growing fuel cell industry.

According to Fuel Cell Canada, there are 13 companies focusing on fuel cell production or system integration, and 28 other firms and organisations heavily involved in the hydrogen and fuel cell industry[47]. They contributed about 275 million dollars per year to the economy, and employed about 1800 people in 2000-2001.

Canada also has several major university and government R&D centres, such as the Institute for Integrated Systems at the University of Victoria (IESVIC), the Centre for Hydrogen and Electrochemical Studies at the University of Toronto and the Institut de Recherche sur l'hydrogène at the Université du Québec à Trois-Rivières. R&D activities are also under way at government-sponsored labs such as at the National Research Council Innovation Centre in Vancouver, and Canmet. In addition, networks of researchers, such as the Automobile of the 21st Century Centre of Excellence and the Quebec Research Network on Fuel Cells and Hydrogen, and University Chairs have been established throughout Canada to facilitate collaborative work.

On the 8th June 2003 the Canadian Government announced C$14.1[48] million in funding for hydrogen and fuel cell initiatives. The money will be spent on the following:

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[47] The Canadian Fuel Cell Industry, a Capabilities Guide; Fuel Cells Canada, June 2002

[48] The Canadian dollar is shown as C$.

- C$9.6 million for the development of advanced technologies that reduce costs and improve the efficiencies of fuel cells and the hydrogen infrastructure;
- C$2 million for a project to develop an energy-efficient, lower-cost hydrogen compressor and dispenser fuelling system. The aim is to reduce the costs associated with hydrogen refuelling, reduce capital and operating costs by 40 to 50 per cent, and cut energy consumption costs by 15 to 40 per cent;
- C$500,000 for a project to develop a 10-kilowatt fuel cell power module for use in utility vehicles, forklifts, mining vehicles and ice resurfacing machines; and
- C$2 million for the Vancouver fuel cell vehicle project that will demonstrate five fuel cell vehicles on public roads.

4.6 Germany

Germany has been at the forefront of hydrogen fuel cell technology development and implementation worldwide. Germany has various federally organised initiatives and numerous regional initiatives in place.

Much of Germany's work focuses on the transport sector.

There has been strong cooperation between public and private enterprises, with involvement from Daimler Chrysler, Opel, Ford, BMW and Ballard Power Systems among others. Particularly well known is the NEBUS passenger bus demonstration project. Another is the hydrogen service station at Munich airport.

In total, public financing is approximately 100 million Euros a year.

Some of the key initiatives include:

- The public/private Transport Energy Strategy (TES). This initiative supports R&D on three alternative fuels (hydrogen, methanol and natural gas).
- The establishment of the Society for the Promotion of Renewable Energy (FEE) in February 2002.
- The Hydrogen Technology Initiative (2002) in the State of Mecklenburg-Western Pomerania.
- In April 2002 the State of Hesse founded the Hydrogen and Fuel Cell Initiative in Frankfurt-Hoechst, in collaboration with universities and industry.

4.7 Multilateral/bilateral initiatives

4.7.1 Partnership for advancing the transition to hydrogen (PATH)

The Canadian Hydrogen Association, the National Hydrogen Association of the United States and the Hydrogen Energy Systems Society of Japan have formed the Partnership for Advancing the Transition to Hydrogen (PATH).

Through PATH, National Associations representing the Hydrogen Industry stakeholders (producers, users, carriers and regulators) can exchange information on the scientific, technical and commercial aspects of hydrogen production, transportation, safety and use.

PATH disseminates scientific, technical and commercial information regarding the production, transportation and use of hydrogen to government and the general public, particularly in the US, Canada, Latin America, Japan and countries of the Pacific Rim. PATH initiatives include the establishment of national hydrogen associations and promotion of hydrogen energy industries in the developing countries of Latin America and of the Pacific Rim.

4.7.2 US-EU cooperation

In June 2003 the US Secretary of Energy Spencer Abraham and European Union Commissioner for Research Phillipe Busquin signed the Fuel Cell Annex to the US-EU Non-Nuclear Energy Cooperation Agreement. The Fuel Cell Annex lays out the framework within which the two entities will collaborate on hydrogen research. Seven topics of research were identified, namely[49]:

- transportation demonstration programs, including fuelling infrastructure;
- Auxiliary Power Units (APUs);
- codes and standards including fuel infrastructure, vehicles, and APUs;
- fuel choice studies and socio-economic and environmental assessment of the availability of critical materials for low temperature fuel cells;
- Solid Oxide Fuel Cells (SOFC) and high temperature fuel cell hybrid systems;
- support studies, including socio-economic assessment of critical rare earth materials for high temperature fuel cells; and
- direct methanol and Polymer Electrolyte Membrane (PEM) fuel cells for transportation and stationary applications.

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[49] US Department of State fact sheet on U.S.-EU Summit: Cooperation on the Development of a Hydrogen Economy, http://www.state.gov/p/eur/rls/fs/21929.htm

The US and EU are currently collaborating on two projects. The IP-SOFC, a US$ 20 million demonstration fuel cell turbine project co-funded by the US and EU, and EIHP 2, which is examining standards and regulations for hydrogen vehicles and infrastructure.

4.7.3 International partnership for the hydrogen economy (IPHE)

The stated aim of the IPHE is to provide a mechanism to organise, evaluate and coordinate multinational research, development and deployment programs that advance the transition to a global hydrogen economy[50]. The Partnership will:

- leverage limited resources;
- bring together the world's best intellectual skills and talents to solve difficult problems; and
- develop interoperable technology standards.

It is also expected to foster public private partnerships that address technological, financial and institutional barriers to a cost-competitive, standardised, accessible, safe and environmentally benign hydrogen economy.

The IPHE will initially review actions being pursued jointly by participating countries and identify additional actions to advance research, development and deployment of hydrogen production, storage, transport, distribution and end-use technologies. It will also consider common codes and standards for hydrogen fuel utilisation and coordination of international efforts to develop a global hydrogen economy.

The US is seeking counterparts that have:

- substantial, long-term resource commitments to hydrogen and fuel cell technology research and development activities;
- a well-defined vision and national strategy to advance technology deployment and infrastructure development; and
- a commitment reflected in policies and strategies that effectively advance private sector development of a hydrogen economy.

The US is proposing a Ministerial-level conference in the latter half of 2003 to formally establish the International Partnership for the Hydrogen Economy.

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50 Framework for the International Partnership for the Hydrogen Economy, http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/iphe_framework_final.pdf

4.8 Implications for Australia

Table 11 presents a summary of the hydrogen and fuel cell research priorities, programs and targets for the countries and regions analysed in this section.

Table 11 **Summary of international hydrogen and fuel cell R&D priorities, strategies and targets**

Country	R&D focus	Strategy	Targets
United States	Directed towards cost competitive production, storage, distribution and delivery of hydrogen	The promotion of the benefits of hydrogen as a fuel through demonstrations, domestic R&D into transport and stationary fuel cell applications, international cooperation and leveraging off international efforts.	Targets for developments in hydrogen production, delivery, storage and conversion that would see hydrogen and fuel and its end-use market applications established by about 2030-40.
Canada	Technological advances to bring down costs and improve efficiency of fuel cells and hydrogen infrastructure.	Government funding and assistance to private / academic R&D programs and the establishment of private/government /academic research networks.	
Japan	Specifically focussed towards technical R&D and technological developments to enable high performance and cost effective fuel cells to penetrate the market	The National Hydrogen Program (WE-NET) being completed this year and a new Hydrogen Program commencing this year.	50,000 fuel cell vehicles by 2010, 5 million by 2020. 2,100 MW of stationary FC generating capacity by 2010, 10,000 MW by 2020.
Iceland	The promotion of hydrogen as a replacement for fossil fuels in road and seaborne transport	The formation of a formal public/private venture entitled Icelandic New Energy that is focussed on undertaking demonstration projects for buses, cars and fishing vessels.	To become the world's first hydrogen economy. Integration of hydrogen powered buses, cars and fishing vessels into fleets by 2010.
Germany	Principal focus is on road transport demonstrations	The NEBUS bus demonstration project and the Transport Energy Strategy, a competitive format strategy to determine the best alternative fuel to replace petrol, of which hydrogen is one.	
EU	Promoting and implementing cooperation in R&D between EU countries	Hydrogen fuel cell bus demonstration projects: The European Integrated Hydrogen Project. The HYNET information network.	

There is considerable commonality in the approaches adopted.

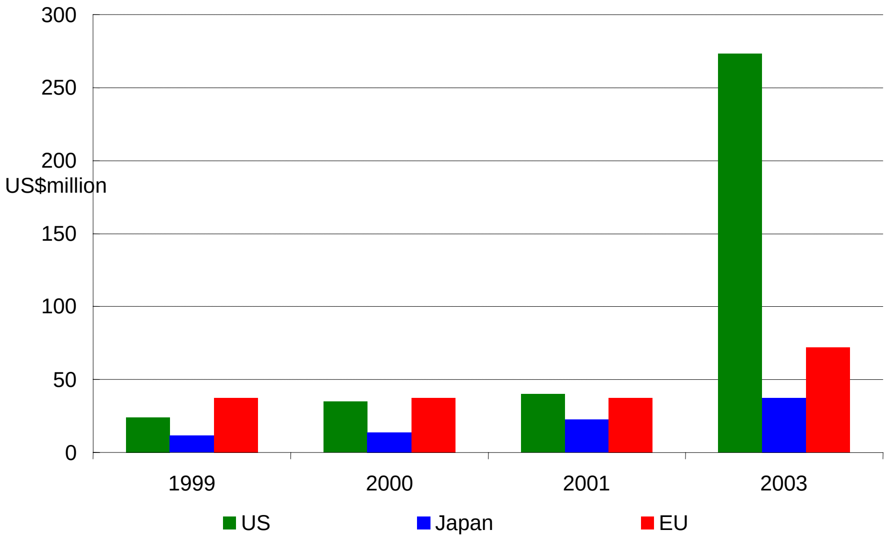
There are considerable areas of overlap in the directions of work being undertaken by various countries around the world. In particular there is considerable commonality in the approaches adopted in the following areas:

- Improving the efficiency and reducing the cost of fuels cells;

- Reducing the cost of producing hydrogen;
- Funding demonstration projects (particularly in the transport sector);
- Work on uniform codes and standards;
- Forming public/private partnerships; and
- Promoting international collaboration.

The increasing level of attention directed towards hydrogen has led to a commensurate increase in the amount of public money allocated to hydrogen and fuel cell R&D. Chart 1 shows change in funding in the US, EU and Japan.

Chart 1 **Hydrogen and fuel cell R&D expenditure trends 1999-2003**



Data source: ACIL Tasman

If Australia is to play a role in any transition to a hydrogen economy then it would be inefficient and most probably impractical for us to seek to do so in isolation from all that is occurring overseas or to adopt approaches that are significantly different from those seen overseas. Rather, collaboration with overseas partners should be pursued where possible to help maximise the value of Australia's R&D funds.

That is not to say of course that there will not be areas where Australia might pursue different directions to those seen overseas. Indeed, it is to be hoped that there will be areas where Australia's competitive advantages will lead us down paths that are unique to Australia, but at the same time ones that open up opportunities to develop and capture markets both in Australia and overseas.

5 Opportunities

5.1 Introduction

A hydrogen economy would bring opportunities.

This chapter outlines the opportunities that might arise for the Australian research community and industry sector (including services) in the event of a transition to a hydrogen economy in this country. In particular, an economy where hydrogen becomes an important energy source for one or more of the following: portable equipment; transport (motor vehicles in particular); and decentralised electricity generation.

Broadly speaking, any transition to a hydrogen economy would most probably be a worldwide development, although different countries might enter and emerge from that transition at different times. The actual time frames would reflect the rates of transfer of information/technology, hydrogen production capacities, the availability of supply infrastructure and end use equipment associated with hydrogen.

In this context the opportunities for the research community and industry in the transition to a hydrogen economy have been examined. Opportunities are discussed using a supply chain approach for each of the above sectors. There is also some high level analysis of the implications for exports and import replacement; for investment levels, for metropolitan and regional Australia and, for skill development and training.

These opportunities will vary over time.

The opportunities in the transition to a hydrogen economy could be quite different to those once hydrogen becomes firmly established as an energy source. This is most pertinent with respect to R&D where the opportunities may well be greater during any transition, especially the early transition. Moreover, the outcomes of that R&D will be particularly influential in determining the nature of production, the infrastructure requirements as well as end use products. Thus the nature of the opportunities in subsequent segments of the supply chain will be significantly influenced by the outcomes of R&D in other segments, both upstream and downstream.

As a consequence the discussion of opportunities is necessarily somewhat limited by the broad caveat of “it depends upon what happens elsewhere”.

The critical issues for hydrogen create opportunities, in particular for R&D. The IEA has suggested that the hurdles facing hydrogen include bringing down productions costs, the challenge of building and paying for a global hydrogen infrastructure system (including transport, storage and final distribution) and the development of end use markets.[51]

In assessing the nature and scope of opportunities, participants in the study workshops in Melbourne and Perth, and the Broome Conference provided valuable input. Opportunities identified in the two workshops are summarised in Table 12.

Table 12 **Key opportunities identified by stakeholder workshops**

Opportunities	Melbourne	Perth
Abundant fossil fuels in Australia to ease transition	✓	✓
Strong skills base		✓
A mechanism to unite energy sources (by using hydrogen as a common storage medium)		✓
Niche demand (mining, remote area power supply, etc)	✓	✓
Provide a storage mechanism for renewable energy		✓
Environment benefits (local, regional, global)	✓	✓
Large renewable energy resource base	✓	✓
Australia a good adopter of new technology		✓
Leverage existing R&D (eg bus trial, Aust/US CAP)	✓	✓
Good sovereign risk profile (to attract investment)		✓
Community support for sustainable solutions		✓
R&D opportunities provided by bus trial (and possibly Coal 21)		✓
Excise free status of hydrogen		✓
Opportunity for a shift to a new order (more focus on energy sustainability)		✓
Efficiency gains from distributed generation		✓
Distributed reforming of natural gas	✓	
Opportunity to take advantage of overseas R&D	✓	
New production/manufacturing opportunities	✓	
National energy autonomy	✓	
Good educational institutions	✓	

5.2 Production

Australia has good supplies of feedstocks for hydrogen.

Australia is well placed to produce hydrogen, either from fossil fuels or renewable sources. Australia's large, accessible and comparably low cost reserves of coal, and natural gas could be used to produce hydrogen. However, perversely, the lower energy prices afforded by the abundance of these supplies (especially for non-tradeable resources such as brown coal) lessen the relative competitiveness of hydrogen in the absence of other pricing signals or regulations on CO_2 emissions. A key issue then is the potential for sequestration of the CO_2 emissions that result from using fossil fuel sources: this applies equally to the continued use of fossil fuel as well as the production

[51] IEA (2003), Standing Group on Longer Term Co-Operation, "Moving to a Hydrogen Economy: Dreams and Realities".

of hydrogen from fossil fuels. Sequestration offers the opportunity to manage emissions in a practical and economical way[52].

Similarly, Australia's substantial renewable energy resources, most notably wind, tidal and solar energy (see Chart 2) could be used to generate electricity for the production of hydrogen by electrolysis. The competitiveness of the energy supplied in this way remains a fundamental issue.

Conversely, the increased use of hydrogen could improve the viability of using more renewable energy for electricity production, since storage of electricity as hydrogen could overcome the problems associated with the intermittent nature of some renewable energy sources. Also, in a greenhouse gas context, hydrogen produced from fossil fuels has the potential to increase CO_2 emissions significantly — up to six times some claim when used as a replacement for unleaded petrol.[53] Thus there is a growing view that the future of the hydrogen economy is inextricably linked to renewable energy.

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52 For power stations, the cost of capture and storage has been estimated as around $50/t of CO_2. Use of this technique would allow continued provision of large-scale energy supplies using the established energy infrastructure. See page 31of the IEA's, Greenhouse Gas R&D Programme, Putting Carbon Back in the ground", February 2001. There is considerable scope for new ideas to reduce the costs of CO_2 capture and storage, which would accelerate the development and introduction of this technology.

53 Renewable and sustainable energy roundtable, comments on the Issues Paper, letter 8 August 2003.

Chart 2 **Assessment of the current commercial success of renewable energy technologies**

Technology	Current level of technical development	Australian resource base	Current level of market uptake	Competitiveness with fossil fuels and other renewable energy technologies	Assessment of current commercial success in Australia
Biomass energy					
• **Biomass electricity**	H	S	M	M - H	Moderately successful
• **Bagasse-fired generation**	H	S	H	H	Highly successful
• **Liquid biofuels**	H	S	M	M	Moderately successful
Cogeneration	H	S	M	M - H	Moderately successful
Enabling technologies	H	S	M	NA	Moderately successful
Fuel cells and hydrogen					
• **Fuel cells**	L - M	S	L	L	Emerging
• **Hydrogen**	L - H	S	L	L	Emerging
Geothermal energy					
• **Hydrothermal**	H	NS	L	H	Less successful
• **Hot dry rock**	L	S	L	L	Emerging
• **Geothermal heat pumps**	M - H	S	L	H	Less successful
Hydro, tidal and wave energy					
• **Large hydro**	H	S existing / NS new	H	H	Highly successful
• **Small hydro**	M - H	S	M	M	Moderately successful
• **Tidal energy**	M - H	S (remote)	L	L	Less successful
• **Wave energy**	L	S	L	L	Emerging
Photovoltaics (PV)	M - H	S	M	L - H	Moderately successful
Remote Area Power Supply (RAPS)	H	S	M	L - H	Moderately successful
Solar thermal energy					
• **Solar thermal electricity**	M	S	L	L	Emerging
• **Solar hot water**	H	S	M - H	H	Highly successful
Wind energy					
• **Large wind**	H	S	H	M	Highly successful
• **Small wind**	H	S	L	M	Less successful

Levels, competitiveness: L = low, M = medium, H = high
Resource base: S = significant resource base, NS = insignificant resource base

Source: Department of Industry, Tourism and Resources, "Renewable Energy Technology Roadmap", October 2002, p.89

Prices for renewable energy are falling.

Analysis by ABARE and others points to significant reductions in the price of electricity from renewable sources (see Table 8). So much so that by 2020 wind power from selected sites could rival conventional electricity supply costs. The principal drivers are expectations of technology improvement and greater manufacturing volumes leading to lower capital installation costs. Even so, these unit costs have to be considered cautiously since the reliability of production and the overall quantum of supply have to be considered. While the share of electricity supply from renewables may well increase, a key question will be the potential achievable share. ABARE itself notes that the question of the intermittent nature of supply (from wind) has been set aside at this stage. Key issues for the development of renewables in the near term will be the policy environment with respect to emissions (including the outcome of the MRET Review), technology improvement, production volumes and developments in CO_2 sequestration options.

Analysis published by the Australian Greenhouse Office suggests that the prospective investment in renewable energy is substantial. As can be seen from Table 13 a substantial increase in wind power capacity is planned. However, hydro will retain its dominant share.

Some of the additional renewable generation could potentially contribute to providing hydrogen supplies, however it is unlikely that it could meet hydrogen demand of the levels portrayed in the scenario analysis in Chapter 2. To that end, and given the relative cost competitiveness of fossil fuels, coal and natural gas are likely to remain a key supply source for hydrogen for some time to come.

The development of other production technologies also offers opportunities for Australian industry and the use of existing resources. For example, processes such as HydroMax, which, it is claimed, offers potential for low cost hydrogen production. HIsmelt is to invest in a US$2m development program with the US firm Alchemiz to assess the HydroMax process in HIsmelt's metal bath processing techniques to produce low cost hydrogen from steam and carbon.[54]. Further application of the HydroMax process is being investigated by Alchemiz in conjunction with CSIRO.

The key to the economics of this process is using carbonaceous by-product materials that are cheap and serve as good feedstock. The other key feature of this process is its ability to process sulphur-containing feedstock (high-sulphur coal, heavy oil and tar sands) as low or no-cost feedstocks. Other feedstocks

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54 http://www.hydrogenus.com/Alchemix6-5-03.pdf and http://www.alchemix.us/NHApaperfinal.pdf

(which typically have a disposal cost) include municipal waste, discarded tyres, animal waste and sewage sludge.[55]

Table 13 **Existing and proposed renewable energy production in Australia (MW)**

	Existing	Proposed
Hydro	7703	64
Solar	3	412
Wind	105	1744
Geothermal	0	30
Biomass (landfill methane)	82	21
Biomass (bagasse)	331	50
Biomass (biogas)	3	20
Biomass (woodwaste)	83	286
Biomass (sewage methane)	20	7
Biomass (digester gas)	9	0
Biomass (municipal waste)	5	37
Biomass (animal waste)	0	10
Biomass (agricultural waste)	0	16
Ocean (tidal)	0	48
Ocean (wave)	0	0.3
TOTAL	8433	2745

Data source: www.agso.gov.au/renewable/

5.2.1 R&D

More R&D is needed to reduce costs.

More R&D is still required in order to deliver cost-effective hydrogen supplies. These R&D needs will create opportunities for researchers. Several specific challenges, primarily aimed at reducing hydrogen production costs, have been identified, including:

- existing production technologies can produce vast amounts of hydrogen from hydrocarbons but emit large amounts of carbon dioxide into the atmosphere. Existing commercial production methods (such as steam methane reformation, multi-fuel gasification, and electrolysis) require technical improvements to reduce costs, improve efficiencies, and produce inexpensive, high-purity hydrogen with little or no carbon emissions.
- while wind, solar, and geothermal resources can produce hydrogen electrolytically, and biomass can produce hydrogen directly, other advanced methods for producing hydrogen from renewable and sustainable energy

55 CSIRO, "US technology a bridge to the hydrogen economy", Process Magazine, May 2003, http://www.minerals.csiro.au/main/pg2.asp?id=36688

sources are still in early research and development phase. Processes such as solar thermo-chemical water splitting, photoelectrochemical electrolysis, and biological methods require long-term, focused efforts to move toward commercial readiness. Renewable technologies such as solar, wind, and geothermal need further development for hydrogen production to be more cost-competitive from these sources.

- stakeholders need a basic understanding of the different mechanisms of hydrogen production before they will be willing to embrace the concepts. Demonstrations are a good way to provide greater confidence. The large scale of some production processes, however, makes them particularly difficult and expensive to demonstrate. Public-private partnerships are one way to address that cost barrier.
- CO_2 sequestration, including research, pilot plants and large-scale application of technology. COAL21 and the CRC for Greenhouse Gas Technologies are significant Australian players in this field;
- education, particularly in relation to the safety of hydrogen, noting that this has whole-of-chain relevance.

In pursuing R&D it is relevant to note that that there are significant market incentives (patents, licence fees and subsequent development) to pursue these areas of R&D. There are also a range of existing programs funded by Australian governments from which hydrogen researchers can seek funding. Further, there are potentially significant opportunities to collaborate with overseas agencies as well as compete for funds from overseas government programs.

A range of R&D activities are already under way within Australia focussed on hydrogen. For example, Hydro Tasmania has recently established a partnership with the University of Tasmania to undertake joint Research into hydrogen production and use.[56] The partnership intends to focus specifically on stationary renewable energy applications in remote areas and explore the potential application of hydrogen in vehicles. More generally, Hydro Tasmania takes the view that Tasmania is an ideal test bed to highlight the opportunities and barriers to establishing significant hydrogen economy on a national scale. Availability of substantial renewable resources (hydro and wind), relatively concentrated population centres and transport fuel requirements centred along a small number of main highways are cited as key supporting factors.

[56] Hydro Tasmania, Hydrogen Energy Research in Tasmania, Press Release 19 July 2003.

5.2.2 Industry and services

A hydrogen economy will create a large demand for hydrogen.

A transition to a hydrogen economy will have significant economy wide effects. For one thing, such a shift would create substantial demand for additional hydrogen production. That hydrogen could of course come from a range of sources including electrolysis using electricity from a variety of sources.

For example, the IEA has estimated that replacing all the transportation fuel used in France with hydrogen would require around four times the present level of electricity production. Producing this amount of electricity would require building 60 new nuclear plants each of 1500MW capacity or covering 6% of French territory with approximately 350,000 wind turbines or covering 1% of the land surface with PV cells.[57] The situation in Australia is comparable.

On the basis of the scenario in Section 2, Australian electricity production (assuming electrolysis is the primary source of hydrogen) would need to increase significantly.

Table 14 **Estimated generation capacity required to generate hydrogen by scenario - Australia (MW)**

	2030 Scenario			2050 Scenario		
Utilisation factor	1	2	3	1	2	3
0.9	8,562	5,137	3,144	20,000	11,989	5,611
0.6	12,843	7,705	4,716	30,000	17,983	8,416
0.25	30,824	18,492	11,320	72,000	43,159	20,199
0.1	77,059	46,230	28,299	180,000	107,897	50,498

Notes: Based on scenario analysis summarised in Table 6. Assumes an electrolysis efficiency of 80%
Data source: ACIL Tasman estimates

Table 14 shows the estimated generation capacity required in order to meet the various total hydrogen demands under the three scenarios developed in Chapter 2. The utilisation factors shown are broadly representative of base load through to peak load utilisation. For example, the utilisation factor for wind is generally between 20 and 30%.

57 IEA (2003), Standing Group on Longer Term Co-Operation, “Moving to a Hydrogen Economy: Dreams and Realities”.

Table 13 shows that considerable additional renewable energy power production would have to be built to ensure it would be sufficient to supply the required hydrogen for any of the three proposed scenarios.

Some opportunities are direct...

The required investment in generation capacity could provide opportunities for suppliers of generation equipment and depending upon whether and in what form CO_2 sequestration is either needed or undertaken, related equipment supply.

The above does not take into account the continuing need for electricity for other purposes. These opportunities are not lost on business. Already there are developers talking about using Australia's ample reserves of coal and natural gas for the production of hydrogen in tandem with CO_2 sequestration. For example, Australian Power and Energy Limited has mooted a 2000MW hydrogen burning base load power station[58].

... others are indirect.

As well as the direct opportunities listed above, the emergence of a hydrogen based energy system is likely to encourage a variety of different ways of applying energy to manufacturing processes and materials production. This might include novel combustion possibilities such as the combustion of pure oxygen and hydrogen in a combustion engine to yield both motive power and low-pressure steam. Other possibilities include the use of hydrogen as a reducing agent. A situation where hydrogen is readily and cheaply available might see new minerals extraction and other industrial processes developed. This might be particularly relevant in cases where the resource used to generate the hydrogen was remote from traditional areas of demand (such as the Kimberley tidal resource).

But building on Australia's current industrial capabilities, the end-use product manufacturing and associated export market opportunities could include the following, although in some instances this would require entry into markets not traditionally supplied by Australian manufacturing:

- internal combustion hydrogen engines: light- and heavy-duty land vehicles, locomotives for light-rail systems, marine vessels, underground mining equipment for haulage, agricultural machinery and ancillary equipment[59];
- fuel cells for electricity production (particularly remote area power supplies);
- gas turbines that use hydrogen and natural gas blends;
- feedstock in the industrial production of ethylene, methanol and ammonia:
- cleaning fluid for electrical components;

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58 'Anglo American buys stake in Latrobe Valley fuel project' The Age, 4th April 2003.

59 This is more likely to be a transitional technology since the efficiency of the fuel cell is so much better.

- process heaters and coolers (catalytic burners, steam generation, boilers, heat pumps, space and water heating and cooling, refrigeration, air-conditioning); and
- weather balloons for monitoring atmospheric conditions.

There are trade implications...

In relation to hydrogen production technologies, the following areas have been identified as having some potential to be a source of exports:

- reformers: natural gas, methanol, syngas, petrol (Integrated Ceramic Membrane reactors, pressure swing absorption);
- multi-fuel gasification and steam reforming (bio-oils, coal);
- high-temperature selective oxidation gas clean-up systems;
- fixed packed-bed catalytic reactors;
- metal support catalysts;
- electrolysis (including thermochemical cycles);
- biological fermentation;
- hydrogen sulphide decomposition; and
- combined photoelectrolysis with water purification/desalination.

...and regional development implications.

Hydrogen production could have significant regional implications, depending upon the source of the hydrogen. In particular,

- hydrogen sourced from either steam reformation using coal or natural gas or electricity production based on coal or natural gas, would bolster activity in the respective supply regions, especially if that demand was additional to existing electricity demand. For instance, if hydrogen became a significant transport fuel.
- electricity from renewables, noting that virtually all renewable resources are regionally located. Significantly, some renewable production can co-exist with little disruption to current regional rural or other activities. However, there can be trade-offs in some areas, for example, wind power and noise disturbance, changes to landscape values and the natural environment. In some instances the development could provide a major stimulus for regional development where it linked to mineral resources, the Kimberley Green Energy proposal has been promoted in that context.

Skilled and trained personnel will be needed.

Hydrogen production would require a new range of skills, with a potentially significant increase in the demand for skills from the renewables industries. For example, if all the hydrogen needed to meet demand under scenario 1 was provided by wind power exclusively this might require in excess of 30,000 new wind turbines. Operation and maintenance of these alone would require a significant increase in appropriately trained personnel.

5.3 Distribution

Any discussion of the transition to a hydrogen economy quickly becomes embroiled in debate about the extent of new infrastructure, particularly for distribution. There is general consensus on two broad approaches:

- Small-scale local hydrogen production, based on either electrolysis or gas reformation, thus utilising existing electricity or gas distribution infrastructure
- Large-scale dedicated hydrogen production infrastructure, including, pipelines and or road transport.

Existing infrastructure might need to be augmented.

The first option has a number of attractions from the viewpoint of minimising distribution costs, although it could make it more difficult to achieve the potential economies of scale associated with large-scale hydrogen production. It might also require augmentation of both gas and electricity production and distribution infrastructure. This investment could be in addition to that required to integrate renewable energy into the electricity grid system, depending upon the renewable energy sources relative to hydrogen demand centres.

Hydro Tasmania saw merit in the distributed hydrogen production approach. It noted that:

> Australia has an extensive electrical and gas infrastructure system. Distributed hydrogen production can take advantage of these existing systems. Large, complex and expensive hydrogen infrastructure is, therefore, not needed in the short term for Australia to start to implement hydrogen technologies[60].

Investors in future gas pipelines have an incentive to consider their suitability for transporting hydrogen as an option for enhancing future returns or reducing future upgrade costs. An option to further that development would be to make hydrogen carrying capability a regulated requirement for any new gas infrastructure, although the costs of such an option would have to be considered.

Australia industry has extensive experience in gas infrastructure.

The role of Australia's manufacturing industries in the design and operation of bulk liquefied natural gas (LNG) facilities could facilitate local development and export opportunities in the following areas[61]:

- high pressure gaseous storage and supporting technologies;
- cryogenic liquid storage, insulation and supporting technologies;

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60 Hydro Tasmania, Comment on the National Hydrogen Study Interim Report, July 2003, page 11.

61 Noting that some aspects of the production, storage and transportation of hydrogen would differ from those for LNG and the skills may not be directly transferable.

- absorbent hydrogen storage media and supporting technologies;
- hydrogen bulk storage systems and bulk dispatch terminals;
- cryogenic tankers for bulk-transport of liquid hydrogen;
- hydrogen pipelines based on natural gas pipeline industry;
- hydrogen compressors;
- compressed gas tube trailers; and
- fuelling stations and supporting technologies.

Opportunities to incrementally incorporate hydrogen into the energy mix and energy distribution system include:

- adding small quantities of hydrogen into the natural gas stream;
- current natural gas pipeline easements could be used for hydrogen pipelines;
- safety standards for both hydrogen and gas pipelines could be standardised; and
- natural gas pipelines could be used to collect and distribute any hydrogen that was produced in regions traversed by the pipelines.

R&D is still needed.

Achieving a reduction in hydrogen storage and distribution costs is a key R&D challenge. As with the production challenges, the R&D needs will create opportunities for Australian researchers.

Industry and services will require investment.

Any new infrastructure for storage and primary distribution will require a substantial investment. While the major components could be locally manufactured or imported, construction and installation are necessarily a local activity.

In considering hydrogen distribution infrastructure, additional primary energy infrastructure will be of equal or greater significance. Augmentation of existing electricity or gas networks may be required. If, however, the primary energy source is renewables located away from the existing grids major additions to the infrastructure may be required to enable integration of the electricity.

By and large the investment to supply hydrogen will be financed by private industry, although in some instances the natural monopoly nature of network facilities such as pipelines may lead governments to become more involved either as an owner or a regulator.

A key issue will be the incentive to invest given considerable uncertainty about the potential market for hydrogen. Specifically, market size, nature, location and its expected durability against technology and policy changes for other energy sources.

5.4 Supply infrastructure to end uses

Much of the discussion regarding production, use and distribution has focussed on the current fuel distribution system for the transport sector as a guide to the way in which the hydrogen economy might develop. From that perspective, investment has typically been envisaged as requiring additional transmission facilities (natural gas, electricity, or hydrogen/methane) to specialised supply facilities.

The border between transport and distributed generation could be blurred.

Another approach, which recognises both the costs of establishing infrastructure and the somewhat unique opportunities offered by hydrogen, is to supply transport through a 'co-supply model'. Lovins makes the argument that hydrogen has particular potential as the energy source for heating and cooling buildings.[62] Fuel cell use in buildings could be capitalised on; turning buildings into hydrogen supply centres for transport. Conversely, vehicles could be used to supply power to buildings or to the grid when they are not being driven.

On the more general point of incentives for infrastructure development, it is worth noting that existing infrastructure owners (including fuel suppliers for cars) are in the business of fuel distribution and product differentiation to consumers using brands, suggesting strong incentives for infrastructure development. As the Chief Executive of Texaco commented:

> We came around late to fuel cells, but we now recognise that the oil and gas business is going to change...whatever fuel emerges eventually as the choice for fuel cells, we want our consumers to fill up at a Texaco station.

5.5 Demand

Fuel cell development and production in Australia will depend upon where the technical advances are made

Whether it is possible for Australia to have major industrial development and manufacturing activity related to fuel cells will very much depend upon the relative level of technical advances made here compared to those in other countries. However, Australia has potential manufacturing and export opportunities for a range of products, which include:

- fuel cell system component development and manufacturing (power conditioning, fuel processing / cleaning equipment especially for on-site or distributed hydrogen production, heat management units, control systems, electric drive trains and associated components;
- fuel cell systems integration, stacks, and balance of plant items for specific end user applications;
- services and maintenance;

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62 Lovins A., *A Strategy for the Hydrogen Economy*, 10th Annual Hydrogen Meeting, National Hydrogen Association, Vienna Virginia, April 1999.

- integration of fuel cells, hydrogen production and renewable technologies;
- fuel storage, handling, transportation, distribution technologies and infrastructure;
- safety and control systems; and
- micro fuel cells for portable power.

Currently much of the technology development, particularly as far as product integration is concerned, is taking place in North America, Europe and Japan. The principal opportunities for industry will follow from maintaining close relationships (with parent companies or as joint ventures/licensing arrangements). In the early stages of any transition to hydrogen, the integration of fuel cells and storage units in products will be likely to occur in close proximity to the R&D centres. This will be further encouraged by the demand for production scale as a means of lowering unit production costs. It may take some time for manufacturing to locate closer to other demand centres, especially if demand grows only slowly. This has important implications for motor vehicle manufacturing in Australia where imported hydrogen-fuelled vehicles could be the new competitive threat to the conventional petro-fuelled ICE vehicles made here.

5.5.1 Portable appliances

Fuel cells could soon replace batteries.

Miniature fuel cells are promoted as a better alternative to conventional batteries because they promise clean, efficient and quiet operation. The constraint to date has been underdeveloped technology, high production costs and small-scale production. Those circumstances are rapidly changing and with it the potential market.

Battery technology has reached a peak while fuel cells have seen improvements in catalysts, loading requirements, water management and temperature control. Micro fuel cell technology has the potential to increase operating life for portable electronic devices, including portable telephones, delivering power up to 50 times longer and reducing fuelling times to less than a minute. Mid range fuel cell technology has potential applications for cordless appliances, power tools, wheelchairs, bicycles, boats, home energy systems, military field radios and portable computers. Recent research has shown ways to reduce the need for expensive catalysts such as platinum, with significant opportunities for cost reductions. Significantly, major players in the portable computer market are very much involved in fuel cell development and can be expected to shape the end product market for fuel cells.

Major players in the phone market are researching the viability of fuel cells in cell phones, especially since the phone makers want to add more energy-draining functionality to phones. The market potential for fuel cells in the portable phone market is at least $1 billion. Nokia assumes 1.84 batteries per cell phone and this, together with the fact that there were over a billion phones in use at the end of 2002, suggests that the market for fuel cells could potentially grow very rapidly.

Market research, particularly for hydrogen fuel cells for portable appliances is being undertaken and promoted by a range of business analysts.[63] Traditionally, manufacturers of portable products rely on third parties to supply the power units. This is in contrast to motor vehicle manufacture where the power train is an integral component of the final consumer product. There is a wide range of portable power users, suggesting a significant market for specialised market research services.

One analyst[64] has suggested that corporations will be successful in the portable market if they:

- properly protect their patents by filing for patent protection and going after infringers;
- continue to innovate in terms of patents (the processes, catalysts, design of the fuel cells);
- share information with their colleagues in terms of informal conferences or partnerships. There are currently many different approaches to creating fuel cells; the culmination of all those methods will definitely lead to great technological break throughs;
- provide a complete power/battery like solution with little to no end-user education required. Find any easy way to recharge that uses current delivery infrastructure or methods for recharging;
- focus on core capabilities and outsource manufacturing to large-scale battery manufactures;
- commercialise the technologies by means such as strategic partnerships, third-party licensing arrangements, creation of invention-specific public or private business entities in which they hold significant equity, and/or combinations of the foregoing;
- create a standardised product when the industry further develops so that economies of scale can be achieved; and
- use the cash flow from early sales to build the knowledge base and then seek sales in more difficult areas. The current focus on the portable phone industry is an example of this approach. That focus is likely to expand to include laptops, PDAs, portable radios and other portable devices.

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63 See for example, Allied Business Intelligence research, (http://www.abiresearch.com) and ResearchMarkets.com (http://www.researchandmarkets.com/reports/1501/)

64 Corcoran, M (2001). Fuel Cells: The Industry and Portable Market, University of Southern California, Technology Commercialisation Alliance, http://www.usc.edu/org/techalliance/Anthology%202002/Fuel%20Cells.pdf

5.5.2 Transport

Hydrogen has the potential to join the transport fuel mix.

Today's transport infrastructure and systems are based around the use of liquid fossil fuels and the internal combustion engine.

Vehicles can be powered by hydrogen fuel in two ways, by using

- a fuel cell, providing electrical energy for traction power; or
- an internal combustion engine in which hydrogen is burnt in the same way as petroleum or gas.

Based on past trends in motor vehicle sales and Australia's projected population of between 24.1 and 28.2 million in 2051[65], annual sales of motor vehicles could be between 1,045,000 and 1,226,000 vehicles by 2051. In recent years about 45 per cent of the Australian motor vehicle market has been supplied by domestic production. By 2051 a significant proportion of new vehicles could be hydrogen fuelled, suggesting a significant demand for Australian manufactured fuel cell vehicles. However, as noted above, part of this demand will substitute for traditional vehicles (although with improved fuel efficiency) and it may be that higher proportion are sourced from overseas rather than locally made.

Australian transport fuel demand shows that the total fuel consumption for the Australian vehicle fleet in 2000 was an estimated 25 billion litres. Unleaded petrol accounted for over half of all fuel consumed, or some14 billion litres. Diesel use was 6 billion litres, while LPG, CNG or dual fuel consumption was 2 billion litres. Fuel consumption rates varied from 11.3 litres per 100 kilometres for unleaded petrol, 25.1 litres per 100 kilometres for diesel and 18 litres per 100 kilometres for LPG/CNG[66].

Total vehicle kilometres travelled (VKT) in 2000 were estimated at 181 billion kilometres. Passenger vehicles accounted for over three-quarters (139 billion kilometres) of the total distance travelled at an average of 14,300 kilometres per vehicle. Passenger vehicles consumed a total of 16 billion litres of fuel, of which 88% was petrol[67].

DaimlerChrysler, General Motors, Honda, Nissan and Toyota are developing fuel cell vehicles and Ford and BMW are developing hydrogen internal combustion engine vehicles. In Australia, The WA Government is investing $8.16 million to trial hydrogen fuel cell buses in partnership with

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65 ABS AusStats Main Features 3222.0 1999-2101

66 Data from ABS AusStats 9208.0 1st November 1999 to 31st October 2000.

67 Data from ABS AusStats 9208.0 1st November 1999 to 31st October 2000

DaimlerChrysler, BP and Murdoch University in Perth over the next three years[68].

As far as R&D is concerned the Perth bus trial provides an opportunity for Australia to contribute to, and benefit from, an important global hydrogen demonstration project (see Box 8).

Box 8 The Perth hydrogen bus trial – industry and market opportunities

The potential market opportunities arising from the successful development of hydrogen technologies are substantial. Therefore, the knowledge and expertise accumulated from the Perth fuel cell bus trial should be extremely valuable to all involved. The Western Australian Government and the transit authorities involved in the trial are looking to capture as much knowledge as possible from it.

The changes required could be huge.

A recent proposal put forward by Tolan gives some idea of the quantum of changes being suggested to advance the hydrogen economy, particularly in respect to motor transport (see Box 9). She argues that the fast route to hydrogen would ultimately cost far less than the approach proposed by the Bush administration, which she claims postpones energy independence until 2040 at the earliest[69].

Some in Australia have suggested that the development of the hydrogen economy could be supported through a similar approach to that adopted for renewable energy, namely the MRET scheme. That is establishing a mandatory target that would require energy suppliers to deliver a specific proportion of total energy in the form of hydrogen. Whether such mandated requirements lead to outcomes that are sustainable in the long-term, or merely distort the market towards less efficient and higher cost options is strongly debated.

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68 The Hon. Clive Brown MLA, Minister for State Development, Tourism and Small Business (Western Australia) , "Minister congratulates HIsmelt on visionary hydrogen venture" Media Release, 13 June 2003.

69 Business 2.0, “Mary Tolan’s Modest Proposal”, 3 June 2003.

Box 9 **The Tolan Plan for hydrogen in the US**

Mary Tolan, Chief Executive of Accenture's Resources Group, believes it is possible to restructure the US energy mix in favour of hydrogen. Her plan has four main features:

- Flood the market with fuel-cell vehicles, with help from at least $225 billion in federal subsidies over a10-year period. By 2015, half the cars on U.S. highways would run on hydrogen, saving $200 billion a year in imported-oil bills.
- Retrofit 30,000 gas stations with hydrogen pumps (at a cost of about $280 billion), to be supplied mostly by North American natural gas piped in and processed on site. Ethanol (derived from crops) and electrolysis (using electricity to extract hydrogen from water) are additional sources.
- Sell petroleum reserves gradually -- and at higher profit margins -- by creating new petrochemical products.
- Tap a new source of power, the electricity generated by fuel-cell cars in "power parks" during the day, which would eliminate the need to build new peak-hour plants.

Tolan stresses that a positive outcome for this scenario requires fuel cell and automobile manufacturers to reduce the total cost of vehicles. In terms of business implications Tolan argues that the power business operators could increase sales/utilisation of base-load plants with the result of expanding sales in a sector not significantly served before. Similarly, gas suppliers and distributors would see significant sales increases and the need to potentially restructure their operating models to address the challenges of serving the transportation sector.

She also argues that it is the very skills that the industry incumbents possess—capital, major project management and operating capability—that would be required for success of this transformation.

In that transformation, starting in 2005, vehicle manufacturers would introduce fuel-cell vehicles, ramping sales up sharply to 8 million units by 2009, with the help of at least $10 billion in annual subsidies to help defray the initial cost of about $40,000 per vehicle. Tolan argues that, by comparison, the Apollo space program at its peak cost $17 billion a year. Tolan calculates her scheme would put about 115 million fuel-cell cars on the road by 2015. She estimates it would cost $70 billion to increase natural-gas and ethanol supplies, $40 billion to lay new pipelines, $40 billion to transport fuel to petrol stations, and the $130 billion to retro fit petrol stations. She claims the scale of investment is in line with what major oil companies already spend on petroleum exploration and production.

At present, Tolan says, the per-mile operating cost of a fuel-cell car is 45 cents, compared with 22 cents for the average internal-combustion car. Tolan thinks 10 cents per mile for hydrogen cars is possible over time as technological advances drive costs down. She argues that it is "just a function of effort and investment".

The private sector is making large investments in hydrogen.

There are clearly already strong incentives for businesses involved in, or aligned with, the production of passenger motor vehicles, commercial vehicles, equipment and appliances to invest in hydrogen related R&D. Substantial investments are already being made by most of the major automotive manufactures in what is becoming a high profile endeavour to attract consumer and government attention, and presumably develop a competitive advantage in what is seen as a potentially significant emerging market.

Corporations outside of Australia are making most of these investments. Nonetheless, there could well be opportunities for Australian businesses to contract for specific areas of work, to develop technologies where the market is more specific to Australia or further develop markets where Australian businesses already have a technology or commercial advantage.

A wide range of factors will influence the extent to which investment in manufacturing hydrogen-using equipment and appliances, and hence component manufacturing and assembly investment, is attracted to Australia. There may be some resistance from existing suppliers especially if they cannot make the change to the new technologies. Further, unless there is the prospect of substantial production volumes, or highly specialised vehicles, Australian manufacturers may find it difficult to compete against imported models from large volume overseas producers.

R&D

Hydrogen will need to compete with alternative technologies.

Hydrogen vehicles will have to compete against other vehicles for market share. It is worth noting that technology development is improving the fuel efficiency and reducing the cost of traditional and hybrid engines. Specific challenges will come from hybrid electric, clean diesel/advanced internal combustion engines and biofuel powered cars.

In terms of funding, overseas opportunities should not be ignored. For example, The U.S. Energy Department has asked for industry proposals for US$150 million in demonstration projects to spur the development of hydrogen-powered vehicles and the service stations and other infrastructure needed to support them. The Energy Department is seeking proposals to share half the cost of between three and five demonstration projects over five years. Teams that will take part in the projects will consist of an automobile manufacturer and an energy company in combination with hydrogen fuel cell manufacturers, small businesses, universities and state and local governments. The winning projects could take several forms: from producing a fleet of hydrogen vehicles, building more fuelling stations and testing fleets in a controlled environment such as on a military base.

Reducing fuel cells costs is a key R&D challenge. The CSIRO, through its Energy Transformed Flagship program is proposing significant continuing investment in this area. As well as R&D the means of achieving a production scale to significantly lower unit costs is important.

5.5.3 Distributed generation

The Australian electricity industry represents a significant opportunity for hydrogen related developments. The industry represents around 1.6% of GDP. Electricity currently accounts for almost 18% of Australia's total energy needs, and in the commercial and residential sectors accounts for 67% and 42% of energy consumed respectively.

Electricity demand has been growing at around 4.3% a year since 1975[70] compared with an economy-wide average of around 3.3%. It is projected to grow at between 2.3%[71] and 2.8%[72] each year from 2001 to 2020.

The opportunities for Australian and overseas industry development in hydrogen fuelled stationary power generation are substantial, and can include hydrogen-using fuel cells and modified existing generators, such as gas turbines or gas engines. To give but one indication of the pace of change, Matsushita Electric announced in late May that it planned to begin marketing a fuel cell-based residential cogeneration system from March 2005. The company said that the system would cost around Yen 1m ($13,150) and would use city gas as its hydrogen source. Matsushita Electric added that it would begin final testing on a prototype in June 2003.[73]

Hydrogen can also provide an energy storage capability for remote area generation from renewable technologies. Power generation from wind and solar energy sources suffers from intermittent operation, and in places that are remote from the electricity grid, continuous power supply can be provided by renewable generation coupled with hydrogen production, storage and generation facilities.

5.6 Capturing the opportunities

Two key themes emerge from the analysis of opportunities in a hydrogen economy. They are:

- the potential Australia derives from its fossil fuel and renewables resource base. Both provide opportunities for hydrogen production. In the case of fossil fuels, much depends upon the policy environment and in the longer term, the ability to sequester carbon dioxide; and

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70 The Commonwealth Treasury Economic Roundup "Developments in Electricity" Spring 1999, available at www.treasury.gov.au/documents/195/HTML

71 Business as Usual Scenario "Electricity sales forecasts by State and class to 2020" A report for the Electricity Supply Association of Australia, April 2002.

72 Electricity Supply Association of Australia "Australian Electricity Supply Development 2000 – 2002" September 2002.

73 Power in Asia - Issue 380 - 12/06/2003

- the potential, if not the necessity, for greater levels of collaboration. Collaboration between researchers, between researchers and industry, and between Australian and overseas interests. Collaboration will be driven by commercial and financial imperatives, recognising that Australian investors and governments do not have the capacity to find and risk the levels of funding required for R&D or industry development.

6 Challenges and impediments

To succeed, hydrogen must overcome three broad hurdles.

There are significant challenges that need to be overcome before hydrogen is likely to play any significant role in Australia's energy mix. These can be summarised under three broad headings, namely:

- the higher cost of buying and using products that are fuelled with hydrogen;
- the long time-frame that is accepted as being associated with any transition to a hydrogen economy; and
- capturing the potential environmental benefits associated with the inclusion of hydrogen in Australia's energy mix.

Each of these is discussed in more detail below.

6.1 The competitiveness of hydrogen

There are three areas where hydrogen is most likely to enter the market:

- portable appliances;
- transport; and
- distributed generation.

Hydrogen may in effect enter the large-scale power generation market as well. For example, the FutureGen project in the US and the Australian Coal Association's COAL21 are both aiming to study the potential for coal gasification to create a syngas (a mixture of hydrogen and carbon monoxide) stream for use in power generation[74].

The timing and rate of market capture by hydrogen will depend largely on the relative performance and economics of hydrogen technologies compared to the alternatives available now. Table 15 summarises some of the current and projected costs associated with the hydrogen supply chain.

Note that the costs quoted in the table are at the plant and do include not any cleaning, compression or delivery costs. Depending upon the intended end use for the hydrogen, these costs could be significant. For example, the cost of gas separation could almost double the price of the hydrogen from coal gasification.

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[74] Both these projects will also examine the geological sequestration of the CO_2 associated with the process.

Table 15 **Summary of costs in hydrogen supply chain**

Component of supply chain	Cost ($/GJ)	Comments
Production		
• Steam methane reforming (without sequestration)	10	For a production capacity of around 150 tonnes/day and a natural gas cost of between $5 and $6 per GJ.
• Steam methane reforming (with sequestration)	13	Assuming a sequestration cost of $50/tonne CO_2 (the range of costs for sequestration is $40 – $140 /tonne of CO_2)
• On site steam reforming	20 - 42	For a production capacity of around 0.25 to 2.5 tonnes/day and a natural gas cost of between $5 and $6 per GJ.
• Electrolysis	22	Based on electricity cost of $0.06 per kWh. If the oxygen produced during the process can be captured and sold this would reduce costs by some $3 to $5/GJ.
• Coal gasification (now)	20 - 30	For a production capacity of between 500 and 650 tonnes per day and a coal cost of between $3.30 and $4.20 per GJ. The cost of hydrogen using coal at around $1.70 would be closer to $10/GJ
• Coal gasification (FutureGen target)	6 - 7	This includes sequestration
Transmission		
• Long distance pipeline	3.30 - 5.80	Note that this would appear to be at the low end of the cost spectrum. Other analysis suggests that hydrogen pipelines cost 50 to 80% more than natural gas and can be five times as high for regional transport.
• Liquefied hydrogen tanker	7	
• Compressed hydrogen tanker	Up to 133	
Storage		
• Storage (now)	80 - 330	
• Compressed storage (future)	13 - 17	
Total Delivered Cost		
• Now	20 - 518	
• Outlook (coal gasification)	10 - 27	
• Outlook (distributed production)	20 -42	

A key component of the cost of electrolysis is the cost of power. In the long term using electricity from renewable sources is seen by some as the key a more sustainable and environmentally friendly solution. Current and projected renewable electricity costs are shown in Table 16.

Table 16 **Average costs of renewable and fossil fuel energy sources**

Technology	Current cost (Cents/kWh)	Projected future costs beyond 2020 (Cents/kWh)
Biomass Energy:		
– Electricity	5 - 15	4 - 10
– Heat	1 - 5	1 - 5
– Ethanol for vehicle fuels	3 - 9	2 - 4
– (c.f. petrol and diesel)	(1.5 - 2.2)	(1.5 - 2.2)
Wind Electricity		
– onshore	3 - 5	2 - 3
– offshore	6 - 10	2 - 5
Solar Thermal Electricity (insolation of 2,500 kWh/m2 per year)	12 - 18	4 - 10
Hydro-electricity		
– Large scale	2 - 8	2 - 8
– Small scale	4 - 10	3 - 10
Geothermal Energy:		
– Electricity	2 - 10	1 - 8
– Heat	0.5 - 5.0	0.5 - 5.0
Marine Energy:		
– Tidal Barrage	12	12
– Tidal Stream	8 - 15	8 - 15
– Wave	8 - 20	5 - 7
Grid connected photovoltaic, according to incident solar energy ('insolation'):		
– 1,000 kWh/m2 per year (cool climates)	50 - 80	~ 8
– 1,500 kWh/m2 per year (temperate)	30 - 50	~ 5
– 2,500 kWh/m2 per year (tropical/arid)	20 - 40	~ 4
Stand alone systems (including batteries), 2,500 kWh/m2 per year	40 - 60	~ 10
Electricity Grid supplies from fossil fuels (incl. transmission and distribution		Capital cost will come down with technical progress, but many technologies largely mature and may be offset by rising fuel costs
– Off-peak	2 - 3	
– Peak	15 - 25	
– Average	8 - 10	
Rural electrification	25 - 80	
Costs of Central Grid Supplies, excluding transmission and distribution:		Capital cost will come down with technical progress, but many technologies already mature and may be offset by rising fuel costs
– Natural Gas	2 - 4	
– Coal	3 - 5	

Data source: Assessment of Technological Options to Address Climate Change – A Report for the Prime Minister's Strategy Unit, ICCEPT, December 20, 2002.

Tidal power is one potential source of hydrogen.

Using hydrogen to store and transport the energy from the tidal power resource in the north west of Australia has been considered for a number of years now. See Box 10.

Box 10 Kimberley green energy

One proposal put forward to both supply and utilise hydrogen is the Kimberley Green Energy proposal centred in north west Western Australia. The substantial tides (6-8 metres) in the region present an opportunity for renewable electricity production and consequent production of hydrogen by electrolysis. Hydrogen could be piped to markets in Western Australia, south east Australia and Queensland. It has been suggested that the supply of green energy from the Kimberley tidal power resource could be as much as 5000 PJ/year — equivalent to the total Australian energy supply.

Development of a major tidal power generation and hydrogen production facility in the Kimberley would require detailed analysis to scope the plant and equipment options and to identify (and address) technical, market, environmental and financing issues.

The investment requirement would be substantial, possibly of the broad order of A$22,000m for development of the Secure Bay resource:

- a barrage-type structure could cost around A$4,500 million (based on utilisation of Secure Bay resource (1500MW) and a unit capital cost of A$3m/MW). Other technologies may require a smaller investment;
- If half the annual energy output for a Secure Bay facility was converted to hydrogen (using electrolysis) the capital cost could be around A$1,200m (750 MW supply and US$30/GJ capital cost; and
- analysis suggests that hydrogen pipelines cost 50 to 80% more than natural gas and can be five times as high for regional transport. New pipelines could cost $1.7million/km. Broome to Perth is around 2600 km, Broome to Melbourne (around 7000 km) — in broad terms a pipeline distance of around 10,000 km assuming separate pipelines. Pipeline costs could thus total $16,000m (suggesting an annual capital cost of $110/GJ, delivered cost would be higher). However, other analysis suggests that large-scale long distance transmission could achieve a delivered cost of $25/GJ of hydrogen.

The relatively high delivered cost of hydrogen (locally, intra- and inter-state) suggest that substantial improvements in generation and transmission technology will be required to lower the cost of hydrogen relative to other sources of energy and other sources of hydrogen. The above costings, which only reflect the capital investment, suggest a delivered cost of hydrogen to the eastern States markets of A$150/GJ, coming down to A$115/GJ if greater utilisation of the pipeline could be achieved. These costs are very much higher than other estimated local hydrogen supply options in these markets (eg coal gasification $20 to $30/GJ[75]) and natural gas at well under $10GJ for industrial uses.

The economics of hydrogen from tidal power might be more attractive if the hydrogen was used locally (either as an energy source or as part of an industrial process) and there was no need for long distance pipeline transportation.

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[75] National Hydrogen Study Issues Paper.

Costs would need to fall before tidal hydrogen could compete.

The preliminary costings for delivered hydrogen from tidal power shown in Box 10 are not favourable at present compared to the alternatives. That does not mean, however, that the tidal resource might not at some time in the future be utilised. As with other resource industries, development must begin with surveys to prove the commercial potential of particular resource sites. This includes the tidal resources themselves, particularly in the context of emerging tidal generation technologies.

Subsequently, there must be in place a workable process to establish property rights for the resource as a basis for facilitating investment. Initially property rights could be established as 'exploration rights', which would aid and most probably stimulate investment in assessing the quality of the tidal resource.

6.2 The time frame for implementation

The time frame for any transition to a hydrogen economy is a long one.

There are many different views on the likely time frame for the emergence of hydrogen as a player in the world's energy mix. They all generally agree that the time frame is a relatively long one, perhaps 20 to 30 years before significant use of hydrogen as an energy source emerges.

That is not to say that hydrogen applications will not appear on the market in the relatively near term. Indeed the scenarios in this document assume that fuel cells for portable appliances will emerge onto the market in the next few years and that they could quickly capture significant market share if the relationship between their performance and cost is better than for batteries.

The reason why portable appliances might be the first common application of fuel cell technology is that the conventional alternative has a relatively high unit cost as well as negative features (eg. short operating and long recharge times) that the fuel cell option may be able to overcome.

While the emergence of fuel cell powered appliances is not particularly important from the point of view of its impact on Australia's total energy mix it would illustrate quite convincingly that if the product meets the consumer's needs then they will buy it. There is every reason to expect that the same thing would happen in the vehicle and distributed generation segments of the market.

While the government should avoid intervening in the normal operation of the market to try to force particular outcomes, the government may have a role to play in ensuring that there is a level playing field that allows hydrogen to find its natural level in the energy mix. The long time frame associated with any transition to the greater use of hydrogen in the energy mix contributes to the view that there is ample time to plan and implement appropriate policies and strategies.

6.3 Capturing the environmental benefits

Use of hydrogen could reduce emissions.

This section presents an analysis of the emissions outcomes of each of the scenarios that were introduced and described in Section 2.2.3. The emissions savings derive from the displacement of conventional fossil fuel use by the production and use of hydrogen in the appliance, transport and distributed generation market segments.

In the case of road transport, the scenarios assume that the production and use of hydrogen will displace conventional road transport fuel consumption. In distributed generation, it is assumed that hydrogen fuel cell generators will be used at the expense of additional coal-fired grid generation capacity. For portable applications, it is assumed that hydrogen fuel cells displace electricity consumed for recharging batteries.

Any emissions released as a result of hydrogen manufacture will reduce the potential emissions savings. The former will depend on the type of production technology employed and the extent to which any emissions are captured and sequestered. In reality, hydrogen is likely to be produced from a mix of different production methods, much as is the case with electricity generation today.

Rather than attempt to specify what that mix might be for each of the scenarios, we have evaluated the potential emissions savings from producing hydrogen from a range of technologies and with or without permanent sequestration. The emission factors for the various hydrogen production methods are shown in Table 17.

Table 17 **Estimated greenhouse emissions associated with selected hydrogen production processes**

Production process	Emissions
	(kg CO_2/kg of hydrogen)
Electrolysis using renewable power (tidal, wind, PV, etc.)	zero
Electrolysis* using conventional electricity (coal fired, plant efficiency 40%)	37
Electrolysis* using conventional electricity (gas fired, plant efficiency55%)	15
Steam reforming of natural gas** (no sequestration)	5.5 - 7
Gasification of coal (no sequestration)	15-16
Biomass gasification	zero

***Assumes that efficiency of electrolysis is 75%. ** For a thermal process efficiency of between 78 and 100%**
Source: OECD, AGO and ACIL Tasman calculations.

The figures in Table 17 have been used to calculate the emissions figures shown in the following tables.

Table 18 presents estimates of emissions savings from the use of hydrogen for road transport for each of the scenarios (figures in brackets are increases in emissions).

Table 18 **Estimated emissions savings from hydrogen consumption in road transport, by scenario – Australia (tonnes CO_2)**

		Production technology				
Year	Scenario	Electrolysis using coal-fired electricity (no sequestration)	Electrolysis using gas-fired electricity (no sequestration)	Steam reforming of natural gas (no sequestration)	Gasification of coal (no sequestration)	Electrolysis using renewables / full sequestration
2030	1	(16,852,880)	10,863,721	22,202,330	9,603,875	29,761,403
	2	(10,654,643)	5,983,308	12,789,743	5,227,038	17,327,366
	3	(7,555,525)	3,543,102	8,083,449	3,038,619	11,110,347
2050	1	(32,408,287)	22,135,171	44,448,404	19,655,923	59,323,892
	2	(19,336,844)	11,842,883	24,598,226	10,425,623	33,101,788
	3	(11,493,978)	5,667,510	12,688,119	4,887,443	17,368,526

Source: ACIL Tasman estimates

The potential for emissions savings and the extent to which they will accrue will be determined by the technology employed to manufacture hydrogen and whether or not capture and permanent sequestration of emissions is possible during production.

As shown in Table 18, there may be a net increase in emissions over the ‘no hydrogen’ case if electrolysis using coal-fired electricity (without permanent sequestration) is used as the source of hydrogen. The biggest emissions savings are achieved if hydrogen is produced via electrolysis using renewable electricity or if permanent sequestration is used. However, considerable emissions savings could still be achieved if steam reforming of natural gas is used. Table 19 sets out the potential emissions savings in distributed generation.

Table 19 **Estimated emissions savings from hydrogen consumption in distributed generation, by scenario – Australia (tonnes CO_2)**

		Production technology				
Year	Scenario	Electrolysis using coal-fired electricity	Electrolysis using gas-fired electricity	Steam reforming of natural gas	Gasification of coal	Electrolysis using renewables/full sequestration
2030	1	(1,732,331)	3,692,762	5,912,118	3,446,167	7,391,688
	2	(1,039,398)	2,215,657	3,547,271	2,067,700	4,435,013
	3	(346,466)	738,552	1,182,424	689,233	1,478,338
2050	1	(7,306,614)	15,575,308	24,936,094	14,535,221	31,176,618
	2	(4,871,076)	10,383,539	16,624,063	9,690,147	20,784,412
	3	(1,461,323)	3,115,062	4,987,219	2,907,044	6,235,324

Source: ACIL Tasman estimates

Distributed generation also offers opportunities for potential emissions reduction, assuming that distributed generation using fuel cells can penetrate into the residential and commercial sectors at the expense of additional fossil fuel-fired generation capacity. The emissions factor for the latter was assumed to be 0.9 t CO_2/MWh (250 kg CO_2/GJ produced) – the emissions factor for an average coal-fired grid generator. As with road transport, the extent of emissions savings varies considerably with the hydrogen manufacture technology. A net emissions increase was estimated to occur if electrolysis using coal-fired generation was the sole production method.

However, it is unlikely that the hydrogen pipeline network that would be required to distribute hydrogen from centralised production / permanent sequestration sites would be available in the first half of the projection. If so, then by 2030 most hydrogen would still be produced at the distributed generation site, by renewables or steam reforming of natural gas, without capture and permanent sequestration of emissions. By 2050 demand may perhaps be sufficient to justify the construction of a pipeline network distributing hydrogen from a central production facility utilising permanent sequestration. This may not be the case in Scenario 3 where demand could be so low that on-site reformers are more likely to still be used.

Nonetheless, considerable emissions abatement is possible if on-site steam reformation is used, indeed 80% of the abatement if permanent sequestration or renewable electricity was used.

Table 20 displays potential emissions savings from the use of hydrogen fuel-cells in portable appliances (mobile phones and laptop computers)

Table 20 **Estimated emissions savings from hydrogen consumption in portable appliances, by scenario – Australia (tonnes CO_2)**

		Production technology				
Year	Scenario	Electrolysis using coal-fired electricity	Electrolysis using gas-fired electricity	Steam reforming of natural gas	Gasification of coal	Electrolysis using renewables/full sequestration
2030	1	(15,223)	32,450	51,952	30,283	64,953
	2	(6,089)	12,980	20,781	12,113	25,981
	3	(1,522)	3,245	5,195	3,028	6,495
2050	1	(32,875)	70,079	112,196	65,399	140,274
	2	(13,150)	28,031	44,878	26,160	56,110
	3	(3,288)	7,008	11,220	6,540	14,027

Source: ACIL Tasman estimates

The use of hydrogen fuel cells in portable appliances offers relatively small potential emissions savings, despite the aggressive penetration rates assigned to the scenarios for these products. This is primarily a function of the small energy requirements of mobile phones and laptops.

There are of course other portable appliances that could potentially be converted to operate with fuel cells, but it is unlikely that the magnitude of the potential emissions savings will differ greatly from those for lap tops or mobile phones.

6.4 Impediments

Table 21 lists the key impediments identified by the participants in the stakeholder workshops in Perth and Melbourne. The two columns furthest to the right identify where a particular impediment was identified as a key one.

Table 21 **Key impediments identified by stakeholder workshops**

Impediment	Melbourne	Perth
Cost and convenience of the technology (across the supply chain)	✓	✓
Public acceptance and understanding	✓	✓
Existing infrastructure not suitable	✓	
Continuing availability of cheap fossil fuels	✓	✓
Lack of commercially mature technologies	✓	✓
Ignorance of technology	✓	
Lack of relevant codes & standards	✓	✓
Inconsistent funding for R&D	✓	
Lack of information for government and consumers	✓	✓
Lack of clear and workable government policy	✓	
Long time frame and associated uncertainty and risk of delay	✓	✓
Lack of financing for R&D, commercialisation	✓	✓
Large investment in existing infrastructure		✓
Lack of economic clout (suggests we should be followers)		✓
"Chicken and egg" problem in relation to infrastructure		✓
No leader/champion hence unable to counter strong fossil fuel lobby		✓
Case for hydrogen still needs to be made		✓
Externalities still not internalised		✓
High complexity of issues associated with hydrogen use		✓

7 Australia's competitive advantage

Australia must use its competitive advantages to compete for funding.

Any transition to a hydrogen economy will require considerable investment, initially in R&D and ultimately in the infrastructure to produce, store, and deliver both products/equipment using hydrogen and the fuel to power them. Australia will have to compete with the rest of the world to attract the required funding and skills. If Australia is to successfully do this then we will need to ensure that we make the best of the competitive advantages we have.

Two areas where Australia might claim to have a degree of competitive advantage are:

- The conduct of R&D; and
- The supply of inputs for hydrogen production.

7.1 Competitive advantages - R&D

Australia has an excellent reputation for good research.

Australia has a credible international reputation and is well-respected in research. Australia has a well-educated population and a strong skills base of researchers who are experts across a wide range of areas. For example, CSIRO is a world leader in the development of new sustainable energy options and offers internationally recognised expertise in developing new technologies to advance the hydrogen economy (see Box 11)[76]. Australia's research bodies are internationally recognised and respected for the quality of their R&D work.

Of course it is not just CSIRO that has expertise in hydrogen R&D. Other examples include:

- a research team at the University of NSW School of Materials Science and Engineering that is investigating mechanisms for improving the efficiency of hydrogen manufacture direct from sunlight using photo-sensitive materials;
- a University of Queensland research team that is investigating hydrogen storage in carbon nanotubes; and
- Ceramic Fuel Cells Limited (CFCL) which is a world leader in planar solid oxide fuel cell technology.

Australia's sovereign risk profile is excellent and this too should assist us in attracting overseas investment for our researchers in areas where we are at the forefront of global R&D efforts.

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76 Technologies for the Hydrogen Economy, CSIRO http://www.cmit.csiro.au/brochures/tech/hydrogen/

Australia is recognised as having a science and engineering sector that is well connected with end users and able to seize the opportunities presented. A particular challenge, given the relatively small size of the skill base and R&D investment support available, will be finding focus for our efforts. A key strategy will be collaboration, between researchers from differing disciplines and between research and industry. As with any research there are likely to be findings that are not directly related to hydrogen but which may offer considerable benefits for industry and the Australian economy as a whole.

Box 11 **CSIRO: Hydrogen related skills and capabilities**

Skills and capabilities

CSIRO has a number of research and development programs related to hydrogen, and scientific capability in a number of disciplines critical for a progress towards the hydrogen economy. They include:

- hydrogen generation (fossil, renewable, solar thermal)
- fuel cell technology
- catalytic chemistry
- heat and mass transfer
- microtechnology
- nanomaterials
- sensors/safety systems
- polymer chemistry
- electrochemistry solid state ionics.

R&D focus

- hydrogen from water/renewable energy
- hydrogen from natural gas, ethanol & methanol
- leading expertise in fuel cell technology
- fossil fuel reforming — natural gas, ethanol, methanol
- integration of hydrogen and renewable energy technologies
- life cycle and energy balance analysis
- liquefaction of hydrogen for fuel cell electric vehicle (BP & Opel/GM)
- drive train for hybrid electric vehicles
- accelerated photosynthesis
- photoelectrolysis
- applications of fuel cell technology
- systems development/modelling

It is unrealistic to expect that Australia can be at the forefront of R&D into every aspect of research that relates to the use of hydrogen as an energy source. It is outside the scope of this report to attempt to identify those areas where we either already are or can become world leaders in hydrogen research. However, we can be confident that such areas do exist and more will emerge if funding is available for R&D.

Our good international research standing will also make us more acceptable as partners in international cooperative research efforts. Australia already has strong international research links and efforts should continue to maintain and grow these. The European Union and the United States are planning to significantly boost their investment in hydrogen R&D and Australia should seek to actively participate in those programs in areas where it can contribute.

The Perth hydrogen bus trials are a good example of a cooperative program, which should assist Australia to gain access to a wide body of knowledge and skills.

Remote area power supplies could be a niche market.

Another potential area for cooperation might be to provide the testing facilities for systems that seek to use renewable energies to generate hydrogen, particularly for applications like remote area power supplies.

Mining applications are another.

Applications in the mining industry are further areas where Australia could potentially be a major player.

Australians are quick to adopt new technology and thus our population provides an opportunity to develop an early market for any new products that may emerge as a result of technological breakthroughs in this country.

In the workshops and consultations there was strong support for Australia increasing its commitment to hydrogen R&D to ensure a first mover advantage in commercialising frontier R&D and securing manufacturing industry development opportunities. As noted above, ensuring that market links are developed, through early industry involvement in particular, is a key step in capturing possible manufacturing opportunities. However, investment in R&D will not necessarily secure those opportunities nor are those opportunities precluded if overseas licenses/joint ventures are utilised. In the broader sense there can be significant gains from specialisation, including importing R&D and products, rather than necessarily pursuing a wide range of R&D areas in expectation of securing manufacturing opportunities.

Significant incentives and funding are currently afforded energy research in general and hydrogen specifically:

- Australian research interests, private and public, have a strong incentive to invest in hydrogen R&D on the basis of market expectations and intellectual property right protection;
- Australian governments, Commonwealth and State, are making significant investments in R&D and other development programs where hydrogen is as relevant as any other energy form or idea capable of improving productivity, the environment or community well being more generally.
- Research agencies are already demonstrating a commitment to hydrogen, reflecting the relative priority they accord the potential from hydrogen. CSIRO's decision to invest in a major energy Flagship Program is one example, see Box 12.

Box 12 **CSIRO's Energy Transformed Flagship Program**

The mission of Energy Transformed is to develop low emissions energy technologies and systems delivering cost competitive energy services that meet the economic, social and environmental needs of Australians.

The mission will be achieved by taking the first steps to the hydrogen economy:

- developing and implementing technologies leading to 'zero emissions' power from fossil fuels and large-scale hydrogen production
- developing cost-effective electricity and hydrogen from renewable sources
- increasing the fuel and traffic management efficiency of urban transport in conjunction with the transition to hydrogen powered vehicles
- doubling the efficiency of fuel (natural gas and hydrogen) use by the generation of power/heat/cooling at point-of-use applications.

The Energy Transformed Flagship Program will commence with an initial budget in 2003/04 of $15 million made up of new Flagship funding, redirected CSIRO Divisional funding and external revenue. The Program is planned to grow to a $50 million enterprise within the next 5 years.

CSIRO has begun discussions on a possible National Hydrogen Centre with a central hub and nodes in every state and further mini or micro nodes in regional Australia[77]. It is being driven by CSIRO's view that there are gains from adopting a national approach in moving towards a hydrogen economy, in particular for industry development, technology development and as a central source of information.

Key functions of the NHC are shown in Box 13. State government agencies, universities and industry are participating in discussions on the Centre.

[77] R. Hannink, "The Hydrogen Economy: Drivers, CSIRO presentation to The Hydrogen Economy, Conference, Broome 2003

Box 13 **CSIRO's proposal for a National Hydrogen Centre**

CSIRO has proposed establishing a National Hydrogen Centre. Participants in the Centre would include CSIRO, industry, educational institutes, governments and other relevant parties.

The draft vision for the NHC is

An integrated Hydrogen Economy within Australian society giving opportunity to Australian industry and manufacturers

The proposed major functions and activities of the Centre include:

- promoting and facilitating the early introduction of the hydrogen economy in Australia
- acting as a broker for technology development projects
- facilitating the establishment of business and manufacturing opportunities in Australia
- assisting with education and training in educational institutes
- acting as a central source of information
- facilitating/coordinating technology demonstration programs
- addressing infrastructure issues such as transportation, distribution, refuelling and safety
- establishing links and collaboration with international organisations.[78]

CSIRO has estimated that the Centre will cost some $3 to 4 million a year to run once it is fully operational. They propose that it be funded in part by subscriptions from participants and in part by charging a fee for services.

Source: CSIRO

7.2 Competitive advantages - supply of inputs

Hydrogen feedstock is plentiful in Australia.

Australia has large reserves of the main inputs for making hydrogen, including plentiful supplies of coal and natural gas at competitive prices. Australia also has substantial reserves of most renewable forms of energy.

Initially at least this will be more relevant to researchers who are doing R&D into the various mechanisms for producing hydrogen, particularly when it becomes time to scale up laboratory experiments to pre-commercial test prototypes and then commercial prototypes.

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78 CSIRO, "Technologies for the Hydrogen Economy", Brochure, November 2002, http://www.cmit.csiro.au/brochures/tech/hydrogen/

Australia's plentiful supply of sources of hydrogen production will also be of interest to firms seeking to establish markets for products and services once they become commercially competitive.

8 Findings and Recommendations

This section of the report presents the findings and recommendations of the Study Team.

8.1 National Hydrogen Study Findings

Governments have to signal that hydrogen is on their agenda.

Governments should provide a clear and unambiguous signal that hydrogen has emerged as an important policy issue in relation to meeting Australia's long-term energy supply and addressing important environmental issues. Such a signal sends an important message to both researchers and industry stakeholders that hydrogen is now very much on the national agenda.

A vision for hydrogen will do that.

The Study Team believes that a good first step would be to adopt a vision for hydrogen. That vision should explicitly recognise hydrogen's potential contribution to Australia's energy mix. It should reflect the understanding that hydrogen could also address a range of environmental issues as well as contribute to the sustainability of Australia's long-term economic growth and improved living standards.

Hydrogen will bring opportunities...

It is likely that the emergence of hydrogen as an energy source will create a large number of opportunities. Not only should there be benefits that Australia's substantial fossil fuel industry and its growing renewable energy sector can capture, but also there are likely to be new industry and service sectors that emerge as a result of that change. In addition, there is significant potential for emissions reductions, both in terms of local air quality and greenhouse gases.

...to capture these opportunities, barriers need to be removed.

However, given that the use of hydrogen as an energy source is still very much in its infancy there may be existing policies or programs that unintentionally act as barriers to realising those opportunities. A commitment by governments to review any measures that might be identified by the industry or research sectors would further reinforce the message that hydrogen is very much on the radar screen as a potential contributor to the energy mix.

New policies and programs should also be reviewed to ensure that they do not unintentionally create barriers to the use of hydrogen as a source of energy. Of course, there may be good public policy reasons for a particular approach that outweighs any potential negative impacts that that approach might have on hydrogen.

Hydrogen is a fast moving subject.

There is still considerable uncertainty about exactly how hydrogen technology will develop and ultimately be brought to market. At any point an R&D breakthrough on a particular aspect of hydrogen technology might significantly alter the relative competitiveness of hydrogen, either in terms of alternative hydrogen technologies, or relative to competing conventional sources of energy.

So hydrogen measures need to be flexible…

Any measures adopted by governments need to be sufficiently flexible to quickly adapt to such developments, both in Australia and overseas. Indeed, there should be a built-in review process to ensure that any strategies adopted remain appropriate. One possible approach would be to ask the Productivity Commission to undertake a review of existing policies and programs to determine if any are creating barriers to hydrogen.

…and subject to regular review.

Internationally, R&D investment in hydrogen and related areas is significant and increasing in the near term. The increase is being driven by both market forces and the capacity for investors to appropriate financial returns from any intellectual property development, and government funding to bolster hydrogen R&D, particularly at the more basic end of the research spectrum.

Hydrogen is still seen as a long-term option.

Hydrogen is one option, among many, for addressing environmental and energy security concerns, whilst enabling continued economic growth. In the market for private and government investment funds to further these objectives, hydrogen R&D proposals should compete on their merits, having regard to the prospective benefits, risks and the time frames involved. From the viewpoint of making the most of limited R&D funds, energy options should be treated in a neutral manner: one form should not be, *a priori*, favoured over another.

This makes attracting private funds harder.

In many instances, the positive attributes of hydrogen will help associated R&D proposals secure funding in this competitive environment. However, one significant factor that can hold back such proposals is the time before the benefits might be delivered and a return to investors realised. In practical terms this means that the potential benefits from hydrogen R&D have to be that much greater in order to justify the investment.

This suggests a role for governments.

The economic case for government funding of R&D rests primarily on the notion of market failure, that is, where investors cannot capture enough of the total benefits to warrant an investment. This is often the case when the research is of a more basic nature, since it is more difficult to identify the potential beneficiaries, and thus secure funding. Similarly, it is usually harder to exclude others from utilising the results of any of the more basic research done.

A wide range of existing government-administered R&D programs provide actual or potential sources of funding for hydrogen R&D in Australia. These include the substantial open funding to CSIRO, the Australian Research Council (ARC), grants to universities and the 125% tax deduction for R&D

investment by industry. In addition, other programs such as Venture Capital Limited Partnerships (VCLP) could encourage overseas funding for hydrogen projects.

Australia must focus on areas of competitive advantage.

A range of factors such as government policy, legislative objectives, missions and mandates, and user needs drive expenditure priorities. A key for efficient utilisation of Australian R&D resources is focusing on investment in those areas of R&D where Australia has a relative advantage either because of its skills base or natural resource endowments. That skills base will enable Australian researchers, either through national or international collaboration or independently, to argue the case for funding specific areas of R&D. National and international collaboration offers the opportunity to maximise the potential contribution of Australia's R&D skills.

The case for Australian funding of hydrogen R&D will be greater where that R&D focuses on issues, including resource utilisation, not being picked up elsewhere. The Commonwealth commitment to the CRC for Sequestration reflects the future wealth creation potential of utilising our natural resources.

This report's discussion of technologies and the problems they currently face identified a range of research directions. It is unlikely that Australian researchers are positioned to advance all of these. The question then is how to assign research priorities to match Australia's skills base and resources.

Technology roadmaps can help define R&D priorities.

Technology roadmaps can be a powerful tool for helping to identify research priorities and funding needs. To be fully effective roadmaps should be tightly focused on areas of hydrogen research that capitalise on Australia's competitive advantages. Examples of such areas might include:

- Integration of renewable energy resources (for example wind, solar, tidal energy) and hydrogen production;
- Fuel cells; and
- Utilisation of fossil fuel resources for hydrogen production, in particular coal gasification and distributed gas reformation.

More collaboration is needed, both international...

This growth in overseas investment provides the potential for new funding sources for Australian researchers. International collaboration on hydrogen R&D is one mechanism for maximising the efficiency of the funds available for R&D in this country. It would also be in accord with the efforts to promote collaboration by many overseas countries.

...and domestic.

The lack of communication between Australian researchers and industry is a barrier to hydrogen. There is a need to better disseminate the nature and results of hydrogen-related R&D. To the extent possible, the government should encourage both the private and research sectors to play a role in any collaborative efforts it decides to enter into. Doing so will help ensure that successful R&D outcomes are more quickly commercialised. It will also assist researchers to prioritise their research. The Perth hydrogen bus trial is a good example of a project that includes stakeholders from a wide range of backgrounds.

Hydrogen needs a champion.

Any transition to a hydrogen economy will be accompanied by the emergence of major players across the entire hydrogen supply chain. However, at present there are few significant hydrogen industry players in Australia. As with any emerging industry sector there is therefore a lack of a champion for the industry.

An Australian Hydrogen Group.

These concerns are valid. To help overcome them the government should support the creation of an Australian Hydrogen Group. This would be a group of interested parties who can assist driving the hydrogen agenda and the implementation of agreed recommendations.

In the first instance the government should identify a group of representative stakeholders from across the whole hydrogen supply chain. The Australian Hydrogen Group should be supported by a secretariat. The federal government should provide funding support for the secretariat.

The Group must be representative…

It will be important that the Group represents the interests of all stakeholders in a manner that both is, and is seen to be, independent of any particular interests. Obviously most parties who are working in this area, and who should properly be involved in an Australian Hydrogen Group, will have their own interests to promote. Maintaining the Group's independence will therefore depend upon maintaining a balanced membership structure and an open and transparent decision making process.

…and will need time to prove itself.

In time, as the hydrogen industry grows and develops, there will be a sufficient number of stakeholders for the industry itself to progressively take on the responsibility of funding the secretariat. Consequently government funding support for the secretariat should be progressively phased out after some appropriate period.

A key task for the Group would be to act as a champion for hydrogen and help to implement the recommendations of this Report. Other tasks should include:

- being responsible for raising community awareness, education and the dissemination of information on issues relating to hydrogen;
- informing government decision makers and assisting policy formulation;
- commissioning technology road maps;
- monitoring overseas hydrogen R&D projects and identifying opportunities for Australian collaboration with these, and assessing the value of such cooperation;

- working to identify and assess any additional barriers that might arise and thus inhibit private sector investment and interest in hydrogen and recommending measures to overcome these;
- helping promote the adoption of global codes and standards relating to hydrogen, and ensuring that Australia's codes and standards conform with international standards unless the former are anti-competitive or have the potential to stultify innovation;
- helping identify and promote export markets for Australian hydrogen related products and services;
- helping coordinate bilateral and multilateral activities on hydrogen; and
- other tasks that may be agreed.

CSIRO's proposal for a National Hydrogen Centre may be able to deliver some or all of the above tasks that the study team has identified as being within the remit of the Australian Hydrogen Group. It would be a grave mistake to have more than one body of this kind and all parties should work together to resolve the membership, structure and roles of a single national body for hydrogen.

Confidence in hydrogen needs to be increased.

An important barrier to hydrogen is what is often referred to as the "chicken and egg problem". Namely, without supply chain infrastructure there can be little confidence by consumers that any demand that they might have for hydrogen will be satisfied. Conversely, potential suppliers of hydrogen have little incentive to put in place the infrastructure to do so in the absence of a clear demand for their product.

Problems of this nature are relatively common. For example, the development of Australia's natural gas resources has often been delayed until long-term supply contracts are in place that reduce the risk of investment in the supply infrastructure, whether it is a liquefaction plant or a transmission pipeline.

The government can help boost confidence.

Governments today are unlikely to play a major role in the provision of supply infrastructure. Nonetheless, there are a number of things that governments can do to help overcome this problem. They include:

- ensuring that the public have assess to the information they require to inform their choices;
- promoting public confidence in the safety of hydrogen as an energy option by working to ensure that internationally accepted codes and standards are developed and adopted;
- encouraging hydrogen utilisation demonstration programs; and
- where appropriate, entering into public private partnerships to help reduce the perceived risk of hydrogen infrastructure provision.

8.2 National Hydrogen Study Recommendations

The recommendations of the Study Team are listed below. Following each recommendation there is a box that provides a reference for further reading on the background to the recommendation, any possible cost implications and views on the timing for implementing the recommendation. In cases where it is relevant the box also lists some examples of possible concrete measures that might be taken.[79]

In developing its recommendations the Study Team has drawn on its own research and analysis into the state of play, both in Australia and internationally, in relation to the production and use of hydrogen as an energy form. The discussions and outcomes of the various consultations that have formed an integral part of the National Hydrogen Study have also informed our thinking.

8.2.1 Guiding principles

Guiding principles

A number of fundamental principles have also guided the development of our recommendations, namely:

- the first priority for Australian governments should be to determine and agree on their desired objectives or outcomes. Those outcomes could be related to any or all of the various drivers for hydrogen, including environmental or energy security outcomes;
- having specified their objectives, governments should allow as much flexibility as possible in how they are achieved;
- any measures should be flexible enough to adapt to new circumstances and developments, both in Australia and overseas;
- any approach adopted should be national in scope (i.e. have the support of both the state and federal governments). It should also seek to be consistent with what the rest of the world is doing, while recognising that Australia should focus on those areas where it has competitive advantages;
- all stakeholders, including governments, researchers and the private sector, should play a role in the implementation of the recommendations. In principle, the resource contributions should be proportional to the ability of the contributor to capture any potential benefits;
- policies and actions should be implemented in a measured way that assesses risks along the way and assigns priority to least-regrets measures;
- recognise the power of the market place to drive investment and innovation; and

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[79] These are meant to be indicative not exhaustive.

- proposed approaches should as far as possible be in accord with existing policies (for example proposals for energy market reform[80] and national research priorities[81]).

Recommendation One – An Australian Vision for Hydrogen

Putting hydrogen on the agenda.

Australia should adopt a vision for hydrogen. The text of the vision should reflect the characteristics identified over the course of the National Hydrogen Study and should be agreed by federal and state governments, researchers and the private sector. A suggested form of words is shown in Box 14.

> Box 14 **Recommendation One**
>
> An Australian vision for hydrogen
>
> Australia recognises the potential of hydrogen to contribute to a more environmentally friendly and sustainable energy mix. Australia will play an active role in the national and international development of hydrogen technologies and related enabling technologies. In doing so, Australia will focus on areas where it has resource, scientific, technical or other advantages
>
> References
>
> - Chapter 1
>
> Cost implications
>
> - No direct cost implications
>
> Timing and implementation
>
> - As soon as possible.

Recommendation Two – Capturing the opportunities

Getting the policy signals right.

Governments should commit themselves to reviewing any policies or regulations that are identified by the industry or research sectors as posing a barrier to hydrogen. In doing so, the bias should be towards removing or reducing that barrier.

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80 http://www.industry.gov.au/content/controlfiles/display_details.cfm?objectid=5E918302-6E82-471E-B57C8153BE86E522

81 http://www.dest.gov.au/priorities/goals_summary.htm

Box 15 **Recommendation Two**

Examples of areas where barriers could emerge

- Mandates either for or against particular energy forms. For example, a policy that precluded new coal fired power stations would rule out an important option for providing the hydrogen needed for a transition to a hydrogen economy.
- Access to the electricity grid for hydrogen fuelled distributed generation facilities.
- The use of at home refuelling facilities for transport.
- The dual use of hydrogen fuelled cars for private transport or power generation when parked.
- The taxation treatment of transformed fuels.

References

- Chapter 3, especially section 3.1

Cost implications

- Difficult to judge, but the cost of leaving barriers in place could be significant.

Timing and implementation

- An early commitment and then an ongoing activity.

Recommendation Three – Flexible strategies and periodic reviews

Maintaining flexibility.

Hydrogen policies and measures should be reviewed every two to three years to ensure that they remain appropriate to the circumstances prevailing at the time. As a corollary to this any policies and programs adopted should be sufficiently flexible to adapt to new circumstances and developments, both in Australia and overseas.

Box 16 **Recommendation Three**

References

- Important policy principle strongly supported by the Broome conference

Cost implications

- The cost associated with the allocation of resources for the period reviews is not likely to be substantial.
- There may also be cost savings associated with removing or revising measures that are no longer necessary.

Timing and implementation

- Periodic reviews, say every 2 to 3 years

Recommendation Four – International Collaboration

More international collaboration.

Australia should seek to participate in bilateral or multilateral hydrogen R&D programs. In line with the recommended vision for hydrogen, particular attention should be placed on ensuring that the subjects for cooperation take into account Australia's competitive advantages.

Box 17 **Recommendation Four**

Examples of possible areas for collaboration

- Possible follow-on projects to international hydrogen bus trials currently under way in Perth.
- Participating in the US FutureGen project, possibly through linkages with COAL21.
- Participating in the International Partnership for the Hydrogen Economy (IPHE).
- Encouraging the use of Australia as a test bed for new technologies, particularly those that relate to our competitive advantages.
- Various activities under the auspices of the climate action partnership with the US.
- Participating in the IEA Implementing Agreement on Hydrogen.

References

- Chapter 4, especially section 4.7;
- Chapter 5, in particular section 5.2.1, and
- Chapter 7

Cost implications

- Will depend upon the nature of the collaboration, but will clearly involve additional costs.
- To be accepted as a serious research partner the effort would need to be proportional to that being provided by the other party or parties. In some cases that cost could be substantial.
- For example, a project (possibly in collaboration with FutureGen or IPHE) involving investment in an Australian IGCC[82] that produced both power and hydrogen and incorporated O_2 feed and flue gas sequestration would cost of the order of $2 billion.
  - At the other end of the spectrum, the cost of the Perth hydrogen bus trial is of the order of $8 million.

Timing and implementation

- Efforts to increase international collaboration should begin promptly and be ongoing.
- One of the roles of he proposed Australian Hydrogen Group would be to harness and coordinate ideas for collaborative programs.

[82] Integrated Gasification Combined Cycle.

Recommendation Five – Encouraging a private sector role

Involving the private sector.

The private sector should be encouraged to play a key role in broadening and deepening collaboration in relation to hydrogen. Government programs and initiatives such as international collaboration should aim to foster the development of strategic relationships, alliances and joint ventures through which Australian businesses can build knowledge and expertise in the field of hydrogen.

Box 18 **Recommendation Five**

References

- Chapter 3 and
- Chapter 7, particularly section 7.1

Cost implications

- Some of these initiatives would have a small cost to government.
- An initiative such as an IGCC would need to be principally funded by the private sector.
- Private sector contributions will either add to existing funding or offset existing public sector funding sources.

Timing and implementation

- Efforts to increase private sector participation should begin now and be ongoing.
- The proposed Australian Hydrogen Group would assist this process.

Recommendation Six – An Australian Hydrogen Group

A champion for hydrogen.

The government should work with industry and research sectors to establish an Australian Hydrogen Group. The Group's participants should be drawn from Australian science and public policy establishments and the private sector, throughout the country. The government should provide support for the secretariat of the Group.

Initial funding should be for a reasonable period to allow the Group enough time to carry out the tasks that this report suggests be assigned to it. Federal government support for the secretariat should be provided for an initial three-year period. Support arrangements should be reviewed at the end of two years. The level and duration of funding should be subject to review with the aim of progressively broadening the funding base for the Group.

Box 19 **Recommendation Six**

References

- Key message from consultations

Cost implications

- The exact amount needed will depend upon the tasks that are agreed should be assigned to the Australian Hydrogen Group
- One estimate of the cost of operating the Group suggests that an amount between $3 and 4 million per annum might be required.
- It is likely that a significant share of the funding for the Group will need to be provided by the public sector in one form or other for the first few years.

Timing and implementation

- There are a number of similar proposals being promoted by various parties.
- Discussions with stakeholders should take place without delay to coordinate the various ideas on the table and agree on a single way forward.
- Provide a multi-year funding commitment, with a review after two years.

Recommendation Seven – Promoting market confidence

Building market confidence.

To help promote market confidence the government should adopt measures aimed at encouraging the early adoption of hydrogen-related technology by consumers, including:

- providing funding assistance for demonstration projects; and
- creating private public partnerships, particularly for infrastructure provision.

Box 20 **Recommendation Seven**

References

- Chapters 3 (especially section 3.4.2);
- Chapter 5 (especially section 5.2.1);
- Chapter 7; and
- Key message from consultations.

Examples of possible projects

- Agreement to work with a wind farm operator to examine the use of hydrogen as a load levelling mechanism.
- A continuation and/or expansion of the Perth hydrogen bus trials.
- Australia as a test bed for new and innovative technologies.
- A coal gasification and CO_2 sequestration project, possible as part of COAL21 and or the Climate Action Partnership with the US.
- A distributed power generation demonstration project with on site gas reformation and power generation using a fuel cell. This could be in a remote location with access to natural gas but not the electricity grid.

Cost implications

- Impact on budget will depend on the nature of any demonstration project(s) and or public private partnership(s) ultimately agreed on.
- Funding could of course be provided from within existing government programs, such as the Innovation Access Program.
- As an indication, the cost of the Perth hydrogen bus trials is of the order of $8 million.

Timing and implementation

- This would be an ongoing activity.
- The proposed Australian Hydrogen Group could act as forum for discussion of possible projects or partnerships. The Group could also serve as a source of information on existing government programs that could be a source of funding for particular projects.

Recommendation Eight – Codes and standards

Codes and standards are important.

Australia should play an active role in the formulation of international codes and standards relating to hydrogen.

Box 21 **Recommendation Eight**

References

- Chapter 3; and Chapter 6 (especially section 6.1)

Cost implications

- Relatively minor

Timing and implementation

- This would be an ongoing activity.
- The proposed Australian Hydrogen Group could act as forum for discussion of possible codes and standards.

Recommendation Nine – Technology roadmaps

Technology roadmaps for hydrogen R&D.

To assist in better targeting available R&D funding, technology roadmaps should be commissioned for areas of hydrogen R&D identified as capitalising on Australia's competitive advantages.

Box 22 **Recommendation Nine**

References

- Chapter 3, in particular section 3.2, Chapter 5; and Chapter 7.

Examples of possible technology road maps

- Integration of renewable energy resources (eg wind, solar, tidal energy) and hydrogen production;
- Fuel cell technologies; and
- Utilisation of fossil fuel resources for hydrogen production, in particular coal gasification and distributed gas reformation.

Cost implications

- The funding implications will depend upon the number and nature of technology roadmaps that are agreed.
- If sufficiently well defined, the cost of each roadmap should be relatively modest. It is unlikely that there would be more than one or two road maps in any year.
- The renewable energy technology roadmap cost several hundred thousand dollars, but this was a far larger exercise.

Timing and implementation

- An early task of the proposed Australian Hydrogen Group could be to review and prioritise possible areas of research that might benefit from a technology roadmap.
- One or two roadmaps a year.

A Technical information about hydrogen

Technical and production

- 1kg H_2 = ~11500 L (STP) = 100 - 140km driving range
- 150cm tall, 20cm diameter bottle at 700bar = ~3kg H_2 = 300km driving distance
- 5kg H_2 is required for ~500km driving distance (ICE cars)
- 5kW water electrolyser, 7h operation = 1kg H_2 = 100km driving range
- 360 litres H_2 = 1kWh = 3.6MJ
- 1GJ = 277.8kWh = 100,000L H_2 = 8.7kg H_2

Hydrogen Conversions and Facts

- 1 mol of hydrogen = 2.0 grams = 22.4 standard litres
- Heat of combustion of hydrogen: 241.8 kilojoules / mol of H_2 (LHZ) 15 British thermal units / gram of hydrogen
- 1 kilogram of hydrogen = 33.3 kilowatt-hours = .12 gigajoules
- 1 standard of cubic foot H_2 = 2.53 grams of H_2 = 28.32 litres of H_2 =.028 cubic metres of H_2.

For a fuel cell with 50% efficiency

FC power Output (kW)	Grams H_2/min	Litre H_2/min
1	1	11
5	5	56
10	10	112
15	15	167
50	50	556
100	100	1120

Other fuel comparisons

- 1 kilogram of gasoline = 13.0 kWh
- 1 kilogram of methanol = 5.58 kWh
- 1 kilogram of propane = 12.9 kWh
- 1 kilogram of ethanol = 7.49 kWh
- 1 kilogram of butane = 12.7 kWh
- 1 kilogram of natural gas (CH4) = 13.88 kWh

Pressure

1 atmosphere = 1.01 bar = 14.7 pounds per square inch = $1x10^5$ pascals

What are some characteristics of hydrogen?

- Hydrogen is a non-toxic, colourless, odourless, and tasteless gas.
- Hydrogen, bound in organic matter and water, makes up 70% of the Earth's surface. It is the most common element in the universe.
- Hydrogen usually exists in combination with other elements, such as oxygen in water, carbon in methane, and in trace elements as organic compounds.
- When cooled to a liquid state, hydrogen takes up 1/700 as much space as it does in its gaseous state.
- Hydrogen is about one-fourth as dense as air.
- The temperature needed to cool hydrogen to a liquid state is -423ºF (-253ºC).

Why is hydrogen used as a fuel?

- Hydrogen has the highest energy content per unit weight of any known fuel—52,000 Btu/lb (120.7 kJ/g).
- It burns cleanly. When hydrogen is burned with oxygen, the only by-products are heat and water. When burned with air, which is about 68% nitrogen, some oxides of nitrogen are formed.
- In fuel cells, electrolysis is reversed by combining hydrogen and oxygen through an electrochemical process that produces electricity, heat, and water.

How is hydrogen produced?

- Most of the hydrogen produced today is made by steam reforming of natural gas, which is currently the most cost-effective way to produce hydrogen. There are many other ways to produce hydrogen, including electrolysis.

Sources:

- CSIRO
- U.S. Department of Energy, Energy Efficiency and Renewable Energy Network, Consumer Energy Information: EREC Reference Briefs, Hydrogen Fuel, February 2001(http://www.ott.doe.gov/facts/archives/fotw204.shtml).
- California Environmental Associates (http://www.ceaconsulting.com/resources/hydrogen.htm)

B The National Hydrogen Study consultative process

This report would not have been possible without the assistance and valuable contributions of a large number of people. Various consultative mechanisms were used during the course of the study in order to:

- Allow as much opportunity as possible for stakeholders to have an input into the study
- Check and verify preliminary findings; and
- Build stakeholder ownership of the Study.

The ACIL Tasman web site

ACIL Tasman maintained a web site on which documents prepared during the course of the Study were made available for public comment and input. In addition the web site provided links to other documents of interest and kept interested parties informed on progress with the Study.

The High Level Advisory Group (HLAG)

The High Level Advisory Group (HLAG) was set up to provide the Study Team with high level strategic advice and feedback during the course of the Study. The members of the HLAG were:

- Lindley Edwards, Managing Director of The Venturebank Limited;
- Simon Whitehouse, Director of Alternative Transport Energy, Department for Planning and Infrastructure;
- Garry Wall, General manager of the Energy Futures Branch of the Department of Industry, Tourism and Resources;
- Greg Bourne, Regional President BP; and
- Dr Joel Swisher, Rocky Mountain Institute.

The HLAG communicated by e-mail throughout the study as well as having two face-to-face meetings[83].

The stakeholder workshops

The National Hydrogen Study held two workshops, one in Melbourne and one in Perth to obtain stakeholders' views on a range of matters, including:

- an Australian vision for hydrogen;

[83] Joel Swisher participated in those meetings via phone hook up.

- hydrogen up-take scenarios;
- important opportunities & impediments for hydrogen and their priority; and
- strategies to address the identified impediments & opportunities.

Workshop participants discussed these matters through a mixture of plenary and breakout groups. The results of the workshops provided a valuable input into the preparation of the Interim Report prepared for the many national and international participants in the Broome conference in May 2003.

The Broome Conference

The international conference *The Hydrogen Economy – Challenges and Strategies for Australia, Including the Tidal Energy Link*, held in Broome from 18-21 May 2003, formed an integral part of the National Hydrogen Study.

On the afternoon of the first day of the conference, Monday, 19 May, three concurrent workshops will be held to allow more focussed discussion of key issues and the policies and strategies for addressing them. The workshop topics were broadly defined to address the range of issues related to a possible transition to a hydrogen economy. Each workshop was chaired by an expert in the field and facilitated by a member of the Study Team. The objectives for each workshop are described below.

Strategic Issues Workshop

This workshop examined and discussed strategic issues associated with a possible transition to a hydrogen economy by Australia. It considered the strategic opportunities, risks and impediments associated with such a transition, and considered and suggested policies and strategies that might help Australia capitalise on those opportunities, minimise risks and overcome impediments.

Technical Issues Workshop

This workshop focussed on technical issues associated with the production, storage, transport, distribution and end-use of hydrogen. It examined technical hurdles that need to be overcome to increase the role of hydrogen in the energy mix.

Implementation Issues Workshop

This workshop focussed on issues related to the implementation of a hydrogen economy. In particular it examined national and international barriers and challenges hindering the adoption of hydrogen as a fuel both in Australia and globally and what policies and strategies could allow Australia to better manage implementation issues associated with any transition to a hydrogen economy.

The Departmental Steering Group

A Steering Group was set up to advise and assist the Department of Industry, Tourism and Resources (DITR) to manage the national hydrogen study. The members of the Steering Group were:

- Randall Wilson, Department of Industry, Tourism and Resources;
- Albert Ofei-Mensah, Department of Industry, Tourism and Resources;
- Gino Grassia, Department of Industry, Tourism and Resources;
- Michael Byers, Department of Industry, Tourism and Resources;
- Peter McLoughlin, Department of Transport and Regional Services;
- Paula Hahesy, Department of Transport and Regional Services;
- Tony Moleta, Department of Transport and Regional Services (on secondment to the Energy Task Force);
- Joe Wyder, Australian Greenhouse Office;
- Collin Boothroyd, Commonwealth Scientific and Industrial Research Organisation;
- Kathy Dunn, Commonwealth Scientific and Industrial Research Organisation (on secondment to the Department of Education, Science and Technology);
- Simon Whitehouse, WA Department for Planning and Infrastructure.

C Glossary

ABARE	Australian Bureau of Agriculture and Resource Economics
ATPB	ACIL Tasman Parsons Brinckerhoff
C	Degrees Celsius
CH2	Compressed Hydrogen
CNG	Compressed Natural Gas
FC	Fuel Cell
FCV	Fuel Cell Vehicle
GHG	Greenhouse Gas
ICE	Internal Combustion Engine
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle (power plant)
IPHE	International Partnership for the Hydrogen Economy
K	Degrees Kelvin
LH2	Liquid Hydrogen
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MCFC	Molten Carbonate Fuel Cell
METI	(Japanese) Ministry of Economics, Trade and Industry
MRET	Mandatory Renewable Energy Target
MWe	Mega watt electrical
Study	National Hydrogen Study
PAFC	Phosphoric Acid Fuel Cell
PEFC	Proton Exchange Membrane Fuel Cells

PV	Photovoltaic
RAPS	Remote Area Power Supply
SOFC	Solid Oxide Fuel Cell
STEP	Sustainable Transport Energy for Perth
US DOE	United States Department of Energy
VKT	Vehicle Kilometres Travelled

D Further reading

All references used during the preparation of this report are identified in footnotes throughout the document.

For those interested to learn more about hydrogen and developments around the world the references listed below may provide some suggestions for further reading.

National Hydrogen Study documents

- The Issues Paper, http://www.aciltasman.com.au/pdf/AT%20Hydrogen%20Study%20Issues%20Paper.pdf
- The Interim Report, http://www.aciltasman.com.au/pdf/Interim%20Report%20FINAL.pdf
- Broome Conference proceedings. http://www.industry.gov.au/archive/hydrogen/

Selected US hydrogen references

- A National Vision of America's Transition to a Hydrogen Economy - to 2030 and beyond, US Department of Energy, February 2002. http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/vision_doc.pdf
- National Hydrogen Energy Roadmap, November 2002. http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf.

Selected Rocky Mountain Institute references

- Twenty Hydrogen Myths, Amory B. Lovins, 20 June 2003. www.rmi.org
- A Strategy for the Hydrogen Transition, Amory B. Lovins and Brett D. Williams, April 1999. www.rmi.org

Selected European Union hydrogen references

- Hydrogen Energy and Fuel Cells - A Vision for our Future, Summary Report, June 2003. http://europa.eu.int/comm/research/energy/pdf/hlg_summary_vision_report_en.pdf
- High Level Group on Hydrogen and Fuel Cells. http://europa.eu.int/comm/research/energy/nn/nn_rt_hlg1_en.html

Icelandic New Energy

- http://www.newenergy.is/

Other selected documents

- Bellona rapport nr. 6 – 2002, Hydrogen – Status and Possibilities, www.bellona.no/en/
- Moving to a Hydrogen Economy: Dreams and Realities, January 2003. http://www.iea.org
- Solutions for the 21st Century – Zero Emissions Technologies for Fossil Fuels, IEA, 2002. http://www.iea.org