TECHNOLOGY FOR SUSTAINABLE ENERGY — A CSIRO PERSPECTIVE

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ABSTRACT
A sustainable energy system needs to meet ecological, social and economic constraints from local to global geographic scales and from now into the future. Therefore creation of a sustainable energy system requires the resolution of a series of tensions. Technology can contribute to the resolution of these tensions but not if pursued in isolation from other dimensions of sustainability.

Climate change resulting from the enhanced greenhouse effect provides a useful model with which to explore some of the ecological dimensions of sustainability because the objective of stabilising greenhouse gas concentrations is amenable to quantitative though illustrative exploration. An exploration of possible requirements upon Australia to meet the ultimate objective of the United Nations Framework Convention on Climate Change suggests somewhere between a 50% and 85% cut in present-day national emission levels, albeit over an extended time-frame.

In essence, four strategies can be used to meet these objectives: greater efficiency in the use of carbon fuels, fuel switching to less greenhouse intensive fuels, capture and sequestration and the deployment of transmission and end-use efficiencies.

A review of technological developments suggests progress can be made in each of these areas and that all have a role to play in producing a sustainable energy system. Since policy and economic factors can act as barriers to the rapid uptake of new technologies there are benefits in harmonising policy with technological developments.

INTRODUCTION
The goal of a sustainable energy system has been with us for the past few decades. Recently however, focus has shifted from concerns over potential depletion of fossil fuel reserves to a broader view of what constitutes ‘sustainability’.

The United Nations inquiry into environment and development conducted during the 1980’s produced a marked shift in the discussion over sustainability and in many ways laid the foundation — in the international policy domain, at least — for contemporary thinking about this issue. The report of this commission is a direct antecedent to the United Nations Convention on Environment and Development (the Rio convention) in 1992. Among other things it produced a commonly quoted definition of sustainability (World Commission on Environment and Development, 1987):

> ‘Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs’.

This definition embedded the concept of inter-generational equity — a social goal —firmly within the idea of sustainability.

Sustainability also needs to integrate two scale issues: size and time. Within the spatial dimension considerations of sustainability that operate at the global scale need to be translated to operations of multi-national corporations and national governments through to small enterprises, local government areas and even individual households. *Triple-bottom-line accounting* is being developed as a tool in recognition of these three aspects of sustainability. It is also a way to implement the concept of sustainability within organisations.

The purpose of this paper is to briefly explore the idea of sustainability in the context of society's demands for energy – or at least for the services that energy offers — and the role of technology in supplying societies' needs.

ENVIRONMENTAL SUSTAINABILITY AND GREENHOUSE EMISSIONS

Concurrent with the activities of the Brundtland commission, climate scientists were bringing the issue of global climate change to the attention of the world's policymakers (eg Bolin et al. 1986).

Global climate change is important to consideration of sustainability for a number of reasons. First, because of temporal lags in the earth's climate system, the damage (or cost) of unmitigated climate change will not primarily be borne by current or even immediately succeeding generations, whereas costs associated with abating greenhouse gas emissions (remediation) need to be borne in the near-term. Thus climate change produces a real-world test for the concept of inter-generational equity. Second, the greenhouse issue covers all planetary space scales. Greenhouse gas emissions produced at the individual or local scale contribute to a globally-distributed problem and the down-side risks of climate change are very likely be distributed differently from the benefits derived from current patterns of fossil fuel use. Finally, the enhanced greenhouse effect and accompanying climate change are driven primarily by the use of fossil fuels. Thus climate change become central to considerations of what constitutes a sustainable energy system.

The greenhouse issue is also interesting in that we can apply a quantitative analysis to begin to identify a sustainable level of emissions to the atmosphere. For this purpose, we can take the objective of the United Nations Framework Conventions on Climate Change (Article 2) as a suitable definition of a sustainable outcome.

> 'The ultimate objective of this Convention…is to achieve…stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure food production is not threatened and to enable economic development to proceed in a sustainable manner.'

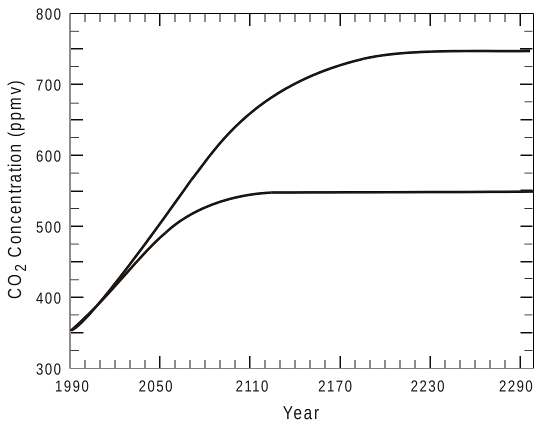
An objective assessment of what constitutes 'dangerous' is not possible. However it is possible to explore what meeting the ultimate objective might look like for a country such as Australia. A starting point is the observation that a broad but tentative agreement appears to be moving to accepting that CO_2 concentrations between 2 and 3 times pre-industrial levels represent the level at which concentrations should be stabilised. Two arbitrary curves outlining pathways to stabilisation of carbon dioxide at about these levels are shown in Figure 1 (after Wigley et. al. 1996). Allowable emissions associated with each of these scenarios for stabilisation are shown in the accompanying panel.

Using a few simplifying assumptions we can illustrate how these global constraints might apply to a country such as Australia. Our purpose is to begin the process of bounding the problem, so that we can begin to identify an ecologically sustainable level of emissions. These assumptions are:

1. There will be a change in relative emissions output between Annex B and non-Annex B countries[1] — with a reduction in the disparity between developed and developing country emissions.

[1] Annex B of the Kyoto Protocol. Those countries that have emissions targets under the protocol.

2. A convenient starting point to assess such relative changes might be one of the SRES[2] emissions curves (for our purposes we select the SRES B2 scenario and proxy) (IPCC, 2000)
3. Australia's 'allowable' energy-related emissions remain a fixed proportion of total Annex B emissions.



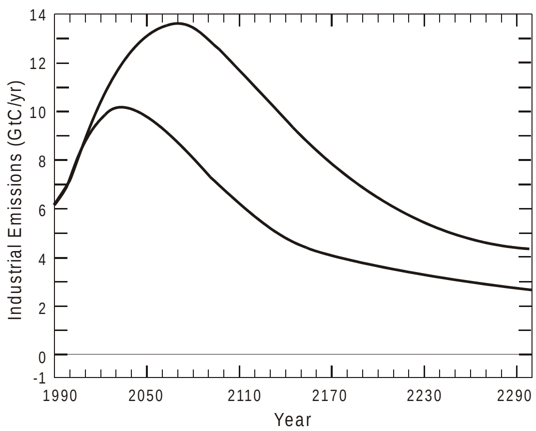


Figure 1: Profiles for stabilisation at 750 and 550 ppmv of CO_2 (left hand panel) and 'allowable' industrial emissions to meet these objectives (after Wigely 2000)

Year	**Ratio of Annex B country emissions to Non-Annex B emissions**
1990	1.8
2020	0.88
2050	0.45
2100	0.34
2200	0.33

Table 1: Change in the ratio of Annex b to non-Annex B emissions used to explore potential constraints on Australian emissions

These three assumptions can be paraphrased as Annex B emissions becoming a declining portion of total global emissions, with Australia's emissions remaining constant relative to the rest of the Annex B parties.

Using these assumptions Fig. 3 shows Australia's 'allowable' energy related emissions under the two stabilisation scenarios that are used (WRE550 and WRE 750, Wigley et. al. 1996 and Houghton et. al. 1997, Wigley 2000).

For the purposes of this paper we assume that international climate measures will require Australia to limit its greenhouse gas emissions. In percentage terms the 'envelope' of what might be ultimately considered environmentally sustainable in terms of greenhouse gas emissions might be a reduction of up to 85% of present-day emissions. With more relaxed constraints (that is a higher level of CO_2 in the atmosphere being accepted as 'not dangerous') a 50% reduction in emissions might be considered.

[2] SRES is Special Report on Emissions Scenarios

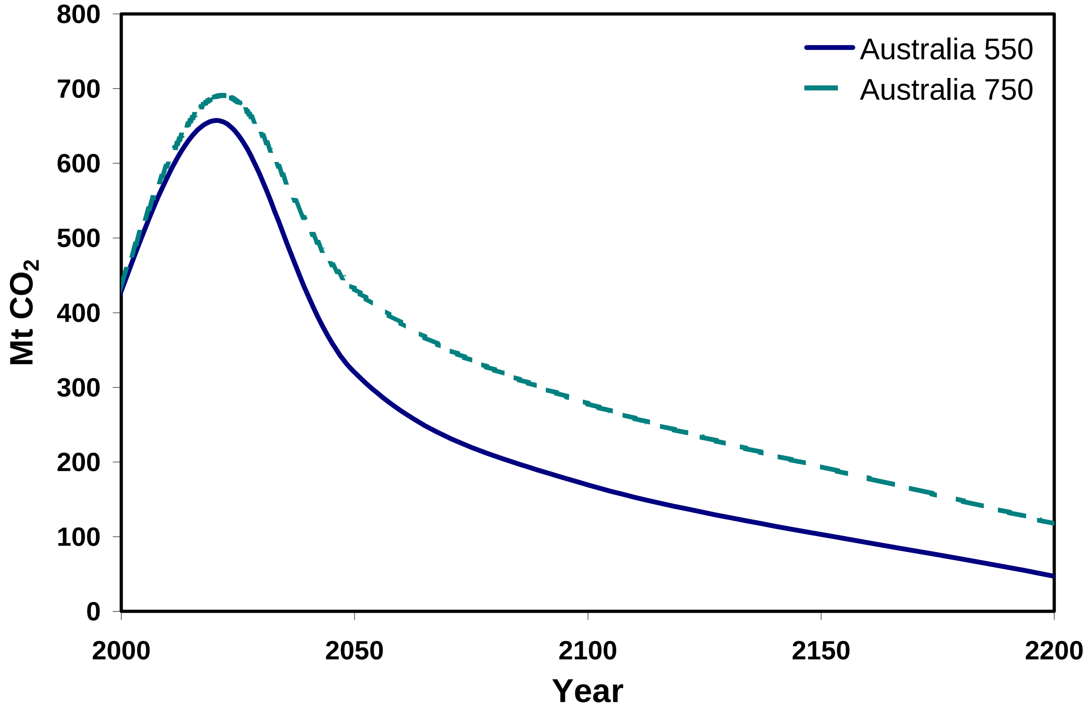


Figure 3 Illustrative 'allowable' emissions for Australia where global stabilisation occurs between 550 and 750 ppmv approximating the WRE[3] 550 and WRE 750 pathways and allowing for a change in the ratio of Annex B and non-Annex B emissions as described in Table 1.

We would argue that this theoretical scientific scenario is policy neutral because it does not impose *severe* time constraints on when such emissions reductions (and hence stabilisation) are to be achieved. In fact, the WRE scenarios on which this illustration is based, deliberately assume a 'business-as-usual' emissions pathway for the first 10–30 years. Australia's Kyoto Target, limiting emissions growth to an 8% increase above 1990 levels during the 2008–2012, *is more stringent* than shown in this illustrative envelope, at least over the next decade.

From this analysis several issues emerge. The first is that in terms of planning for a sustainable energy system, the current imperative of meeting targets defined under the Kyoto Protocol is only the first step in the transition to sustainability. A corollary perhaps is that very long time-frames need to be considered. Nonetheless, greenhouse implies a severe constraint on emissions that might be considered *environmentally* sustainable even allowing for these long planning horizons.

ECONOMIC SUSTAINABILITY

Australia in common with several other energy markets is deregulating parts of its energy supply and distribution sector. This has resulted (ESAA 2000) in a decrease in national electricity prices by 15% since 1993. At the same time, demand, dependent on population change and economic growth, is forecast to rise from 179,000 GWh to 254,000 GWh in 2010. While emissions intensity is falling it is not at a rate sufficient to stabilise CO_2 emissions from the power generation sector.

In the Australian economy we see a number of tensions. The first is that there is an immediate requirement for return on investment sufficient for generators and distributors to remain in business and for a stable electricity supply to be maintained. In contrast, other economic definitions of sustainability require '*non-declining utility over time: future generations should be no worse off than the current generation*' (Neumayer, 1999). Here we see in practice the tension over time-scale

[3] Wigley, Richels and Edmonds

outlined previously. The second tension lies between the decrease in power prices and mandated actions to reduce greenhouse gas emissions. One way of looking at these tensions is to regard limitations on carbon emissions as a process of internalising environmental costs of the use of fossil-fuel based energy, particularly electricity. These tensions have yet to be resolved.

SOCIAL SUSTAINABILITY — EQUITY, ACCESS AND ACCEPTABILITY?

Social sustainability cannot be determined in terms of technology and technological options. We do not intend to explore the social dimensions of sustainability in any depth, except to note that within the greenhouse-sustainability nexus, social attitudes can produce an additional constraint on what might be considered sustainable.

In some instances, strong social community signals define, for individual countries, *socially acceptable* forms of energy production. In Australia, for example, it might be argued that the community has identified generation of electricity from nuclear sources as being socially unacceptable. Thus for Australia, meeting greenhouse gas targets through a nuclear energy program is socially unsustainable, irrespective of technical arguments.

A broader dimension of social sustainability is captured within the United Nations Framework Convention on Climate Change through the concepts of 'equitable burden sharing' and 'developed countries take the lead,' the latter is most forcefully expressed in Article 4 (7) of the Convention.

Other parts of the Convention (e.g. parts of Article 4, parts of Article 9, Article 11) are intended to provide technology transfer, capacity building or revenue flows to less developed nations as a way to reduce the prospect of rapid and massive emissions increases from the developing world.

The social dimensions of energy supply and use cannot be neglected in assessments of sustainability. Technological optimists have frequently misjudged the social acceptability of proposed 'solutions' to societal problems. Given the social constructs operating within the greenhouse issue, it will be necessary for technologists to conduct careful conversations with communities if proposed solutions are to be accepted. This is likely to be particularly true where CO_2 sequestration is concerned. Community disquiet over the appropriateness of oceanic sequestration is already evident in Australia.

STRATEGIES FOR REDUCING ENERGY-RELATED GREENHOUSE GAS EMISSIONS

National strategies such as Australia's National Greenhouse Strategy (Australian Government 1998) the United States Climate Change Action Plan or the Netherlands' CO_2 Reduction Plan each contains dozens of measures intended to abate greenhouse gas emissions, or enhance sinks. However, these measures can be collapsed into four underlying strategies that are encapsulated in the greenhouse gas mitigation map shown in Figure 4.

These strategies are:

1. ***Improved Efficiencies from Carbon Fuels* —** efficiency improvement of primary energy conversion through its life cycle from extracting the fuel, through to power generation so that fewer units of fossil fuel are required to provide the same converted energy output. In practice the key intervention points are upstream from wholesale distribution.
2. ***Carbon Sequestration* —** the removal and utilisation or storage of greenhouse gas throughout the power generation life-cycle that would otherwise be emitted to the atmosphere.
3. ***Fuel Switching* —** the use of lower-carbon or carbon-free energy sources that will reduce emissions of greenhouse gases. Fuel switching may involve a structural change in the energy supply system, and specifically includes *decarbonisation*.

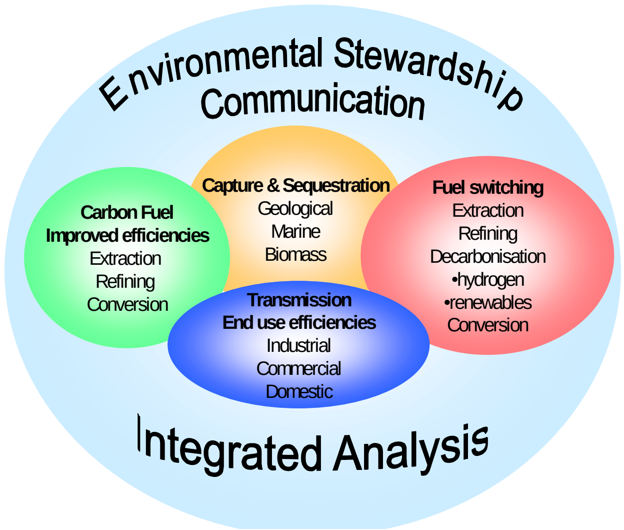


Figure 4: Four underlying strategies available to reduce greenhouse gas emissions. These need to pursued within the context of a capacity to analyse potential ecological and environmental costs, economic costs and benefits and operate successfully within a context deemed acceptable by society. The overlapping sets signify that these strategies are not mutually exclusive and can be applied in combination

4. ***Transmission and End Use Efficiencies*** — efficiency improvements that lead to reduced energy demand, which can be transmitted up through the energy chain.

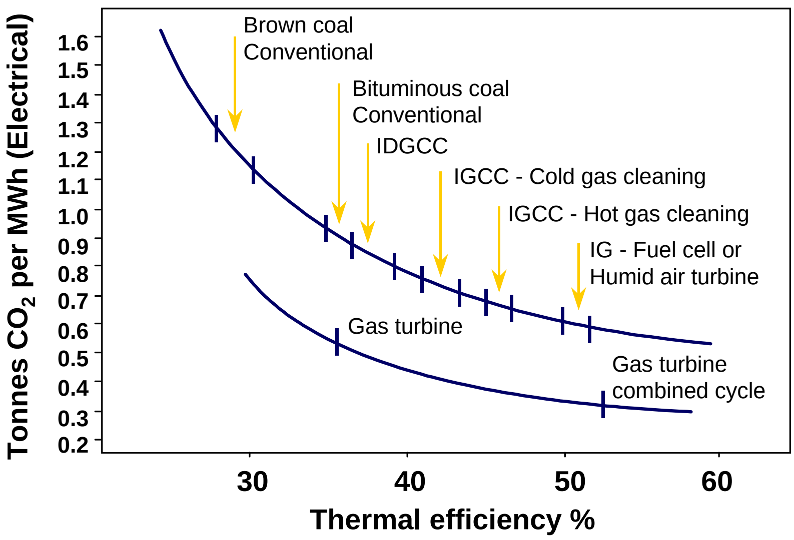
These strategies address both supply-side and demand-side aspects of the energy system. None of these strategies can, employed in isolation from the others, lead to a sustainable energy system.

Unintended, unforeseen or incidental damage might be associated with either widespread or inappropriate use of any technology. In particular abatement of greenhouse gas emissions offers opportunity for emissions shifting, or 'leakage' where emissions savings are off-set by greater emissions in other parts of the economy. For this reason implementation of greenhouse gas abatement needs to be embedded within a strong analytic framework to assess environmental, social and economic issues, using tools such as life-cycle analysis, risk assessment, cost-benefit analysis, econometric techniques or some of the more comprehensive integrated modelling approaches that are becoming available. Communication with stakeholders is vital if technological approaches to sustainability are to be widely accepted.

IMPROVED CARBON FUEL EFFICIENCIES

Base load power supply will continue to be the province of large fossil-fueled power generation systems. However, over time newer more efficient technologies will be introduced with attendant greenhouse gas benefits (Figure 5).

Figure 5: Greenhouse gas emissions at the generation point for various coal and gas technologies. The figure also allows comparison between fuel switching and gains from within fuel efficiencies.



SEQUESTRATION — RETAINING COAL AND GAS WITHIN THE MIX

Coal is considered the most problematic of the fossil fuels in terms of greenhouse gas emissions because it has the highest greenhouse intensity per unit of electricity sent out. Gas is seen as a preferable fuel to coal because of its lower greenhouse gas intensity; however, a fuel switch from coal to gas would still produce about 0.4 tCO_{2-e} per MW electricity sent out at source using present-day GTCC technology (Figure 5).

Continued use of coal to generate electricity in present-day combustion systems is considered unsustainable in terms of greenhouse gas constraints previously identified. Yet a rapid shift away from coal for some countries may be considered unsustainable on economic and social grounds. In Australia for example coal is not only a major export, but is also the major source of our electricity generation. For those communities dependent upon the mining, marketing and utilisation of coal the path towards ecological sustainability risks major dislocation and potential damage in social terms. Within this context a *rapid* shift away from coal utilisation might be argued to be both socially and economically unsustainable.

We see a series of very tight constraints emerging:

- continued downward pressure on greenhouse gas emissions
- social pressure to switch to renewables with concerns about costs
- concerns about landscape sustainability
- greater market competition
- increased market sensitivity to electricity quality
- decreased viability of Australia’s power generation base.

It is within this context that CO_2 capture and sequestration sits as an option to abate greenhouse gas emissions. Capture and sequestration appears to be a likely approach if we are ultimately seeking to reduce greenhouse gas emissions consistent with the objectives of the Framework Convention on Climate Change. Depending on the extent to which nations will be required to meet their Kyoto obligations, and the world-wide cost of carbon should emissions trading occur, the more costly abatement options such as sequestration might be required.

Within a ‘trading’ context CO_2 sequestration, particularly in geological structures should have a few advantages over some other methods of abatement. Whereas there may be debates over whether an efficiency-based abatement measure constitutes an ‘additional’ activity under the clean development mechanism, there could be little debate over additionality as far as sequestration is concerned. Second, capture of CO_2 from industrial plant and subsequent sequestration is relatively straight-forward to quantify. This is in contrast with the situation with some biological sinks which are more difficult to quantify within an acceptable level of uncertainty.

Further there is a number of technical contexts in which this approach can be envisaged. In the first instance, countries such as Australia might be required to abate emissions from existing industrial infrastructure.

In 1998 electricity generation alone contributed 37% (168 Mt CO_{2-e}) of Australia’s national emissions. This was 10% higher than in 1997 and up 30.6% on 1990 (AGO, 2000a&b). Given the importance of this sector to the Australian economy and the long capital turnover times for base-load plant, it is prudent to seek to develop processes that can be retrofitted to existing power stations. This is clearly a transitional strategy between current generation and future fully renewable or closed fossil systems (Figure 6).

At this stage, commercially available technologies for CO_2 capture based on MEA capture from flue gases are not economically viable given that their use with subsequent geological sequestration would at least double the cost of electricity sent out (Dave et al. 1999). Considering that approximately 75% of the cost of capture and sequestration lies in the cost of capture, there is an urgent need to develop more cost-effective methods of capture from large point-source emitters where the CO_2 is at ambient pressure in the waste stream. A further complication, flue gas desulfurisation is not employed in Australia, so that the economic evaluations conducted in the United States and Europe for example, are unlikely to be directly applicable to Australian circumstances (Dave et al. 2000). A complementary approach might be to modify the generation process using techniques such as oxygen combustion with CO_2 recycle although it is not clear whether it is practical to retrofit existing facilities.

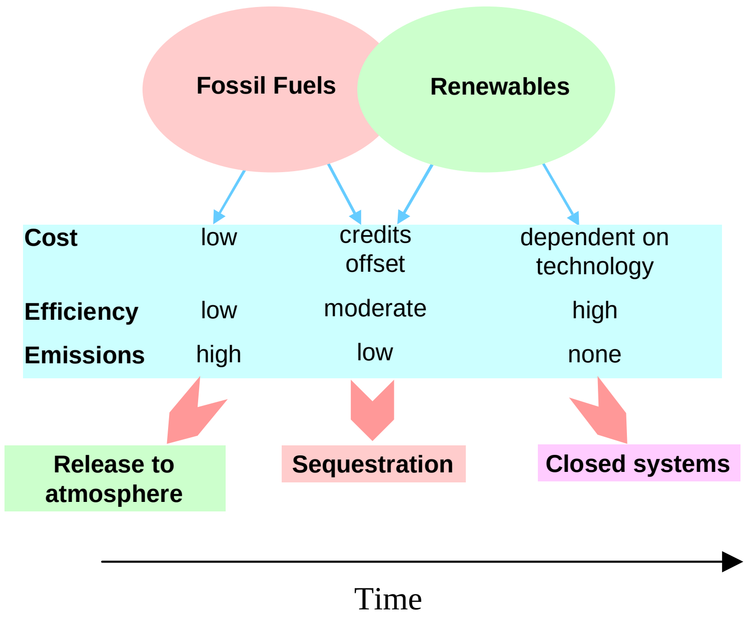


Figure 6: CO_2 sequestration may be a transitional strategy between current use of fossil fuels with free-emission to the atmosphere and an energy economy based on renewables or a combination of closed fossil systems and renewables. The transition is likely to occur only where some kind of carbon credits off-set (carbon tax, direct subsidy, tradable carbon right) is implemented.

Ultimately, continued greenhouse constraints may require ‘zero greenhouse emission’ fossil fuel generation systems. At this stage, given that we are at the start of what might be a very long process, it is possible to imagine a wide variety of configurations that involve zero emissions. All of these require CO_2 sequestration into a suitable storage reservoir, but they vary considerably in terms of approaches to capture. Apart from the ‘add-on’ approaches to capture, a number of schemes that require a process modification have been proposed. Audus et. al. (1998) for example suggest pre-combustion CO_2 removal system in concert with Gas Turbine Combined Cycle.

These suggestions rely on a fossil-only approach. However, hybrid solar-fossil systems that result in no emissions could be also very attractive. Figure 7 is a block diagram showing how such a result could be achieved. This concept integrates a number of supply-side technologies discussed here. Decarbonisation using solar-thermal energy is being demonstrated in a CSIRO project described by Edwards et al. (see this conference). This decarbonisation process will produce clean high pressure CO_2 suitable for sequestration. In Australia, it is likely that the methane needed for this process could be obtained from coal seam gas from deep unmineable coal seams in areas where there is sufficient solar flux to support decarbonisation. Thus CO_2 sequestration could be used to enhance coal bed methane recovery to partly off-set capture and sequestration costs.

Additional benefits of renewables could be captured towards the user-end by augmenting supply-side technologies with distributed renewables technologies such as photovoltaics.

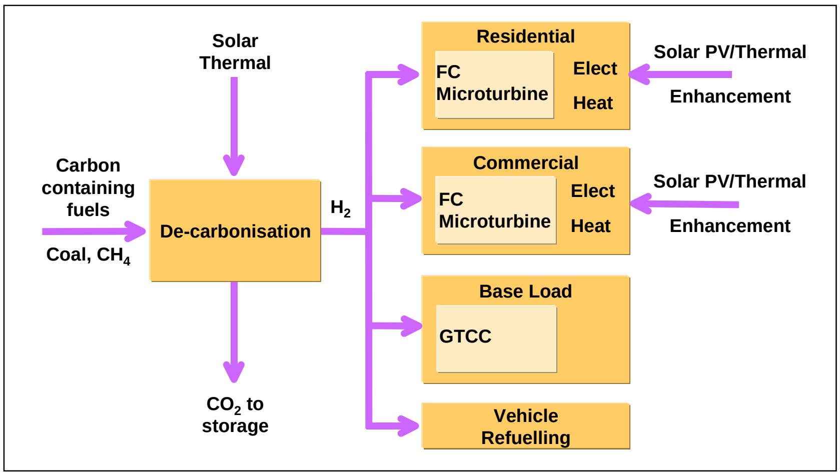


*Figure 7**:** A zero greenhouse gas emission hybrid solar/fossil energy system that integrates technologies across the energy chain.*

FUEL SWITCHING — PROSPECTS FOR RENEWABLES IN AUSTRALIA

Switching from greenhouse gas intensive to less greenhouse gas intensive fuels is a strategy being employed by many within the electricity generation sector. For example several generators in Queensland have plans to convert from coal-fired to gas-fired plant. In the longer term attention is being focussed on renewable forms of energy supply with companies such as Stanwell Corporation (Stanwell Corporation, 2000) arguing that renewable energy sources represent a major business opportunity.

Within Australia renewable energy provides 6% of national energy consumption (ISR 1999, ABARE 1999) and 9.5% of Australia's electricity (Redding 1999; see Table 3 for summary). The Australian Government recently mandated an increase in the contribution of renewable energy to Australia's electricity supply mix to achieve a target of 9,500 GW hours per annum by 2010. This measure is expected to generate at least $2 billion in renewable energy investment in Australia and will be a significant driver for the industry's growth. The Electricity Supply Association of Australia believes that the policy will cost $3–5 billion to implement with an emission reduction of 4–5.5 Mt CO_2 pa. Penalties of $40 per megawatt hour will be imposed on liable parties who fail to meet their purchase obligation.

The potential for renewable energy to meet Australia's Kyoto commitment has been reviewed extensively (Redding 1999). Table 3 summarises the potential for renewable sources as identified in that report. The intention of the study was to provide a basis for estimating the potential contribution renewable energy sources could make to Australia's energy supply during the first Kyoto commitment period. Two indications of potential are given in the table. The first is based on commentary within the report, the second is based on a scenario of a 'feasible' technology mix. For simplicity we have omitted an additional 107 MW of supply from geothermal, and tidal demonstration projects. In addition, we have provided additional commentary on potential constraints to the utilisation of these resources.

Perhaps what emerges most crisply from that study is the poor basis on which existing resource estimates are made. For example CSIRO work consistently reveals the importance of local topographic features in proper siting of wind turbines. Existing standard meteorological data sets are not only an inadequate basis upon which to make commercial decisions but they are probably insufficient for the more specific purpose of assessing national resources for wind energy. A comparable situation is likely to exist for biomass sources. To some extent the paucity of reliable information on potential renewable resources is being addressed by the Sustainable Energy Development Authority in New South Wales, but being a state organisation lacking a national mandate, evaluations of renewable resources that use up-to-date evaluation techniques is still required.

Source	Installed capacity (MW)	Electricity generated (GWh/yr)
Hydro		
Large hydro	7580	16000
Mini hydro	200	700
Biomass		
Bagasse cogen	250	400
Black Liquor	49	90
Other	6	40
Waste		
Landfill gas	80	400
Sewage gas (wastewater)	15	20
Municipal solid waste	0	0
Wind		
Wind main grid	6.81	ne
Wind small grid/diesel	4.05	ne
Wind RAPS	1	2
Solar		
PV grid connect[1]	1.1	0.3
Solar thermal	0.045	0.9
PV RAPS	13	29
Solar Hot Water	190	500
Total	**8395**	**18182**

[1] 1999 estimate used

Table 2: Australian renewable energy sources used in generating electricity (end 1997 for all sources except for wind which is updated) Sources: Redding (2000) and Australian Wind Energy Association (2000).

Biomass

The brief survey of supply-side renewable energy options reveals that in the near term biomass for energy in Australia is highly prospective. One recent study suggests that sufficient biomass could be grown to provide a significant proportion of liquid fuels by the middle of this century but with unknown consequences for the landscape (Foran and Mardon 1999).

The promising future for biomass to provide energy needs to be considered within a social-political context somewhat different from those operating with other sources of fuel. The opportunity in Australia (not necessarily mirrored elsewhere), exists for energy to emerge as a value-added product from a sustainably managed natural resource base. In the best case energy from biomass may assist in paying for a massive landscape remediation bill. The threat is that energy-related demands for biomass add extra pressure on resources further entrenching poor or unsustainable land management practices.

Source	'Absolute' Potential	'Feasible' to 2010	Issues
Hydro			
Major hydro	Limited	114	Major limitation is construction of new dams. Likely opposition on the basis of other environmental considerations.
Small hydro	5-8 projects of 1-3 MW in Qld 36 sites totalling 1000+ MW	102	Interannual variation in steamflow is very significant by world standards. Water resources in many catchments are over-committed
Biomass	300 sites 2000 MW		
Wood waste	23 Mt, to 1500 MW yr^{-1}	202	
Bagasse co-gen	500 MW	227	
Energy crops	Not assessed	42	
Waste			
Municipal solid waste	200 MW	54	Could decline over time through improved waste reduction strategies
Land fill gas	150 MW	77	Resource already extensively exploited
Wet wastes agriculture and food processing	200 MW	12	Assumes 50 MW from piggeries another 50 MW from cattle feedlots
Municipal wastewater	50 MW	54	Outer boundary estimate for 2010.
Wind	'Ample'	433	Poorly quantified nationally notwithstanding studies conducted through the 1970s and 1980s.
Wind RAPS		4	Technology dependent
Solar			
PV rooftop & RAPS	300 MW	87	'Absolute' estimate assumes PV on all new houses in 2010
PV grid-connect	?	73	
Solar thermal	Not assessed	192	Study estimate was not based on availability of resource, but cost of utilisation.
Solar hot water	?	413	Mature technology further uptake unlikely without change in costs

Table 3 Summary of Australia's major renewable energy resources. Data source from Redding Energy management (1999) except where otherwise indicated.

In the Australian context a plethora of issues will need to be resolved before biomass can be used for energy supply:

- Maintenance of the soil base including ability to ameliorate or exacerbate salinisation, and maintaining adequate soil nutrient status
- Fertilisation requirements and silvicultural treatments of tree-crops
- Tree/crop selection
- Water resource requirements
- Biodiversity
- Sustainable yield considerations
- Potentially competing land-uses
- Integration with other agricultural commodities within the value chain.

In South-west Western Australia, for example, the widespread planting of mallee eucalypts, primarily to stabilise salinisation resulting from rising water tables might be integrated with a number of forest products, including energy (Shea et al. 1999).

In summary, while renewable sources of energy are going to increase in importance over the long term, they are only part of the answer, with technology gaps still evident in many areas. In the short term, particularly over the next decade, some very major actions will have to be undertaken if Australia is to get anywhere near its Kyoto target. With major initiatives in relation to renewables in place we will need to look more closely at sequestration and demand-side efficiency measures.

END USE EFFICIENCY

As has been pointed out by Hawken et al. (1999) energy efficiency and energy conservation are very attractive from a sustainability perspective. Efficiency at the user-end of the energy chain can potentially produce a 'win-win' where potentially cost-effective technologies can provide a market edge to innovative companies and reduce greenhouse gas emissions with few of the other environmentally problematic issues requiring attention.

CSIRO's approach to the development of energy efficient technologies on the demand-side is to link directly with the industry sectors closest to the potential market. This means that there is not a self-standing 'energy-efficiency' portfolio, instead research projects are tuned to meet individual industry's needs.

In the minerals industry for example research is being directed to more efficient grinding (comminution) where only about 1% of the energy input results in smaller particle size. The extensive use of electric motors in the minerals and metals processing industries is another source of potentially significant emissions. Strategies to replace existing motors with higher efficiency units are potentially attractive.

In the building and construction sector technological innovations that improve end-use efficiency are many and varied. Within its own research portfolio CSIRO is investigating:

- Energy-smart windows and facades
- New forms of concrete that require less energy to make, utilise microwave curing, or reabsorb CO_2 during the lifetime of the product
- Software tools for evaluating energy embodied within building and construction materials
- Smart switches that monitor appliances within a building envelope, detect when the appliances are not being used and put them in rest mode
- High efficiency pulse-combustion.

About 17% of Australia's greenhouse gas emissions arise from transport (AGO 2000a). In this sector CSIRO has been involved in the development of two all Australian hybrid electric vehicles.

One of these cars, the showcase aXcessaustralia Car, uses a number of innovative technologies including: 'double impact' lead acid batteries, super capacitors, a specially designed on-board energy management system and an electric traction motor with a new "switched reluctance" technology (http://www.axcessaustralia.com/). It is estimated that a 'typical' hybrid electric vehicle emits about 2 tonnes CO_2 equivalent per annum on a lifecycle basis. This is about a 66% reduction compared with the average Australian passenger vehicle (Beer 2000). The aXcessaustralia vehicle is designed to accommodate fuel cell technology when available. Low emission vehicles will not assist problems of congestion, so the organisation is also developing tools and techniques such as intelligent transport systems to assist urban planners.

This very brief overview of some of the demand-side technologies that are under development in one organisation is illustrative of the technological opportunities that exist to improve demand-side energy efficiency and to reduce greenhouse gas emissions. In order to substantively contribute to sustainability, these ideas need to find more rapid routes to market. Part of the solution is the innovative integration of technological advances into re-engineered products such as those described by Hawkin et al. (2000) and exemplified by the new concept vehicles. But more prosaic barriers still exist. Barriers including lack of knowledge within the market, the landlord/tenant problem and market distortions need to be addressed.

As far as greenhouse is concerned at the user end we do not see the polluter pays principle in operation, unless there are local air quality concerns that add costs to fossil fuels. In fact the market is asked to pay *extra* through 'greenpower' schemes that enable consumers to buy 'green' (greenhouse friendly) energy, presumably off-setting some of the additional costs of electricity generated from these sources. On the other hand generous subsidies exist for renewable remote area power supplies and for household photovoltaic systems. It will be necessary to harmonise technological developments with policy if end-use efficiency is to fulfil its potential within a sustainable energy system.

CONCLUSION

A genuinely sustainable energy system is a major challenge. At the global scale the prospect of climate change imposes a major long term constraint on the use of fossil fuels.

Development of a sustainable energy system for a country like Australia will require multiple interventions and a pluralistic approach to national energy management. Ingredients within the mix are likely to require:

- continued integration and greater penetration of renewables
- greater use of embedded and distributed energy generation
- aggressive end-use efficiency
- development of technologies to enable continued use of fossil fuels until the transition to sustainability is completed.

A combination of market and regulatory measures is likely to force this change.

ACKNOWLEDGMENT

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