



**Beyond 2025:
Transitions to a
Biomass-Alcohol
Economy Using
Ethanol and Methanol**

**Barney Foran and
Chris Mardon**

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**CSIRO Wildlife and Ecology, GPO Box 284, Canberra ACT 2601
AUSTRALIA**

Beyond 2025: Transitions to the biomass-alcohol economy using ethanol and methanol

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Foreword

This research report was developed in response to a request from the Land and Water Resources Research and Development Corporation that the CSIRO Resource Futures Program prepare a discussion report on 'biomass opportunities for fuel generation and recharge reduction'.

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Executive summary

- 1 In the context of national environmental policy, it is generally recognised that the function of Australia's farmed landscapes requires policy attention and large-scale remediation. Diverse sources note that by 2020, between 10 million and 40 million hectares of more-intensively used land may have declining function because of the combined problems of dryland salinity, soil acidification, nutrient and structural depletion and fragmentation of biodiversity resources. This report explores scenarios that envisage replacing large areas of cropping and pasture lands with perennial deep-rooted production systems which help halt, and then reverse, the dryland salinity challenge. The rationale for such an undertaking is to facilitate the transition from the hydrocarbon economy to the carbohydrate economy by using biomass to produce ethanol and methanol as replacements for traditional oil-based fuels and feedstocks.
- 2 The control of dryland salinity and associated problems of landscape function pose an immense challenge for monetary investment and physical action. The scale of the problem will require action over one to four human generations, or 25 to 100 years. In implementing a biomass-based economy this study provides wider rationales for the solution of the problem, rather than just the refurbishment and rehabilitation of broadscale landscape function. The first of these is to present a new industry which requires deep rooted plants, large areas and which has the ability to attract investment and produce employment and prosperity for rural Australia. The second is to prepare in advance for the possible constraints to national production and prosperity posed by a run down in Australia's domestic stocks of oil. The transition to a biomass-alcohol economy is able to link these seemingly separate future issues.
- 3 Australia relies heavily on transport services and petroleum fuels that maintain its far-flung economy. Within the next human generation the domestic stocks of traditional oil may become constrained, the shortfall having to be sourced from imports, thereby contributing to an increasing import bill and additional balance of payments tensions. There are a number of domestic energy sources which could meet this shortfall. These sources include natural gas condensate, liquefied natural gas, oil from oil shale deposits and liquid fuels from biomass.
- 4 Many developed economies in Europe and North America are investing heavily in the research and development needed to underpin the transition towards renewable forms of energy, including biomass fuels. The strategic reasons are: biomass-based energy sources for heat, electricity and transportation fuels are potentially carbon neutral, that is, they recycle the same carbon molecules; domestically sourced energy reduces reliance on imports which might be affected by market and political instability; biomass-based fuel cycles potentially employ more people than fossil-fuel based cycles.
- 5 Australia's farmed landscapes, the industries sourced from them and the regional economies that depend on them require deep-rooted perennial crops to help mimic the function of ecosystems that are now gone or non-functional. The key physical attributes needed from these systems are such that they halt the leakage of water and nutrients which now contribute towards dryland salinity and soil acidification. Tree and shrub crops, many of them Australian native plants, are potentially suitable for this task. Supplying biomass fuels and carbohydrate feedstocks may provide a strong economic, political and market rationale, one human generation from now, when Australia's domestic oil stocks may be constrained.
- 6 In the international and Australian context there are two biomass based liquid transportation fuels that might replace petrol. These are ethanol and methanol. Bio-diesel is also a well-

developed technology. Ethanol is viewed in North America, Brazil and Australia as a more useable fuel that can be readily blended with petrol, used as an octane enhancer and even as a 100% replacement for petrol with suitable engine modifications. Methanol appears to be the substitution fuel of choice in Europe, particularly for new generation cars powered by fuel cells. Methanol is more toxic, acidic and corrosive than ethanol, it requires larger fuel tanks per unit of energy, but is still amenable to 100% replacement of petrol with appropriate engine technology. Current commercially available cars (flexible fuel vehicle or FFVs) in the United States have sensing technology which adjusts engine tuning and performance to the fuel in the tank (petrol, ethanol, methanol and blends), so future vehicle fleets need not be disadvantaged by the regional availability of different fuel types.

- 7 The ethanol process is produced by biologically catalysed reactions (fermentation) after pre-processing with dilute acid solutions (hydrolysis) which make five carbon sugars (pentoses) and six carbon sugars (hexoses) more available to the fermenting organisms. A wide variety of feedstocks can be used, including grains, whole crops, wastes and woody materials. The yield (in terms pure ethanol yielded per 100 kg of dry feedstock) varies from 40 kg for high sugar crops (sugar cane, sugar beet and sweet sorghum) to 25 kg for waste streams (bagasse, newspapers and processing waste) to 16 kg for woody materials. A commercially sized ethanol from wood plant producing 50 million litres per year is expected to require a capital investment of \$50 million to \$70 million per plant and 200,000 to 300,000 dry tonnes of feedstock per year supplied from a 30 km to 40 km radius of the plant. Commercial developments currently under way in Australia promise the possibility of a step change in the process efficiency of the ethanol production system. In particular two parts of the process, the concentrated acid hydrolysis of the feedstock to liberate sugars for fermentation, and the acid-alcohol separation and subsequent acid recycling, have received US patents and are being integrated into a pilot production plant.
- 8 Methanol is manufactured primarily by thermal processes where biomass is gasified to a synthesis gas, and the carbon monoxide and hydrogen in the synthesis gas are reacted over a catalyst to form methanol. Much commercial methanol is also sourced from natural gas in very large industrial-scale plants. The yield from the woody biomass process is 40% (400 kg of methanol per 1000 kg of dry wood) and should soon increase to 50% with process development. The methanol process can be undertaken in smaller-sized modules which may suit small business scales. These modules can be transported between sites, thus reducing the biomass transport component inherent in a large centralised plant if the source of feedstock becomes more remote.
- 9 Simulation experiments with the OzEcco embodied energy modelling framework showed that a transition to an ethanol transport fuels system is feasible. By the year 2020, an ethanol fuels industry could replace traditional oil-based hydrocarbon fuels for transport and could generate around 160,000 direct jobs, most of them in rural Australia. By 2050, it could reduce carbon dioxide emissions by more than 300 million tonnes per annum. If feedstocks not digested in the ethanol process were used to cogenerate electricity, then the carbon dioxide reductions could total 500 million tonnes per annum compared to the base case. Other advantages include a reduction in the fossil energy intensity of gross domestic product (GDP), expressed as megajoules of fossil energy required to generate a constant dollar, and considerable reductions in hydrocarbon imports with subsequent advantages in the visible balance of payments account. However, there are some areas of concern arising out of the simulation experiments. These are driven in turn by the initial assumptions used in the studies. Since crop biomass is assumed to make up 50% of the biomass feedstock for the production chain, the large tonnages required drive up the energy inputs to the agriculture and forestry sector by a factor of six times compared to the base case. The energy ratio for the whole ethanol

production system declines from 6:1 initially to between 2:1 and 3:1 (two to three times the output of useable energy per unit of energy input to the production system). More detailed work on modelling the biomass production system in the model might improve these outcomes, but the results accord with the published literature internationally.

- 10 Similar simulation experiments for a transition to a methanol transport fuel system in Australia gave superior results due mainly to the assumption of a superior yield of dry wood to methanol on a weight for weight basis (compared to the ethanol production system). The methanol system reduced carbon dioxide emissions by between 200 million and 500 million tonnes per annum, depending on whether the experiment produced methanol alone, or electricity by cogeneration in addition. There was a substantial change over time in the energy intensity of GDP and by 2050 it reduced to one-quarter the level of the base case (2 MJ of fossil energy per constant dollar compared to 8 MJ per constant dollar in the base case and 6 MJ per constant dollar for ethanol). Up to 400,000 direct jobs were stimulated by the methanol fuels system by 2050. The energy ratio (output versus input on a system-wide basis) varied from 4:1 to 5:1, almost double that of the ethanol fuel system. One radical version of the methanol system managed to decrease carbon dioxide emission back to 1990 levels by 2050, but it also decreased physical measures of per capita affluence and reduced rates of yearly growth in GDP.
- 11 The land required for a managed perennial tree and shrub production system varied from 12 million to 31 million hectares, depending on the particular set of simulations undertaken. These are large areas of land and were assumed to come from the higher-rainfall pasture lands, and from croplands requiring rehabilitation due to dryland salinity, soil acidification and general problems of depletion. Although these are large areas in an immediate policy sense, the transition process is a steady one over long time scales. The areas required are within the land stocks and rainfall zones representing Australia's more intensively farmed zones. Simplifying assumptions of a 20-year rotation with a 20 m³ per hectare mean annual increment (ie 400 m³ of wood per hectare after 20 years), drove the gross demand for biomass plantation area noted above. These assumptions are consistent with a range of current studies on carbon sequestration and carbon trading.
- 12 12 As well as providing a source of liquid fuels for Australia's transportation systems, the development of biomass farming allows Australia to progress from the hydrocarbon economy to the carbohydrate economy where feedstock for chemicals and plastics is also derived from biomass rather than petroleum. A common characteristic for integrated bio-refineries is that ethanol is just one of a number of valuable co-products produced. The range of co-products would include chemicals, lubricants, solvents, plastics, paints, building materials and a range of starch and protein by-products. Gaining a foothold in the practice and the knowledge required for this new form of energy agriculture or the green chemistry of the future, could allow Australia to leap-frog many of its international competitors and gain market position and market advantage. The mallee oil developments under way in the Western Australian wheatbelt show the way ahead for these next-generation agricultural industries.
- 13 As well as helping the Australian economy meet some long-term strategies through energy self sufficiency and import replacement, the biomass-based alcohol fuel transition over the next 25 to 50 years could be expected to stimulate many opportunities for employment, mainly in regional and rural Australia. Replacement of today's 1000 PJ of petroleum consumption with alcohol fuels, could provide 50 long-term jobs in each of 1000 to 1600 local alcohol production units (50,000 jobs nationally), and four to five times that number (200,000 jobs) to grow and deliver biomass and to service these primary activities. The

construction and maintenance of the biomass fuel system, phased in over the next 25 to 50 years, would ensure many more jobs in construction and engineering sectors as well as revitalising Australia's light industry base. The transport of Australia's biomass-alcohol fuels from country to city could stimulate a revival in transport infrastructure and services in rural and regional Australia, especially in rail services.

- 14 Current economic assessments based on price alone do not make a compelling case for a transition to a biomass fuelled economy. Step changes are possible in the efficiency of use for both transport fuels and electricity by applying technologies and management methods currently available off the shelf. The overall efficiency of coal fired thermal electricity plant is still below advanced technologies that are currently available. Coal in Victoria and southern Queensland is relatively low in sulphur and cost approximately \$0.5 per GJ. The opportunity cost of woodchips for export is \$164 per tonne dry weight or \$8.3 per GJ, or 16 times the cost of coal. Ethanol or methanol with a future production cost of \$0.8 to \$1 per litre is still four times more expensive than unleaded petrol before excise and taxes. Much of the rationale for the transition to a biomass will therefore not rest on simple price arguments. Instead issues such as new industries for the twenty first century, jobs for rural Australia, productive refurbishment of farmed landscapes, carbon neutral fuel cycles and import replacement of transport fuels will form a richer and more complex suite of rationales.
- 15 The future of petroleum industries, transport technologies and the alcohol fuel systems cannot be predicted with assurance in the 25 year to 50 year time frames used in this analysis. New forms of vehicle transportation systems based on fuel cells could stabilise, and then reduce, Australia's overall requirement for domestic transportation fuels. However, those developments seek to use ethanol, methanol and hydrogen to help meet global greenhouse requirements and city air pollution challenges. Australia might find new oilfields and thereby delay the economic and trade-balance imperative to move to new fuel systems. At the same time, technological developments within the science of alcohol fuel production promise substantial increases in the process efficiencies and potential cost decreases. Whatever the fallout between these issues, Australia's farmed landscapes will still be seeking and requiring, deep-rooted perennial cropping systems to help redress the problems of landscape damage caused by the land clearance and annual cropping systems developed over the past 150 years.
- 16 The choice of alcohol fuel produced by the biomass-alcohol system is the subject of increasing debate particularly in the United States. The future of methanol, particularly MTBE the octane enhancer derived from methanol, is under increasing scrutiny following evidence of ground water contamination by MTBE in California. The Governor of California has issued a regulation calling for a total ban on the use of MTBE by 2002 and other US states are considering similar legislation. The degree to which the combustion of ethanol and methanol in appropriately engineered and tuned cars contributes to air, land and water contamination, now and in the future, is beyond the scope of this report. Both alcohol fuels should be closely examined in relation to a range of key environmental issues and also compared to the current fossil fuel transport cycle.
- 17 Biomass-based alcohol fuel systems are not yet proven to be ecologically sustainable. It would be a mistake to impose short rotation woody cropping systems on Australian farmed landscapes on vast scales without addressing the issue of long-term sustainability. There are four issues with which to contend. The retention of branches and leaves is probably necessary to ensure nutrient recycling and maintenance of soil organisms. Large-scale tree and shrub plantings may dry up overland flow from catchments, further affecting our challenged inland river systems and restricting water flows for our irrigation industries. The use of productive biomass systems that are exotic, regionally or nationally, could further reduce the function of

native ecosystems and further depress survival and resilience of native plants and animal communities. Finally these initial analyses should be viewed as a guide to further work needed, rather than the final answer. The analytical approach is, by nature and design, broadscale, approximate and ignores much of the detail that is important at the fine scale of how society, governance, markets, real people and real landscapes function. More detailed investigations are required to explore the many unknowns highlighted in this study.

Chapter 1

Biomass fuels from a world perspective

‘What is certain, however, is that fossil fuels will face ever increasing competition from renewable energy. I believe that over time, surpluses will arise and we may – ultimately – leave oil and gas in the ground – as we are leaving most of the coal in the ground.’

Heinz Rothermund, Managing Director

Shell UK Exploration and Production

20 May 1997, Glasgow

ABSTRACT

A number of drivers operating on long time-scales and from regional to global scales are suggesting the possibility of a paradigm shift in how energy supplies, so crucial to the functioning of societies and economies, will be sourced and delivered. The drivers are a unique combination of threats and opportunities. The threats are obvious and are usually highlighted by the environmentally concerned and aware part of society. They include depletion of oil supplies, concern about greenhouse gas emissions and possible global warming, and the challenges posed by the inequitable distribution of economic production within and among countries. The opportunity part of the shift is built on the possibility of a carbohydrate economy. In this economy a lot of transportation fuels, heat, electricity, chemical feedstocks and commodity products would come from plant or biomass resources. This opening chapter brings together some of the relatively new directions in technology, land use and energy supply that might form the basis for the carbohydrate economy as the transition is, or might be, made over the next 100 or more years.

OVERVIEW OF THE CONTEXT OF BIOFUELS

The business and political climate

The views of economic writers, market analysts and business leaders towards global greenhouse gas emissions, the prospect of global warming and the contributions that fossil fuels make to these issues, are changing. Robinson (1999) notes that on Wall Street markets ‘the renewable-energy growth stocks are outperforming the fossil fuels groups for good reasons...they are facing monumental litigation...New York State has just launched a massive lawsuit against 17 coal-burning plants in upwind states citing pollution and the failure to update their emission control systems’.

Major multinational energy companies are now promoting views that respond to the question ‘how far it is sensible to explore for and develop new hydrocarbon reserves given that the atmosphere may not be able to cope with the greenhouse gases that will emanate from the utilisation of the hydrocarbon reserves discovered already’ (Rothermund, 1997a). These views also note the ‘renewables could provide half of the world’s energy by 2060’. This scenario is now part of a company catch-cry: the ‘50-50 Vision, that is ‘that by 2050, 50% of world energy will be supplied by renewables’ (Rothermund, 1997b).

There are immense barriers to implementing these visions, many of which are embodied in the layers of the institutions that maintain the modern economy. Rosch and Kaltschmitt (1999) note that the impediments lie in five key areas: difficulties with funding, financing and insuring; unfavourable administrative conditions; organisational difficulties; lack of knowledge or adequate flow of information; and insufficient perception and acceptance. Faced with these institutional barriers and the considerable technical difficulties still to be surmounted, a crisis may be required to provoke community and political action.

The carbohydrate economy

Many writers see that we are now at the beginning of the transition from the hydrocarbon economy (or more specifically fossil fuel economy) to the carbohydrate economy. Lynd et al. (1999) make the point that 'biocommodity engineering is the application of biotechnology to the production of commodity products and offers huge benefits in terms of sustainable resource supply and environmental quality...and is the only foreseeable source of organic fuels, chemicals and materials'. They also note that 'multi-product and integrating refineries which produce fuels, chemicals, power and feed will be essential for the viability of economic systems and will need to be integrated into the broader resource, economic and environmental systems in which they operate'. Some authors, for example Okkerse and van Bekkum (1999), claim that the world as a whole will have to move to a plant-based economic and social system just to survive past the year 2050. They also note that land area may be limiting and that the socioeconomic implications for achieving this transition are immense. Other authors, for example Morris and Ahmed (1998), claim that the carbohydrate economy is the way to solve both the environmental crisis and the farm crisis in the United States. Morris uses the symbolism of current activity and technology in the ethanol industry as 'the runway from which to launch the carbohydrate economy' and further notes that 'the challenge now is to move plant matter derived products from the margin of the economy to its centre'.

Carbon-neutral fuel cycles

The main advantage of a biomass-based fuel cycle is that it has the potential to recycle the same carbon molecules and thus reduce the emissions of carbon dioxide into the atmosphere. Examples of biomass-based transportation cycles which reduce carbon dioxide emissions in comparison to a gasoline fuel cycle include: ethanol from corn (-16%), ethanol from biomass (-76%), and methanol from wood (-66%) (International Energy Agency, 1998). The process of accumulating carbon molecules to transform into a biofuel such as ethanol or methanol can be understood in a pine forest under a 28-year rotation cycle. A total of 230 tonnes of carbon per hectare is accumulated by photosynthesis over the 28 years and 115 tonnes is located in the logs harvested at the end of the management cycle. The remaining 115 tonnes of carbon remains on site after harvest and oxidises over time. This stored carbon in the logs is released again during the process of making and then using the biofuel.

Developing a carbon-neutral fuel cycle is a complex process and to date has been seen as too costly in dollar terms and too inefficient in useful energy output, compared to transportation fuels from the highly developed and highly integrated fossil fuel and petrochemical industry. Grado and Chandra (1998) have evaluated a fully integrated ethanol fuels system using biomass where the production cost was US\$0.45 per litre of ethanol. In a sensitivity analysis of the important determinants of final price per litre, Grado and Chandra found that the ethanol yield from feedstock accounted for 44% of total variability of final cost, the capability of harvesting equipment accounted for 37% and the plantation yield accounted for 9%. Analyses such as these emphasise the requirement for critical breakthroughs in processing technology before carbon neutral fuel cycles can compete on cost and dependability. However, taxes on emitted carbon, as currently levied in some European countries,

could make the carbon-neutral fuels equally cost competitive to current liquid fuels from fossil sources.

Industrial systems in place

The Brazilian ethanol-from-sugar cane system produces 15 billion litres of ethanol each year saving 250,000 barrels of oil imports per day. There are 339 distilleries providing 700,000 jobs and each production system, producing 50 million litres of ethanol per year, is responsible for more than 2000 jobs. These are much lower paid jobs than in Australia, but this picture provides some idea of the scale of the enterprise. A total of 220 million tonnes of sugar cane is grown each year in Brazil and 65% or 175 million tonnes is used to produce sugar cane. The sugar cane productivity is 65 tonnes per hectare for an average of 5000 litres of ethanol per hectare, which, at US\$0.45 per litre, gives returns of US\$2250 per hectare. Over the whole production system a capital cost of US\$20,000 was required to make one job.

The ethanol-from-corn system in the United States produces 5.3 billion litres of ethanol from 550 million bushels of grain. There are 51 ethanol plants in 19 states and five more are being built. Canada has six ethanol plants and produces 201 million litres per year. A detailed life cycle analysis (Shapouri et al., 1995) shows that the ethanol-from-corn system is not particularly defensible from an energy yield point of view. The net energy ratio is estimated to be 1.24; that is, for every unit of fossil energy input over the whole production system, 1.24 units of useful ethanol energy are produced. The authors of this report go on to argue that 'ethanol production utilises abundant domestic energy supplies of coal and natural gas to convert corn into a premium liquid fuel that can extend petroleum imports by a factor of 7 to 1'. Other authors report a net energy ratio of 1.38:1 for an average-efficiency corn farm, rising to 2.5:1 for state-of-the-art practices, while cellulosic crops based on current data would have a net energy ratio of 2.62:1 (Lorenz & Morris, 1995). A more detailed life cycle analysis of a soybean-to-biodiesel process for urban buses produced an energy ratio of 3.2 which reduced carbon dioxide emissions by 78% compared to petroleum diesel (Sheehan et al., 1998). The modelling simulations reported in chapter 5 achieve a net energy ratio of 2:1 for ethanol production using biomass as a feedstock, so the modelling results lie within the correct order of magnitude.

A new ethanol-from-biomass plant is being constructed by BC International in Jennings, Louisiana, United States (United States Department of Energy, 1999). This is the first industrial-scale plant of the biomass-to-ethanol process and uses the genetically engineered strain of the organism *Escherichia coli* developed by the University of Florida. The feedstock for the plant is derived from sugar cane residues, rice hulls, forestry and wood waste and other organic materials. The plant costs US\$90 million and produces 25 million gallons of ethanol per year, displacing 500,000 barrels of oil imports annually, creating 350 jobs during the construction phase and 50 full-time jobs for full-time operation. Numerous other smaller ethanol projects are under way in the United States using crop residue, processing waste and domestic refuse. One of the key rationales, particularly close to urban communities, is that the digestion process is a more societally acceptable way of disposing of waste which to date has been burnt or disposed of as landfill.

From a historical context it is interesting to note that in 1935 over 439 million litres of ethanol were used in Europe alone, but that after 1945 ethanol was replaced by petrol or diesel produced by the petrochemical industry (Classen et al., 1999).

Scenarios for the future

A number of wide-reaching scenario studies including biomass fuels have been conducted as part of designing future options for delivering world energy and limiting greenhouse gas emissions.

Leemans et al. (1996) concluded that 796 million hectares were required for biomass production and that this would have significant effects on agricultural food production and biodiversity values. They also noted that the effectiveness in reducing greenhouse gas emissions would have to be evaluated in combination with many other environmental, land use and socioeconomic factors. By 2050 in their main scenario analyses (LESS B1), biomass energy was supplying 181 exajoules (10^{18}) of a world total of 574 exajoules (that is, 14%) and by 2100 the contribution had risen to nearly 50%. The carbon dioxide emissions from energy use had declined by 30% in 2050 and by 60% in 2100 compared to 1990 levels. Similar studies by the International Institute for Applied Systems Analysis and the World Energy Council (Nakicenovic et al., 1998) suggested a source of potential land use conflict between food production and biomass land requirements of 610 million hectares in 2050 and 1350 million hectares in the year 2100. The energy productivity of biomass land in these later studies was assumed to be 6 tonnes of oil equivalent per hectare per year by 2050 and 10 tonnes per hectare per year by 2100.

A study by Gielen et al. (1998), which focused on continental Europe using the MARKAL MATTER modelling framework, assessed the possible competition in the use of biomass resources both for energy and material uses. The feasible operation of their scenarios required 22 million hectares of high-yielding crops (eucalyptus, sweet sorghum, miscanthus and poplar) to supply both bioethanol and petrochemical feedstocks. A key tension highlighted in the analysis was the availability of land for biomass production with production targets of 400 to 800 million dry tonnes of biomass per year. The total biomass production per hectare was assumed to be approximately 10 tonnes of dry matter per hectare per year for crops (miscanthus, wheat, poplar and rape) to 23 tonnes per hectare per year for eucalyptus.

A wide range of studies has been undertaken on biomass energy in Sweden where Johansson and Lundqvist (1999) note that the current gross felling of forest has an energy value of 860 PJ per year. They note that Sweden has 2.8 million hectares of arable land, of which 2 million is regarded as essential for food and fodder production, leaving 0.8 million hectares potentially available for biomass energy production. Borjesson (1999), assessing the use of short rotation Salix forest and reed canary grass, noted a wide range of environmental benefits that might flow from converting land from traditional agricultural usage to energy crops. These include decreased water and wind erosion from perennial crop cover, the ability to treat sewage sludge and waste water, the augmentation of biodiversity habitat and the increased banking of below-ground carbon in the energy crop systems.

National economic agenda

The international literature notes a number of benefits in biomass energy systems for the national economy in a more holistic sense. The case of ethanol production from sugar cane in Brazil is a well-documented example. Moreira and Goldemberg (1999) report that US\$12.3 billion has been invested in the program in the 15 years 1975 to 1989. Some 174 million cubic metres of ethanol have been produced, displacing the consumption of 141 million cubic metres of gasoline. This has saved US\$33 billion of hard currency in fuel imports, which could have risen to US\$50 billion if interest rates had been included. This represents 85% of the current reserves in hard currency and 50% of the total government secured external debt. The total annual saving for the country has been US\$4.9 billion and ethanol production can be viewed as an effective mechanism to use soft money to control international debt. In addition, the program has created more than 700,000 rural jobs with a modest investment cost of US\$20,000 for each job, whereas petrochemical projects in the same region are referenced as costing 20 times more per job to implement.

Being self sufficient in strategic areas such as transportation fuels is an important national policy issue according to Lugar and Woolsey (1999), who note that 'America's addiction to middle eastern

oil forces dangerous foreign policy compromises, worsens global warming and strengthens unreliable Persian Gulf countries'. The Renewable Fuels Association in the United States reports that its industry will provide a net saving to the Federal Treasury of US\$4 billion over the next seven years, create US\$60 billion of final demand in the economy, support 55,000 jobs annually, generate more than US\$15 billion in farm income and reduce the merchandise trade deficit by US\$2 billion a year (Urbanchuk, 1996). Sims (1998) reported that 'even densely populated Europe has a land surplus of 50 million hectares which could be used to grow energy crops to meet 30–40% of the demand'. He noted that 'in Bavaria alone over 18,000 jobs use biomass as an energy resource and that 4–5 times more labour is required using bioenergy than when using fossil fuel energy carriers'.

Issues of sustainability

A wide range of sustainability issues relating to the implementation of bioenergy systems at the scale required to provide sound practical and economic alternatives to the fossil fuel system, remain unresolved. Kimmins (1997) suggests that a 'key issue in sustainability is the retention of foliage and branches on site at the time of harvest...although this material is potential bioenergy, on many sites it should be left to supply soil organisms with an energy source and to supply nutrients'. Evans (1997) suggested four key issues around sustainability as follows: the failure to conserve organic matter between rotations; the physical damage to the site during harvesting; weed problems; and nutrient depletion. He suggested that coppiced systems were particularly prone to these four problems. On the positive side, he noted that many silvicultural systems improved site productivity through drainage and rectification of nutrient imbalances and that tree selection and breeding had much to offer because 'compared to crop plants the great bulk of forest crops still consist of unselected material from wild populations'.

The cumulative effects literature (Boyle et al., 1997) notes that large-scale perturbations to the current systems such as that proposed by large-scale biomass energy plantation will have effects that: tend to accumulate incrementally; may combine with other effects through space and time; and can result from dissociated and unrelated activities of various land owners. Boyle et al. note the importance for each watershed of integrating the possible effect of the location of road corridors (effects on water flows, sediments, stream habitats, spread of diseases), with the felling and delimiting of trees (plant succession, altered composition of vegetation, new organisms and weeds), with hydrogeologic processes and overall forest management practices.

Finally all biomass-alcohol production systems require a constant source of process water which could be reallocated from agricultural usage. More importantly the conversion of cropland and grassland to forest will have profound effects on the hydrological cycle (Vertessy and Bessard, 1999). It is possible that streamflow from forests in areas with less than 600 mm per year will be negligible since mean annual evapotranspiration is usually less than 650 mm in grasslands, but more than 1300 mm in forests.

Future developments

The literature survey of international developments noted two key areas of importance to the potential of future biomass energy systems. These are the technological developments in the production of both ethanol and methanol which promise significant improvements in yield and improved development of plant production systems which could double the biomass yield per unit area and develop species selection procedures which allow designer ecosystems to be implemented for each soil type, water catchment and farming zone.

The development of ethanol production systems relies on making biomass depolymerisation more rapid and less costly (Himmell et al., 1999) through 'directed evolution' of microorganisms to develop industrially hardened strains, able to perform at higher temperatures and without suffering toxicity problems. The evolution of these new fermentation technologies aims to produce not only alcohols but a wide range of commodity products which are currently sourced from crude oil and its derivatives. As well as maximisation of the conversion of cellulose and hemicellulose to sugars for subsequent fermentation, a large technological barrier has existed to the ethanolic conversion of pentoses, the five carbon sugars, (Ogier et al., 1999). Only recently has a University of Florida team used genetic engineering to combine two genes into a 'portable ethanol production cassette' (Ingram et al., 1999). This cassette has been integrated into the chromosome of *Escherichia coli B* to give a strain, KO11, which produces ethanol efficiently from the hexose and pentose sugars present in the polymers of hemicellulose. Ingram et al. (1999) further note that 'many opportunities remain for the further improvements in these biocatalysts as we proceed toward the development of single organisms that can be used for the efficient fermentation of both hemicellulosic and cellulosic substrates'.

The methanol conversion process is already a well-developed and efficient process but work continues to improve its yield from 40% on a weight-for-weight basis to 50% or more. Hybrid processes such as the HYNOL process (Dong and Steinberg, 1997) combine hydrogasification of biomass and the introduction of a natural gas feedstock, avoiding the need for an expensive oxygen plant and delivering a capital cost of methanol plant considerably cheaper than conventional designs, and an overall methanol cost that is competitive with current United States gasoline prices.

Biomass production systems are still centred on optimising yield from well-known crop and tree plants. Thus late maturing sweet sorghum genotypes are becoming available that are capable of producing 6000 litres of ethanol per hectare (Dolciotti et al., 1998). These genotypes yield between 20 and 27 tonnes per hectare dry weight per year, have three times the sucrose content and have cellulose and lignin contents 40% to 50% lower than standard varieties. Applied in a broad brush manner, this productivity provides sufficient ethanol to run three Australian family sedans for one year, that is, 4 million hectares would support the current Australian private vehicle fleet. This ethanol productivity is similar to the sugar cane system developed over the past 25 years in Brazil where the mean yield is now more than 5000 litres per hectare. Dryland farming in Australia will not be able to match these forage productivities over large areas, but they provide insight into practical production systems that are possible.

New Zealand tests of coppiced eucalypt plantations in a temperate environment, planted at the equivalent of 2200 stems per hectare, were conducted over a 15-year period and gave mean annual yield that varied from 12 to 34 oven-dry tonnes per hectare per year, depending on the species and management regime (Sims et al., 1999). A limited number of eucalypt species from the trial yielded in excess of 16 tonnes per hectare per year (for example, *E. brookerana*, *E. ovata*, *E. botryoides* X *saligna*, *E. botryoides*, *E. obliqua* and *E. elata*).

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Chapter 2

Biomass fuels from an Australian perspective

‘With the uncertainties that surround the many alternative solutions for the coming shortage of oil, it would be prudent to keep open all options on liquid fuels for transport as the lead time for research, development and substantial implementation of new alternatives are at least 10 to 20 years.’

Alan Stewart et al.

in the 1979 CSIRO publication

The Potential for Liquid Fuels from Agriculture and Forestry in Australia.

ABSTRACT

This chapter presents a brief overview of some key Australian studies and activities that relate to the past and recent history of biofuel production in Australia. A wide-reaching set of CSIRO studies in the late 1970s by Alan Stewart and colleagues reminds us that this is not a new issue. Part of the report relating to global warming issues shows that the team was well ahead of its time. There is a considerable amount of activity by the Fuel Ethanol Association of Australia which represents a diverse group of industry partners, university departments and regional communities. Separate in a spatial sense, but related in the context of perennial vegetation cover on landscapes, are the oil mallee developments in Western Australia. These diverse and seemingly separate developments form an important grounding for the analytical chapters that follow.

OVERVIEW

Natural resources at a national scale

A soon to be released national report charts the scale of landscape challenges in Australia through the following issues (table 2.1):

- 24 million hectares of Australia’s land are affected by soil acidification and possibly a total of 43 million hectares will be in the future;
- 2.5 million hectares are affected by dryland salinity and possibly a total of 15 million hectares will be in the future;
- 3 million hectares are affected by soil decline and soil loss and possibly a total of 10 million hectares will be in the future;
- one-third of Australia’s inland rivers are in extremely poor health and a further 405 show clear signs of degradation;
- less than 10% of Australia’s original vegetation is left in many areas; and
- many species of mammals, birds, reptiles and amphibians have declining trends.

Table 2.1 Macro indicators of the state of biophysical land, water and biodiversity resources in Australia

Total agricultural land	469M ha					
Landscape functional decline	Soil acidification		Dryland salinity		Soil fertility decline and soil loss	
Area currently affected	24M ha	5.1%	2.5M ha	0.5%	3M ha	0.6%
Area possibly affected in the future	43M ha	9.2%	15M ha	3.2%	10M ha	2.1%
River health	Extremely poor			33%	Clear signs of degradation	
					40%	
Vegetation	Forests	Woodland	Open woodland	Shrubland	Grasslands	
Area covered in 1788	9%	21%	21%	40%	7%	
Area covered in 1993	5%	14%	18%	17%	16% (includes sown grasses)	
Remaining original vegetation	<10% in many areas					
Biodiversity	Mammals	Birds	Reptiles	Amphibians	Freshwater fish	
Declining trend	23%	9%	7%	16%		
Endangered species	33	32	13	12	10	
Vulnerable species	16	50	41	2	8	

Refurbishing and repairing these resources is an immense task. Part of the requirement is to re-establish perennial vegetation over vast areas. It is anticipated that perennial vegetation cover, much of it native Australian species, will:

- deal with the problem of leaky landscapes by increasing water and nutrient use due to ability of deep-rooted plants to tap these resources currently out of reach by annual crop types;
- be permanently on the landscape and so deal with the dynamics of water and nutrient flows;
- be a source of new production methods and opportunities; and
- create new designer ecosystems that can act as expanded habitat for biodiversity resources.

This report aims to explore the synergies that might be created between the requirement to revegetate vast areas of Australian farmlands and the following five factors:

- the possible constraint to domestic petroleum supplies when stocks run low in approximately 25 years and the effect that this might have on external trade indicators as we are forced to import more from abroad;
- the possibility of developing a biofuels industry which aims to gradually replace petroleum-derived products with biomass-based products such as bioalcohols;
- the place that this new industry would have in refurbishing the economic, social and employment opportunities in rural Australia;
- the synergies that this new and large-scale industry might recreate between regional and urban Australia, the scientific and industrial communities and the possibility of radically new products developed for export markets; and
- the place that such an industry has in reducing Australia's greenhouse gas emissions by introducing a carbon-neutral fuel cycle.

This chapter of the report presents some key Australian literature as a context for the more detailed process and modelling chapters that follow.

Commercial ethanol developments

The Fuel Ethanol Association of Australia (1999) is an industry group given to the realisation of an alcohol fuels industry in Australia. A recent policy paper from the group makes the following points:

- The biophysical and social infrastructure in rural Australia urgently needs new industries that will bring new opportunities to bear upon a complex set of intertwined problems.
- The biomass-ethanol cycle could introduce a carbon-neutral fuels system to help deal with the problems of Australia's greenhouse gas emissions; 120 million tonnes (that is, 25%) of Australia's carbon dioxide equivalents are due to the transport cycle.
- Technology advances in the United States by Ford, General Motors and Chrysler have developed 'flexible fuel vehicles' with the capacity to use 100% petrol or up to an 85% blend of ethanol and petrol without engine modification.
- There is potential for between 1200 and 1600 bioethanol plants in Australia of different sizes producing between 10 million litres and 100 million litres annually.
- A 1996 study in the Gwydir area of New South Wales indicated the area could support two to three bioethanol plants, with each new plant bringing 159 direct jobs to the area and 600 to 800 indirect jobs.
- Studies quoted from the United States Department of Energy found that 80 cents in every dollar spent on fuel are exported outside the region when oil is used, while the same amount remained in the region when a locally produced biofuel was used.
- A Tasmanian study estimates that the private forests of Tasmania could support 10 bioethanol plants, each with a capacity of 50 million litres per year, creating 3200 direct jobs (320 per plant) and 12,000 to 15,000 indirect jobs. This would produce more than 500 million litres of bioethanol or 65% of the annual usage.
- The 644,000 tonnes of biomass waste produced by Sydney each year could support three bioethanol plants producing in total, approximately 125 million litres of bioethanol per year.
- The development of a bioethanol industry in Australia would require between \$60 billion and \$90 billion in investment over 20 to 30 years and most of this would be cycled through Australian industry, generating immense returns to skills, capability and export potential.

The report recommended a steady progression to the implementation of a biofuels industry so that 540 million litres would be produced by the year 2005, 1.4 billion litres by 2010, 11 billion litres by 2025 and 85% of all transport fuels from biomass by 2040.

The Stewart study of biomass fuels

The Stewart study of biomass fuels (Stewart, Gartside, Gifford, Nix, Rawlins & Siemon, 1979a, 1979b; Stewart, Hawker, Nix, Rawlins & Williams, 1982) was set in an historical context following a number of oil shocks in the 1970s which, having given cause for alarm in many industrialised countries, promoted the cause of self sufficiency in liquid fuels. Since then, Australian self sufficiency in oil has been maintained so avoiding any cause for immediate concern. In addition, world oil prices have been maintained at relatively low levels with occasional price blips caused by short-term production constraints, heavy demand during northern hemisphere cold snaps and a

number of political events such as trade tactics and regional wars. The Stewart report was, however, well ahead of its time when it noted in its summary, 'if future research shows that rising carbon dioxide levels in the atmosphere are likely to have a deleterious effect on climate, and that the rise is largely due to the combustion of fossil fuels, a rapid move to non-fossil fuels would be necessary, and renewable fuels, which recycle carbon dioxide would be one possibility'.

A number of the key findings of the Stewart report are:

- Some 237 million hectares of land were potentially available for biomass feedstock production. Of that area, 132 million hectares were not available because of terrain. Soil qualities brought the total down to 77 million hectares, of which 51 million were already developed and 26 million were new development.
- There was potential to generate 287 PJ of methanol and 132 PJ of ethanol to give a total of 419 PJ of useable liquid fuel per annum, equal to about half of the liquid fuel requirements of that time.
- This liquid fuel production was possible without altering the food and fibre production from the managed farmlands of that time.
- The 415 PJ net production of biofuels would require a gross production of 630 PJ, requiring 260 conversion plants and providing 60,000 jobs.
- The labour requirements for the study assumed that 100 person years would be needed for both biomass production and harvesting for each petajoule of biofuel produced, and a similar amount would be needed for the conversion process, a total of 200 person years per petajoule.
- A renewable fuel industry would stimulate decentralisation and have important social and defence considerations.
- The cost of production of alcohol fuels from biomass at the time was estimated to be three times that for petroleum, and methanol from coal gasification would also be a much lower cost option.
- Other reports concluded that 13 million hectares of forest plantation could provide 90% of the 1977–78 transport fuel usage.

Oil mallees and the Western Australian wheat belt

The search for deep-rooted plant production systems is attempting to deal with a number of linked problems in Australian farming lands. In particular the deep rooted systems are required to help transpire elevated water tables typical of dryland salinity and to use the perched concentrations of nutrients which are both symptoms typical of the leaky landscape problem. This in turn has led to wide-scale research and development of plantation systems and in particular the oil mallee production system. Key points from Bartle (1999a, 1999b) are:

- There are 18 million hectares of land in the wheat belt of Western Australia, 15 million hectares of which currently does not have a perennial plant option.
- There is wide-scale community concern about, and willingness to act on, the problem of dryland salinity at a landscape scale.

- A range of non-grazing trees and shrubs are available to form the basis of a biomass crop production system.
- Farmers and growers in the Oil Mallee Association have planted more than 12 million oil mallees in the past six years and it is projected 8 million shrubs will be planted in the year 2000.
- For sprouting tree and shrub types, a harvesting regime has been developed which requires a four-year establishment period and then harvests every second year. In more marginal and drier country this regime extends to a five-year establishment period and harvests every three years.
- A detailed investigation of harvesting operations has developed harvesting approaches using sugar cane and forestry equipment that make feasible the development of an efficient and integrated regional biomass flow system within a 40 km to 50 km radius of a central plant.
- The perched water and nutrient resources that form part of the dryland salinity problem can act as a free supplement to the growth of the woody biomass systems allowing a 10-year mining and rehabilitation period before nutrients have to be applied from external sources.
- Biomass yields of 5 tonnes per hectare dry matter per year are feasible and, with spaced plantings of 20% of total land area, 15 million dry tonnes would be available per annum.
- In related work in New South Wales for a trial period over four years, Milthorpe, Hillan and Nicol (1994) and Milthorpe, Brooker, Slee and Nicol (1998) obtained dry matter yields between 5 and 7 tonnes dry matter per hectare per year on an annual harvesting cycle using both oil mallee and blue mallee.
- Control of the dryland salinity problem may require a landscape cover of 80% and this potentially could produce 75 million tonnes per annum, enough to make the State self sufficient in liquid fuels and allow for some export.
- Piloting of an integrated oil mallee processing and electricity cogeneration plant is under development.

DISCUSSION

What the next five chapters do

The logical base for the remainder of this report is constructed through the following themes:

- Chapters 3 and 4 describe the process details of both the ethanol and methanol approach with some examples of energy budgets and costings, and some indications of technological breakthroughs that might be imminent or required.
- Chapter 5 provides a detailed examination of six scenarios for transitions to biofuels and compares them to the base case scenario for a range of indicators of success for the physical economy.
- Chapter 6 provides an initial examination of the feasibility for supplying the land requirements for biofuel production at the scale required for a growing economy.

- Chapter 7 discusses briefly a range of caveats or uncertainties that need to be appreciated when reading this report, particularly with respect to the modelling methodology.
- Appendix 1 provides a description of the structure and operation of the OzEcco embodied energy model of the Australian physical economy.

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Chapter 3

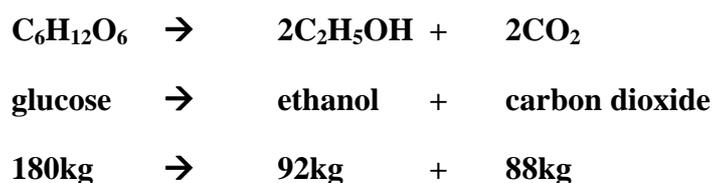
The production of ethanol from woody biomass

ABSTRACT

As a consequence of their dependence on a cheap source of raw materials, alcohol distilleries have generally been small. However, in the case of plants based on wood sugars, the size of the front end acts as a restraint. The front end of the plant that converts the wood to sugar by acid hydrolysis is very large and expensive, and consumes a considerable amount of energy to recycle the acid and concentrate the sugars. The yield of ethanol is limited by the fact that the carbohydrate only represents part of the wood substance and not all of the sugars are fermentable. The cost of ethanol from wood using the Rheinau process is estimated to be \$2424 per tonne of ethanol (\$1.91 per litre). The overall mass yield is 12% and the energy yield 16%. In this cost estimate, the raw material accounts for 57% of the cost of the ethanol, but there is considerable scope to reduce the cost by the use of more efficient processes or cheaper raw materials. By developing alternative processes which include feedstock pre-treatment, enzyme hydrolysis and simultaneous fermentation using organisms which utilise both hexose and pentose sugars, significant improvements in efficiency and reductions in cost are possible. Costs as low as 44 cents per litre have been suggested in the literature, but at best such estimates are based on laboratory or small pilot plant performance, so they have yet to be tested on a larger scale. A completely different approach would be to produce ethylene by flash pyrolysis and hydrate the ethylene to produce ethanol. This completely dispenses with the need for hydrolysis and fermentation, but the process is still experimental.

DESCRIPTION OF PROCESS

Ethanol is the waste product of the respiratory metabolism of yeasts grown on hexose (six-carbon) sugars in the absence of air. The overall fermentation reaction and theoretical yield are:



Suitable raw materials for ethanol production include sugars from sugar cane and sugar beet, starch from grains and cassava, and cellulose from wood, straw and bagasse. Plants have been built in the past to produce ethanol from each of these materials. As a general rule, however, only production from sugar-containing wastes such as molasses has been profitable in the face of competition from synthetic ethanol produced from ethylene.

Wood is a complex raw material made up not only of carbohydrates, but also of phenols, resins and lignin (an aromatic polymer based mainly on phenyl propane). The carbohydrate fraction in turn contains a mixture of polysaccharides, only some of which can be hydrolysed and fermented to ethanol. Hence, the yield of ethanol is dependent on the particular wood species and is generally in the range of 230 to 320kg per tonne (dry weight) of wood. Plants for wood hydrolysis have been built only during exceptional economic circumstances and the last published account of an

operating plant was in 1960. This was the Rheinau plant in Germany, which produced specialty wood sugars (Riehm, 1960).

Figure 1 Production of Ethanol from Woody Biomass

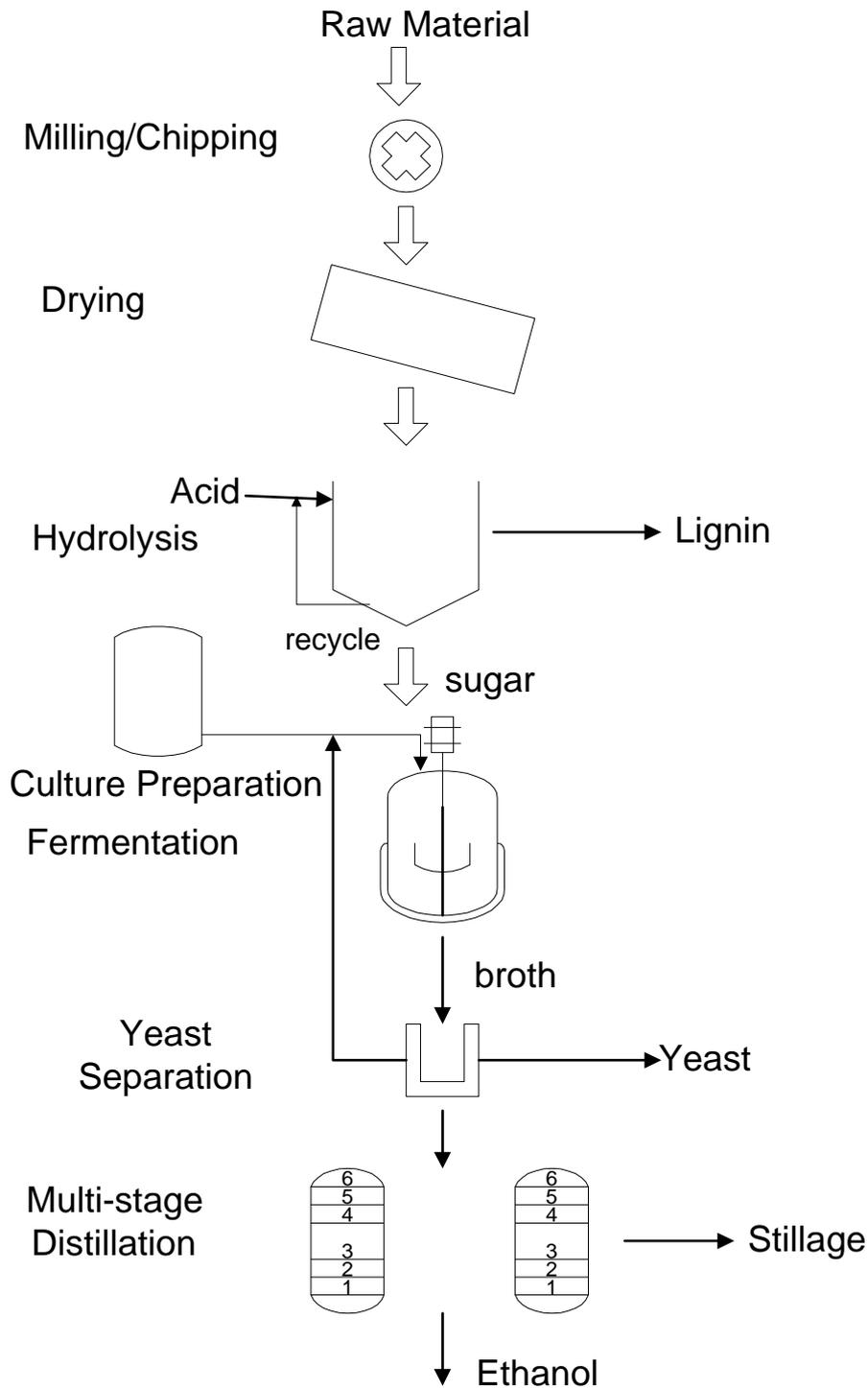
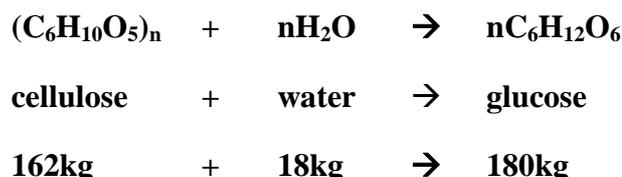


Figure 3.1 Production of ethanol from woody biomass

A generalised flow sheet for ethanol production from woody biomass is given in figure 3.1. Details will vary depending on the nature of the particular feedstock, but woody materials would generally be milled or chipped and dried prior to hydrolysis. In the hydrolysis step, the carbohydrates are

reduced to the corresponding sugars by the catalytic action of heat, acid or enzymes. The overall reaction for cellulose is:



In the Rheinau process and in other processes using strong acids, the acid must be separated from the sugars and lignin after the hydrolysis step and concentrated for reuse. The sugars are also usually concentrated by evaporation prior to fermentation. These operations require a considerable amount of energy, so additional wood must be burnt as fuel.

Recycled yeasts are then added to the syrup, some nutrients may be added and the solution is allowed to ferment. Competing side-reactions (including yeast growth) mean the maximum ethanol yield in the laboratory is 94.5% of the theoretical yield. Allowing for the additional inefficiencies of large-scale processing, the actual yield based on the fermentable sugars present in the syrup is usually closer to 90%. After centrifuging to recover the yeast, the broth is then distilled to recover an alcohol-water mixture which can be distilled further to recover ethanol of the desired purity. The residue from the distillation step, called stillage, contains unrecycled yeast, unreacted sugars and other organic materials from the wood, so it has a very high biological oxygen demand and must be treated prior to disposal. The revenue from by-products produced from distillery wastes (spent yeast, lignin and stillage) is assumed to just cover the costs of disposal. If the revenue proves to be lower, the data presented will be an underestimate.

PROCESS YIELDS AND COSTS

Dependence on a cheap source of raw materials means alcohol distilleries have generally been small. Even plants constructed in Brazil for fuel ethanol production average only 33 ML per year. The largest Australian distillery at Sarina in Queensland has a capacity of 50 ML per year. Although there are generally economies of scale to be realised by the construction of larger plants, physical constraints such as water or raw material supplies or economic constraints such as the cost of additional supplies must be considered in the selection of the optimum plant size. In the case of plants based on wood sugars, the size of the front end acts as a restraint. Taking the example of a wood ethanol plant given by Stewart, Gartside, Gifford, Nix, Rawlins and Siemon (1979b), 8.48 tonnes (dry weight) of wood would be required for feedstock and fuel for every tonne of ethanol produced (that is, 149 L of ethanol is produced per tonne (dry weight) of wood). Some 975,200 tonnes (dry weight) of wood per annum would be required for a 115,000 tonnes (145.7 ML) per year ethanol plant. Since green wood has moisture content of about 50%, this means an annual wood requirement of about 2 million tonnes fresh weight. If the plant operates for 330 days a year, then it would need more than 6000 tonnes per day and the chipping, drying and hydrolysis plant would be truly enormous. For example, the hydrolysis step would require a diffusion battery consisting of four parallel sets of four 300 m³ towers made of teflon-coated steel. The wood driers and evaporators for the concentration of sugars and acid recycling are also multiple units, so the plant is complex and expensive and economies of scale are lost because of the sheer scale of the front end. Much of the equipment must also be constructed from acid-resistant materials, so the capital cost is very high.

The cost of producing ethanol from wood using the Rheinau process is estimated to be \$2424 per tonne of ethanol (in 1999 Australian dollars). This estimate, detailed in table 3.1 below, is more than twice the estimated cost of producing methanol from wood and is based on unpublished studies

originally conducted by CSIRO for the production of fermentable sugar from kenaf. The plant was sized to process 1250 tonnes (dry weight) of wood per day, which was the amount of kenaf expected to be available from an area such as the Ord River region. The plant was of a size comparable with the AMCOR paper mill at Maryvale in Victoria.

The estimate of the ethanol yield is based on the use of Eucalyptus woodchips which are estimated to yield 600 kg of sugar or 275 kg (348 L) of ethanol per tonne (dry weight) of wood. As the process energy requirements are greater than that which can be generated from the lignin residues, additional wood is required as fuel. The net production of liquid fuel as ethanol is estimated to be 80 litres (or 1.85 GJ) per tonne (dry weight) of wood (table 3.2). The process heat requirements for the hydrolysis step are substantial and additional wood is required as fuel as indicated in the tables. Note that diesel fuel required for the forestry, harvesting and transport of the feedstock to the processing plant has been included in table 3.2. The cost of the feedstock is based on the opportunity cost of woodchips for export at A\$82 per tonne wet weight or A\$164 per toone dry weight.

Table 3.2 Estimated cost of ethanol production from wood

Plant capacity:	115,000 tonnes of ethanol per annum or 3.37 PJ per annum	
Plant operated:	330 days per year	
Employment/plant:	277	
Fixed capital cost:	\$347.7 million	
Working capital:	\$39.4 million	
Total capital cost:	\$387 million	
	\$/t ethanol	
Raw Materials:		
Wood (\$164/t (DW))		
• as feedstock (3.64 t(DW))	597	
• as fuel (4.84 t(DW))	794	1391
Operating costs:		
Other supplies	46	
Other utilities	43	
Labour (including supervision)	32	
Maintenance	207	
Overheads	32	360
Capital charges at 20% per year		673

TOTAL	2424
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This cost is equivalent to \$1.91 per litre or \$83 per gigajoule.

Table 3.2 Estimated energy inputs (GJ/t) for the production of ethanol from wood

	<u>Direct energy used as:</u>		Indirect energy used	<u>Biomass energy used as:</u>		Total energy used
	Liquid fuel	Purchased electricity		Fuel	Feedstock	
Plantation, harvest, transport of 8.5 tonnes (DW) of wood	8.5		4.3			
Feedstock 3.6 tonnes (DW) of wood					70.9	
Fuel 4.9 tonnes (DW) of wood				96.5		
Conversion Plant						
• Construction (i.e., capital)			1.8			
• Operating			2.4			
Electricity		0.0				
Total	8.5	0.0	8.5	96.5	70.9	184.4

Gross liquid fuel output (1t ethanol) 29.3 GJ

Less direct liquid fuel energy 8.5

Less liquid fuel in indirect energy 2.6

Less liquid fuel equivalent of coal in indirect energy 2.5

Less liquid fuel equivalent of coal used for electricity 0.0

Net liquid fuel output 15.7 GJ

Ratio of net liquid fuel output to gross liquid fuel output = $15.7/29.3 = 0.54$

Overall energy efficiency = gross liquid fuel output/total energy inputs = $29.3/184.4 = 0.16$

Conversion efficiency = gross liquid fuel output/inputs to conversion process = $29.3/171.6 = 0.17$

CONVERSION TO HYDROGEN

Having produced ethanol at great expense from wood, it would make little sense to then spend more converting it to hydrogen. It would be better to produce hydrogen directly via the gasification/shift

reactor route. Racing cars with high-compression engines have been running on methanol for many years and normal cars have been converted to run on ethanol in Brazil. However, recent developments suggest that conventional spark ignition engines may eventually be replaced by fuel cell vehicles running on methanol (Kable, 1997). There are already prototypes of fuel cell vehicles that can run very efficiently on alcohol fuels. These vehicles contain an on-board reformer, which converts the fuel to carbon monoxide and hydrogen, and a fuel cell containing a proton exchange membrane with a platinum catalyst, which converts the hydrogen to electricity. Hence, the vehicle has an electric motor instead of an engine, but uses the fuel cell instead of a battery to provide the electricity. Fuel cells are still expensive to produce, but development aimed at reducing costs and enabling mass production is proceeding rapidly (United States Department of Energy, 1998). DaimlerChrysler has done extensive work on both liquid hydrogen and methanol fuel cell vehicles and appears to have concluded that liquid hydrogen is more appropriate for fleet vehicles, while methanol fuel cells are better for consumer vehicles (Sotero, 1999).

BREAKTHROUGHS REQUIRED TO REDUCE COSTS

Similar to the oil refining industry, the cost of biofuels will be impacted by the range and number of high value co-products produced by a bio-refinery. In the oil industry it is generally accepted that refining petrol and diesel fuel alone is not commercially viable. The complexity of developing both the full product line and the processes associated with them should be taken into account in assessing the range of possible technological issues that follow.

The main problems with current technologies for the production of ethanol from woody biomass are the low yields obtained, the large amount of extra fuel required to recycle the acid and concentrate the sugars, and the high capital cost of the equipment required for the hydrolysis/acid recycle/concentration steps. The high cost of raw materials is another reason for the overall high cost. If cheaper materials are available in sufficient quantities, then that component of the cost would decrease. Recent research has come up with enzyme hydrolysis techniques, recombinant organisms capable of utilising pentose sugars, and alternative techniques for the acid recycle/concentrations steps. Unfortunately, enzyme hydrolysis consumes some of the sugars for the production of the enzymes and the microorganisms. Also the recombinant organisms are not as robust as common yeasts such as bakers' yeast and often require antibiotics to maintain selection, having lower yields on hexose sugars and lower alcohol tolerance. However, pretreatment methods for urban garbage and straw have now reached the point where enzyme hydrolysis represents a practical alternative to acid hydrolysis and costs considerably less. A recent report from the National Renewable Energy Research Laboratory (1999), describes the enzyme hydrolysis process in considerable detail. Published literature for the fuel requirements for acid recycle/concentration in the acid hydrolysis process have still not come down to the point where the process is remotely near self sufficient in fuel and capital costs are still high. However developments of the ion exclusion chromatography process (Reeves and Farina, 1997) could offer a breakthrough if pilot plant results are able to be scaled up to full sized operating plant.

It is often suggested that the lignin residue from hydrolysis can be used to fuel the process. However, in a report to the Energy Research and Development Corporation, Mendelsohn and Sweeny (1994) developed an energy balance for the strong acid hydrolysis process but without the important acid recycle and concentration steps. They calculated that the process would require 16.47 GJ of fuel energy to produce 960 L of ethanol from 4 tonnes (dry weight) of hardwood chips. The process produces 0.96 tonne of lignin with a fuel value of 20.06 GJ. However, the dewatered lignin contains 50% moisture, so the combustion efficiency would be 75%, giving useable heat of 15.05 GJ. This is lower than the 16.47 GJ the process needs, so it is difficult to see how the process will work without burning extra wood. When the omitted acid recycle and concentration steps is

included, the fuel energy requirements increase substantially and the extra wood required will reduce the effective yield of the process.

In an attempt to reduce the cost of acid recycle, Ragg and Fields (1987) of ICI have developed a new process for the acid hydrolysis of woody biomass which uses a calcium chloride catalyst with hydrochloric acid, and the acid is recovered by electrodialysis. This process speeds up the hydrolysis, reduces the temperature required and facilitates the acid recovery. Ragg and Fields claim that the process is economic, but do not present any cost details or an energy balance.

In a review of technologies available for the production of ethanol from lignocellulose, Davy John Brown Ltd (1994) states that:

Because of the cost of the feedstock component in the cost of ethanol, some organisations concentrated on feedstocks that must be disposed of (eg. garbage) – the negative value lowers the cost of ethanol considerably. As very few laboratories work through the entire process to measure yields, major discrepancies can arise in quoted yields. There are no fully operational modern commercial plants in the world converting lignocellulose to ethanol, though it has been done in some centrally planned economies and during wartime. Hence, any capital and operating cost information has been based on parts of processes operated on a laboratory or pilot plant scale. The estimates were generally low in capital cost through not including all the necessary plant items, and low in operating cost, particularly through over-estimating the yields and time the plant would be on stream.

The average capital cost was A\$1.75 per litre per year. With no feedstock cost included, assuming a full-sized plant could achieve best laboratory results at all times, calculations showed that ethanol could not be produced for less than A\$0.63 per litre. Lignin was quoted as being a valuable by-product which could subsidise the cost of ethanol. However, there was no evidence that it could be economically recovered at a profit (because of the high cost of drying) and one 100 ML per annum distillery would produce four to five times the Australian consumption. However, it has value as a fuel and 'could usefully be used to make a lignocellulose to ethanol facility energy self-sufficient'.

Speculation on possible very long-term future savings from untried technologies may only drop the price by A\$0.30 per litre from the present estimate of A\$0.90 per litre, even assuming yields larger than ever achieved in laboratory trials. The cost of A\$0.60 per litre is still far short of the present unleaded petrol cost of fuel of A\$0.257 per litre.

In table 3.1, the raw material accounts for 57% of the cost of the ethanol. If the raw material were free, or even cost money to dispose of (that is, negative cost), and if the process energy could be eliminated so that no extra fuel was required, the cost of ethanol could be reduced to less than 81 cents per litre. This is why so many figures in the literature look so cheap. Grethlein and Dill (1993) examined the cost of ethanol from a number of new experimental processes using corn stover at 1993US\$30 (1999A\$53.30) per dry tonne, considerably less than the A\$164 per dry tonne assumed here. They estimated costs of 76.4 cents per litre (1999 Australian dollars) for a concentrated acid process with separate hexose sugar fermentation, 55.1 cents per litre for the ammonia freeze explosion process (AFEX) with 98% cellulose conversion and separate pentose and hexose sugar fermentations, 53.3 cents per litre for the modified ammonia freeze explosion process (MAFEX) with 80% cellulose conversion and combined pentose and hexose sugar fermentations, and 44.4 cents per litre for the MAFEX process with *Pichia stiptis* yeast, high hydrolysis yields and combined pentose and hexose sugar fermentations. These figures give some hint of what might be achieved with new technologies, but the cost figures and the yields upon which they are based must be interpreted with caution.

There are also possible improvements in methods of separating the ethanol from the fermentation broth. Instead of conventional distillation, it is possible to use pervaporation membranes (Ballweg et al., 1982), solvent extraction or molecular sieves to dehydrate the ethanol.

A completely different approach would be to produce ethylene by flash pyrolysis and hydrate the ethylene to produce ethanol. This completely dispenses with the need for hydrolysis and fermentation, but the problem is to obtain adequate yields of ethylene from the flash pyrolysis step. Experimental ethylene yields of up to 27% have been obtained and hydration of the ethylene has a yield of 97%, so it could result in ethanol yields twice as good as the hydrolysis/fermentation process. The capital and operating costs would also be very much lower. Research is still under way to optimise the product distribution of the flash pyrolysis step. A pilot plant is currently in operation in Canada, so the process may become available commercially in about 2010 (Joosten, 1998).

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Chapter 4

The production of methanol from woody biomass

ABSTRACT

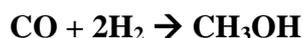
The conversion of woody biomass materials to methanol involves thermal gasification followed by chemical synthesis. If an oxygen gasifier is used, the production of oxygen for the gasifier requires large amounts of electricity. However, alternative gasification processes are being developed which do not require oxygen. Adequate technology is available for all stages except the gasification stage. The production of synthesis gas by gasifying wood, straw, bagasse or similar materials has yet to be demonstrated in large-scale plants, but it has been done in small demonstration plants. Unlike the production of ethanol, the production of methanol from wood is relatively insensitive to wood quality or species since the whole wood substance (not just the carbohydrates) is broken down into carbon oxides, hydrogen, water and so on, so the type of wood does not affect the yield. The cost of producing methanol from wood (including pre-drying) is estimated to be \$1027 per tonne methanol (81 cents per litre) for a plant of 100,000 tonnes per annum capacity. The overall mass yield is 38% and the energy efficiency is 33%. In this cost estimate, the raw material accounts for 41% of the cost of the ethanol, but there is considerable scope to reduce the cost by the use of more efficient processes or cheaper raw materials. However, at this time, methanol from natural gas is a far cheaper option than methanol from woody biomass.

DESCRIPTION OF PROCESS

The conversion of woody biomass materials to methanol involves several stages, as shown in the generalised flow sheet in figure 4.1 below. The raw material is first milled or chipped, partially dried, if necessary, and then gasified by heating the material in the presence of oxygen to produce a mixture of carbon monoxide, hydrogen, carbon dioxide and steam. In the shift reactor, the proportion of hydrogen is increased by passing the gases over a nickel catalyst:



The steam, most of the carbon dioxide and any sulphurous gases are removed in an absorber, leaving synthesis gas – a mixture of hydrogen and carbon monoxide. Finally, methanol is synthesised by passing the gases over a copper catalyst at about 250°C and about 50 atmospheres pressure:



carbon dioxide + hydrogen → methanol



carbon dioxide + hydrogen → methanol + water

A methanol-water mixture is condensed from the reactor gases, the unreacted gases being recycled to the reactor inlet. Finally, the aqueous mixture is distilled to separate the methanol from water.

Methanol can be made from a variety of feedstocks, including coal, natural gas and biomass. The gasification stage is similar in principle for all the feedstocks, but because of their different physical properties, the gasifiers are quite different. The shift reaction is unnecessary when using gas as the feedstock, but desulphurisation of the synthesis gas is required in all cases to avoid poisoning the synthesis catalyst. Thereafter, processing is the same for all raw materials.

There are a number of effluent streams from the plant. The primary gaseous effluent is a small purge from the recycled reactor gases that is necessary to remove excess inert gases such as nitrogen. This stream will be clean and will contain no sulphur, so its combustion will not be an environmental hazard. Ash and slag from the gasifier will be inert and can be disposed of by landfill. An effluent requiring treatment is the bottoms portion from the distillation step which contains organic matter and has a high biological oxygen demand. This stream can be treated in conventional waste water treatment plants, either using activated sludge or aerated ponds. The costs to the process are not expected to be large.

It is proposed that the gasification of woody biomass would be achieved in a PUROX reactor. This process was developed for the gasification of urban refuse using oxygen instead of air in order to obtain a gas of higher calorific value with little diluent nitrogen. For the production of methanol, the presence of substantial quantities of nitrogen is undesirable because of the increased size of the subsequent reactors, and the substantial losses of valuable materials when purging the nitrogen after the reaction stages.

Pre-drying may be desirable if the raw material has a dry matter content of less than 80%. Some water is necessary in order to maximise the production of hydrogen, but, above this amount, there are energy losses in the product gas, so more raw material has to be used. The capacity of the gasifier is also reduced both by the lower dry weight loading and the larger heating zone required in the top section of the gasifier. Most importantly, the amount of oxygen consumed increases since more carbon has to be burnt to provide the heat for drying. It can be shown that it is economically justifiable to use some of the raw material as fuel to dry the remainder.

The production of oxygen for the gasifier requires large amounts of electricity. In the areas where the conversion plants would be located, it can be assumed that generally electricity produced from coal will be available at lower costs than from biomass feedstock. It has therefore been assumed that electricity will be purchased rather than generated from the available raw material. If the wood could be gasified without using oxygen, then an integrated cogeneration plant might be feasible.

Water requirements for cooling are substantial, being about 1000 m³ per hour for the production rate of 300 tonnes per day of methanol. However, with appropriate cooling towers or cooling ponds, the actual consumption would be much less. Water costs would normally be less than \$3 per tonne methanol. However, in some areas the supply of water could be critical.

PROCESS YIELDS AND COSTS

The production of methanol from synthesis gas is practised commercially on scales ranging from 50 to 2500 tonnes per day. Indeed, recent developments in the leading concept methanol (LCM) process developed by ICI Katalco in the United Kingdom could be used to build single methanol plants with capacities reaching 14,000 tonnes per day (Australian Institute of Petroleum, 1999b). This technology may be applied to produce methanol on floating production facilities using gas from large offshore gas fields in remote regions such as the North West Shelf or the Timor Sea.

There is therefore no question that adequate technology is available for all stages except the gasification stage.

Figure 1. Production of methanol from Woody Biomass

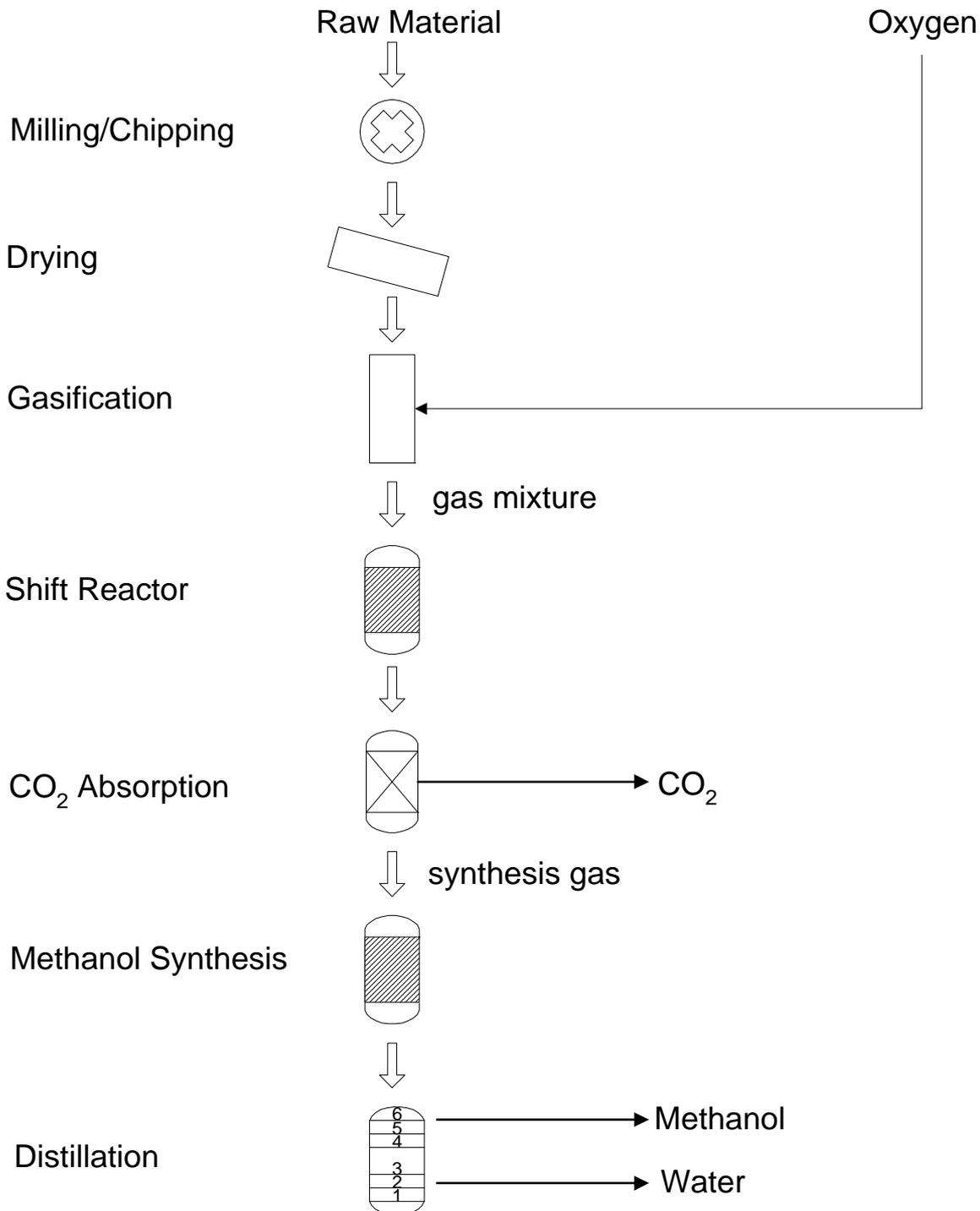


Figure 4.1 Production of methanol from woody biomass

The production of synthesis gas by gasifying wood, straw, bagasse or similar materials has yet to be demonstrated in large-scale plants, but it has been done in small demonstration plants. Recent developments with pyrocatalytic gasification suggest that gasification of wet biomass can be achieved without pre-drying or the use of oxygen, but this technology is still experimental.

Studies of the PUROX type gasifier suggest that it can handle about 250 tonnes dry weight per day, but reports from the former International Harvester Co. (Mamers et al., 1983) suggest that prefabricated skid-mounted methanol plants handling 126 tonnes dry weight per day could produce 50 tonnes per day of methanol. The use of skid-mounted plants allows the plant to be relocated to wherever wood is available (over a 20-year lifetime), so transport costs can be kept to a minimum if the supply of wood in the vicinity of the plant declines. A range of values is available for the amount of dry material required per tonne of methanol produced. For wood, the values vary from 1.87 to 3.2 tonnes, depending on the moisture content (Stewart, Gartside, Gifford, Nix, Rawlins & Siemon, 1979). In this example, a value of 2.2 for wood at 80% dry matter and a value of 3.0 for wood at 50% dry matter have been taken. Values for other raw materials are shown below (table 4.1).

Table 4.1 Quantities of raw material used in methanol production

Raw Material	% dry matter	<u>Dry weight per unit of methanol produced</u>	
		Without pre-drying	With pre-drying*
Wood	80	2.2	
Wood	50	3.0	2.2 + 0.4
Bagasse	50	3.1	2.3 + 0.4
Sugarcane field residues	50	3.3	2.4 + 0.4
Cereal straw	80	2.4	

* Pre-drying materials of 50% dry matter requires 0.4 units of raw material as fuel.

Unlike the production of ethanol, the production of methanol from wood is relatively insensitive to wood quality or species since the whole wood substance (not just the carbohydrates) is broken down into carbon oxides, hydrogen, water, and so on. Hence, the source of the wood is not important. As we saw in the section on ethanol, wood contains lignin (an aromatic polymer based mainly on phenyl propane). Lignin is an almost pure hydrocarbon, containing 79% carbon. Therefore, it contains about 40% of the carbon in wood, but this carbon cannot be utilised in the ethanol process. Apart from the difficulty of fermenting the significant quantities of 5-carbon sugars and acetate present in the wood hydrolysate, the fermentation process does not touch the lignin at all, so the conversion efficiency is very low. Even in the methanol process, not all of the carbon is converted to methanol, but the conversion efficiency is twice as good as the ethanol process.

Table 4.2 Estimated cost of methanol production from wood with purchased electricity and pre-drying of the feedstock

Plant capacity: 100,000 tonnes per annum methanol = 2.24 PJ per annum

Plant operated 330 days per year

Employment/plant: 248

Fixed capital cost: \$155.8 million

Working capital: \$16.4 million

Total capital cost: \$172.2 million

\$/t methanol

Raw Materials:

Wood (\$164 per tonne (DW))

- | | | |
|-----------------------------|-----|-----|
| • as feedstock (2.2 t (DW)) | 360 | |
| • as fuel (0.4 t (DW)) | 66 | 426 |

Operating costs:

Other supplies	25	
Power	40	
Labour (including supervision)	100	
Maintenance	92	257
Capital charges at 20% per year		344

Total		1027
-------	--	------

This cost is equivalent to \$0.81 per litre or \$46 per gigajoule.

Taking the example of the 300 tonnes per day wood methanol plant given by Stewart, Gartside, Gifford, Nix, Rawlins and Siemon (1979), the combined wood requirement for feedstock and fuel is 2.6 tonnes (dry weight) per tonne methanol produced (that is, 486 L methanol is produced per tonne (dry weight) of wood), or 260,000 tonnes (dry weight) per annum for a 100,000 tonnes per annum (126.4 ML per year) methanol plant. This is only about one quarter of the quantity required by an ethanol plant of a similar capacity. Hence, the chipping, drying and gasification plant does not need to be so large and the raw material cost is greatly reduced.

Moreover, the plant does not need to be constructed from acid-resistant materials because no acids are used, so it is much cheaper to build. Finally, since most of the plant (after the gasifiers) is more like a conventional oil or gas processing plant, it is much easier and cheaper to run.

Table 4.2 gives the estimated cost of producing methanol from wood (including pre-drying) as \$1027 per tonne methanol for a plant of 100,000 tonnes per annum capacity. There has been little attempt to scale-up the production costs beyond about 300 tonnes per day capacity because there

are no reliable estimates of the maximum size and cost of large wood gasifiers. On the contrary, it has been suggested, in connection with the International Harvester Co. plants mentioned above, that small, prefabricated skid-mounted methanol plants with separate, free-standing gasifiers could be built for just \$30 million, thus costing less per tonne of methanol than a large field-constructed plant. Moreover, being skid-mounted, it could be moved to another area at a modest cost if the wood supply situation changed. Similarly, small oxygen plants are also available as skid-mounted units. The total cost of methanol from such a small plant is estimated to be 73.4 cents per litre, slightly less than the cost from a large unit. The net production of liquid fuel as methanol is estimated to be 284 litres per tonne (dry weight) or 5.0 GJ per tonne (dry weight) of wood (table 4.3). The process heat requirements are not so great in this case, but some additional wood is still required as fuel as indicated in the tables. Note that diesel fuel required for the forestry, harvesting and transport of the feedstock to the processing plant has been included in table 4.3. With an overall mass yield of 38% and an energy efficiency of 33%, it is a significantly better option than an ethanol plant.

Table 4.3 Estimated energy inputs (GJ/t) for the production of methanol from wood

	<u>Direct energy used as:</u>		Indirect energy used	<u>Biomass energy used as:</u>		Total energy used
	Liquid fuel	Purchased electricity		Fuel	Feedstock	
Plantation, harvest and transport						
of 2.6t (DW) of wood	2.6		1.3			
Feedstock 2.2t (DW) of wood					43.3	
Fuel 0.4t (DW) of wood				7.9		
Conversion Plant						
-- Construction (ie. capital)			1.0			
-- Operating			0.9			
Electricity – 800 kWh		11.4	0.2			
Total	2.6	11.4	3.4	7.9	43.3	68.6
Gross liquid fuel output (1t methanol)					22.4 GJ	
Less direct liquid fuel energy				2.6		
Less liquid fuel in indirect energy				1.0		
Less liquid fuel equivalent of coal in indirect energy				1.0		
Less liquid fuel equivalent of coal used for electricity				4.8		
Net liquid fuel output					13.0 GJ	
Ratio of net liquid fuel output/gross liquid fuel output					= 13.0/22.4 = 0.58	
Overall energy efficiency = gross liquid fuel output/total energy inputs					= 22.4/68.6 = 0.33	

$$\text{Conversion efficiency} = \text{gross liquid fuel output/inputs to process} = 22.4/64.7 = \mathbf{0.35}$$

CONVERSION TO HYDROGEN

Since hydrogen is one of the main products of the shift reactor, it would be possible to take the gases leaving the carbon dioxide absorber, purify the hydrogen and liquefy it instead of converting the gases to methanol in the methanol synthesis unit. This is a perfectly feasible way of producing hydrogen from biomass, but it has yet to be tested on a large scale because much cheaper fossil fuel feedstocks are available at a much lower cost. As mentioned in the ethanol chapter, it would also be possible to convert methanol to hydrogen using an on-board reformer in a fuel cell vehicle. Since fuel cell vehicles are far more efficient than spark ignition vehicles, it is quite likely that this will happen, but, at this time, methanol from natural gas is a far cheaper option than methanol from woody biomass. In fact, the current world price for bulk quantities of methanol is only US\$105 (A\$162) per tonne (Australian Institute of Petroleum, 1999a) compared with the estimate of \$1027 per tonne above for methanol produced from biomass. Clearly, the latter could only be viable on a local supply basis in areas remote from the capital city markets.

It is still, however, a much better proposition than ethanol from wood. On an energy basis, the price of \$162 per tonne (12.8 cents per litre methanol) is \$7.23 per gigajoule, which can be compared with crude oil (\$25/barrel) at \$4.22 per gigajoule, liquefied natural gas (delivered to a capital city port) at \$5.47 per gigajoule, gaseous hydrogen produced from natural gas at \$7.05 per gigajoule, liquid hydrogen produced by electrolysis of water (using electricity at 5 cents/kWh) at \$31 per gigajoule, methanol from wood (\$1027 per tonne from above) at \$45.86 per gigajoule and ethanol from wood at \$82.73 per gigajoule. Liquid hydrogen produced from wood would cost even more than methanol because of the lower yield and the high energy cost of liquefaction, even if cheap fossil fuel electricity is available. If emission permits are sold to fossil fuel plants at the currently proposed value of \$20 per tonne of carbon dioxide, then it would add \$0.27 per gigajoule to the price of methanol from natural gas and \$0.10 per gigajoule to the price of liquefied natural gas, so it would not make much difference unless the producers of fossil fuels are made responsible for downstream emissions resulting from the combustion of their products.

BREAKTHROUGHS REQUIRED TO REDUCE COSTS

Developments in catalytic steam gasification, hydrogasification and pyrocatalytic gasification could eliminate the need for pre-drying the feedstock or producing oxygen for the gasifier. If successful, such developments could significantly reduce the cost of producing hydrogen or methanol from woody biomass, but the task is still daunting. The downstream parts of the process are already well established and unlikely to change much, though there has been some development of improved methanol synthesis catalysts.

As an example of progress in steam gasification, a team at the Technical University of Vienna (<http://www.edv1.vt.tuwien.ac.at>) has developed a fast internally circulating fluidised bed gasifier which can convert partially dried woodchips to a nitrogen-free gas without the use of oxygen.

The Brookhaven HYNOL process 5 (Dong and Steinberg, 1997) uses a fluidised bed hydrogasifier in which the biomass is reacted with a hydrogen-rich gas to convert the carbon and carbon dioxide to methane and carbon monoxide. A steam reformer then generates the synthesis gas required for methanol synthesis. Methane (natural gas or biogas) is required as a co-feedstock.

As an example of progress in pyrocatalytic gasification, a team at the University of Zaragoza (García et al., 1996) in Spain has developed a nickel-alumina catalyst which enables good

performance in biomass pyrogasification, in order to obtain high gas yields and a long-term catalyst activity.

The catalysts have been tested for the pyrolytic gasification of biomass using the Waterloo Fast Pyrolysis Process (WFPP) technology. Wood is fed into a continuous bench-scale fluidised bed reactor at 650°C and at short contact times.

It appears that whatever gasification technology is used, some drying of materials containing more than 20% moisture will probably be required, but oxygen can be dispensed with. Much remains to be done with the practical development of biomass gasification systems, but significant reductions in cost are likely. Since the cost of producing methanol from woody biomass is already much lower than the cost of producing ethanol, this is probably the process to pursue. However, as the work on ethylene production quoted in the ethanol chapter shows, thermal processes such as flash pyrolysis can produce a range of organic chemicals which may provide useful substitutes for many petrochemical materials in the future.

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Chapter 5

Modelling the transition to biofuels

ABSTRACT

Solutions are tested for a set of future, and interconnected, challenges that centre on the losses of landscape function in Australia's farming zones, the possible depletion, one human generation away, of domestic oil stocks and increased greenhouse gas emissions from the fossil energy sector. A partial solution to these intertwined problems is the establishment of biomass plantations over the next 50 years that cover between 10 and 30 million hectares of Australia's croplands and high rainfall pasture zones. These biomass feedstocks produce either ethanol or methanol to gradually replace liquid transportation fuels currently produced from crude oil and its derivatives. The deep-rooted perennial production systems help control hydrological problems that lead to dryland salinity, create jobs in rural Australia, replace future energy imports and help with international trade issues such as balance of payments problems.

The OzEcco embodied energy model of Australia's physical economy was used to test the feasibility of six different transition routes to solving these problems. Three scenarios used the methanol process (methanol alone, methanol plus biomass electricity, methanol plus a radical economy) while the other three scenarios used ethanol (ethanol alone, ethanol plus biomass electricity, ethanol plus methanol). Each scenario was related to a base case and judged on its success in maintaining the acceptable outcomes of the base case, but improving on those areas that required improvement.

The methanol scenarios produced good outcomes with equivalent rates of growth in gross domestic product (GDP) and per capita affluence, reduced energy intensities of GDP, large reductions in oil imports and an energy ratio (output to input) of around 5:1 for the whole production cycle. The reduction in carbon dioxide emissions from the energy sector varied from 200 to 400 million tonnes in the year 2050 in comparison to the base case. A methanol scenario with a radically changed economy was successful in stabilising and then reducing carbon dioxide emissions by 2050, but it had lower rates of growth in GDP and lower levels of per capita affluence.

The ethanol scenarios were less effective because of the assumptions of lower yields from the fermentation process that guided the implementation of the scenario. Nevertheless they were effective in substantially replacing oil-based transportation fuels, reducing greenhouse gas emissions and generating direct employment. A combined scenario that produced 40% ethanol and 50% methanol was particularly effective in producing a range of environmental outcomes.

The choice of scenario strategy eventually comes down to a political ideology or what particular outcomes of a scenario are considered most important by a decision maker or an industry group. Each scenario had substantial advantages over its competitors whether it was rates of growth in GDP, reductions in carbon dioxide emissions, the energy ratio of the production process, the direct generation of jobs or the area of plantation biomass required to make the production system feasible. Subsequent research is required to further refine the estimates of feasibility for each preferred scenario.

INTRODUCTION AND METHODS

This chapter sets out to test the feasibility of introducing the biomass fuel technologies, described in the earlier chapters, to Australia's physical economy. This is undertaken using the OzEcco embodied energy model which tracks the flows of energy through the physical economy and then assesses the degree to which technologies, policies and consumption patterns might be changed to produce different outcomes. A paper describing the model and its operation is included in appendix 1.

A key concept used in this chapter is that of a scenario: the description of an integrated set of outcomes based on a range of fair or valid assumptions. The most important scenario is the base case scenario, which uses the grounding of the OzEcco model in a calibration period. This period allows the analytical framework or model to be tuned so that the results from the model approximate real data which are collected from a wide variety of sources. Thus the base case scenario is correct in history, and the policies (control variables) that run the model out to 2050 include a wide range of assumptions that are agreed (more or less) to be part of a future set of realities or policies. Some of the assumptions in this base case scenario include:

- human population growth to 25 million by 2050;
- food exports to continue at current levels;
- future discoveries of natural gas and oil to be in line with the 50% probability estimates from the Australian Geological Survey Organisation;
- exports of natural gas, coal and minerals to continue growing in line with world economic growth;
- the partial phase-in of renewable energy types and more efficient electricity production plant in line with the government policies on greenhouse gas emissions; and
- expansion of forest plantation to reach three million hectares by the year 2020.

Thus the base case scenario sets a foundation against which other scenarios can be compared. It is usually the intention of the analyst to retain the best features of the base case while attempting to improve other outcomes. Three outcomes in the current base case that might be retained are economic growth, per capita affluence and strong growth in exports. Three areas that might bear improvement are the level of carbon dioxide emissions, the energy intensity of GDP (the megajoules of fossil energy needed to produce a dollar of GDP) and depletion of domestic oil and gas stocks 25 to 50 years away.

The following scenarios are explored in detail. Each case is referenced to the base case and judgments are made as to whether the scenario is more or less successful:

- the base case as described above;
- transition to *methanol* biofuel production to supply 90% of the energy value of oil demand (Methanol-0 or Meth-0 on graphs);
- transition to *methanol* biofuel (as above) but with biomass electricity generation phased in to take over from fossil thermal plant as it ages and is phased out (Methanol-1 or Meth-1 on graphs);
- transition to *methanol* biofuel plus biomass electricity (as above) but with radical alterations to international monetary flows to control growth and the rebound effect (Methanol-2 or Meth-2 on graphs);
- transition to *ethanol* biofuel production to supply 40% of the energy value of oil demand – early tests had shown that 90% of oil was infeasible under assumptions which restrict the expansion of ploughed farmland (Ethanol-0 or Eth-0 on graphs);

- transition to *ethanol* biofuel plus biomass electricity generation (Ethanol-1 or Eth-1 on graphs); and
- transition to a mixture of 40% *ethanol* and 50% *methanol* (Ethanol-2 or Eth-2 on graphs).

RESULTS

Scenario 1: The base case

Short abstract

The base case scenario presents an Australia that is capable of sustained growth in its physical economy, with a simulated growth in GDP of 3% per annum which declines gradually to 2% at 2050. There are a number of challenges which might face Australia out to 2050 in the areas of oil and natural gas depletion, emissions of carbon dioxide from the energy sector and difficulties with the merchandise or balance of payments area if the nation requires large imports of liquid and gaseous hydrocarbons. Domestic oil reserves might become constrained from the year 2025 onwards and domestic gas reserves from around 2040 onwards. Under the assumptions in the base case scenario, emissions of carbon dioxide from the energy sector could triple from around 400 million tonnes per annum currently to around 1200 million tonnes by the year 2050. The visible or merchandise balance of trade could substantially worsen if Australia has to replace oil and gas currently sourced from domestic stocks, with imported oil and gas. These issues are used as a stimulus for the design and testing of a range of feasible future physical economies which are more resilient and robust in dealing with these issues.

Key assumptions

Based on model development during the last five years, a wide literature review and a limited amount of industry consultation, the eight important assumptions in the base case are as follows:

- that human population will grow to 25 million by 2050;
- that food exports will continue approximately at current levels;
- that future discoveries of natural gas and oil will be in line with the 50% probability estimates from the Australian Geological Survey Organisation;
- that exports of natural gas, coal and minerals will continue growing in line with world economic growth;
- that the partial phase-in of renewable energy types and more efficient electricity production plant will continue in line with the government policies on greenhouse gas emissions; and
- that expansion of forest plantation will reach three million hectares by the year 2050.

Results

The top level indicators in this simulation of the base case scenario show the following trends (figure 5.1):

- The growth rate in GDP gradually declines from 3% to 2% per annum over the simulation period with troughs around the mid-2020s and 2040 caused by the depletion of domestic stocks of oil and natural gas respectively.

- The per capita affluence measure (gigajoules of embodied energy per capita per year) doubles over the simulation period and reaches 150 GJ per capita by 2050.
- The energy intensity of GDP (megajoules of fossil energy per constant dollar of GDP) declines to 8 MJ per dollar by 2010 and stabilises at that level out to 2050.
- The emissions of carbon dioxide from the energy sector triple over the simulation period from a level currently of around 400 million tonnes per annum to nearly 1200 million tonnes per annum by 2050.

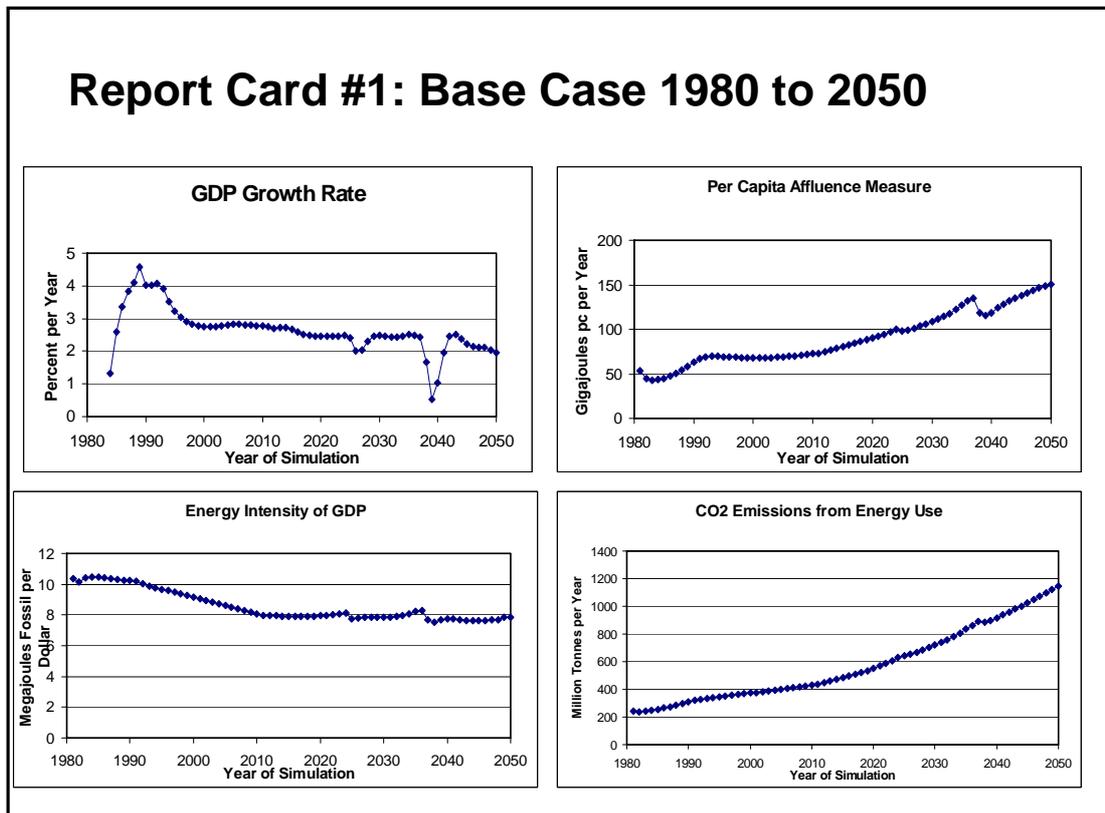


Figure 5.1 Report card #1 for the base case scenario showing growth rate in GDP (top left), per capita affluence index (top right), energy intensity of GDP (bottom left) and carbon dioxide emissions from energy use (bottom right)

The implications in the base case scenario for important fossil energy parameters of the physical economy are (figure 5.2):

- The depletion date of domestic oil stocks is around 2025. This date is simulated from a series of moderately optimistic assumptions on the discovery of new petroleum stocks combined with increasing consumption of petroleum in line with growth in the physical economy. The sharp decrease in the graph depicting the rate of production of oil would be moderated in the real world by market mechanisms which might use world market conditions and price as inputs which cause a more gradual cessation of domestic production.
- The requirements for domestic oil and imports show a steady increase, notable in the sharp rise in import requirement after the date of oil depletion. The separation of the demand and import graphs after oil depletion is caused by a modelling boundary artefact. The modelling approach imposes an oil system boundary which includes a requirement for petroleum consumption in the discovery, production and refining of petroleum .

- The rate of domestic production of oil rises markedly as stocks approach depletion levels. This effect is due to an assumption that the final 30% of an oil reservoir is more difficult, in a physical and energy sense, to extract. The abrupt cut-off point is caused by the physical equivalent of the energy profit ratio which passes a threshold value and causes oil to be 100% imported. Real world market and political mechanisms would ensure that this transition was less abrupt.
- After the year 2000 the yearly growth rate in energy use by transport averages around 2% with sudden dips during the oil and gas depletion periods, but recovery afterwards when the physical economy has adjusted to the costs of imports.

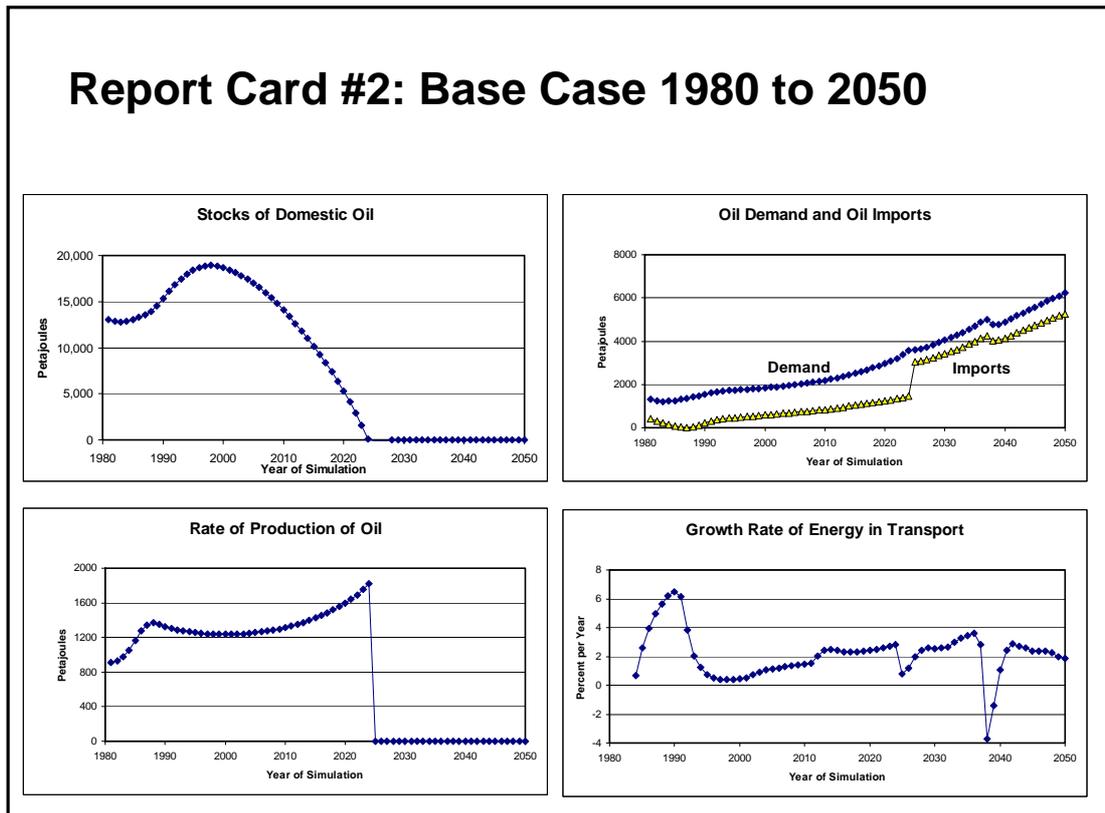


Figure 5.2 Report card #2 for the base case scenario showing stocks of domestic oil (top left), oil demand and oil imports (top right), rate of production of domestic oil (bottom left) and the growth rate of energy use by transport (bottom right)

Other outputs from the base case scenarios are (figure 5.3):

- A stock of nearly six million hectares of biomass plantation is available by the year 2050. The planting rate for both pine and eucalypt plantations is set to achieve the Forests 2020 Vision of three million hectares of forest plantations by 2020 and these planting rates are continued until the completion of the scenario. This achieves a positive wood balance for the period of the simulation and by 2050 an annual export of 25 million cubic metres.
- The fossil energy inputs to the agriculture and forestry sectors increase gradually to around 200 PJ per year by 2050.
- The degree to which the physical economy is being decarbonised is shown by the difference between the fossil energy inputs and the outputs of embodied energy in goods and services. In

the base case there is a gradual divergence between the graphs out to 2050, with an eventual difference of 3000 PJ per year. The difference is due to virtual energy produced by renewable sources and subsequent scenarios will attempt to widen this gap.

- The indicators describing visible (merchandise) and invisible (services) balance of payments show a gradual decline into a negative situation over the simulation period. The indicator for visibles is maintained at a relatively neutral or positive status until the depletion of oil in 2025 substantially increases imports, and an additional effect in 2038 when gas reserves decline. The invisibles indicator declines to the year 2020 and then stabilises due to a balancing effect of investment and loan inflows and outflows from repatriation of profits and interest payments. Subsequent scenarios will attempt to redress these declines in the visibles account, which are due to energy imports.

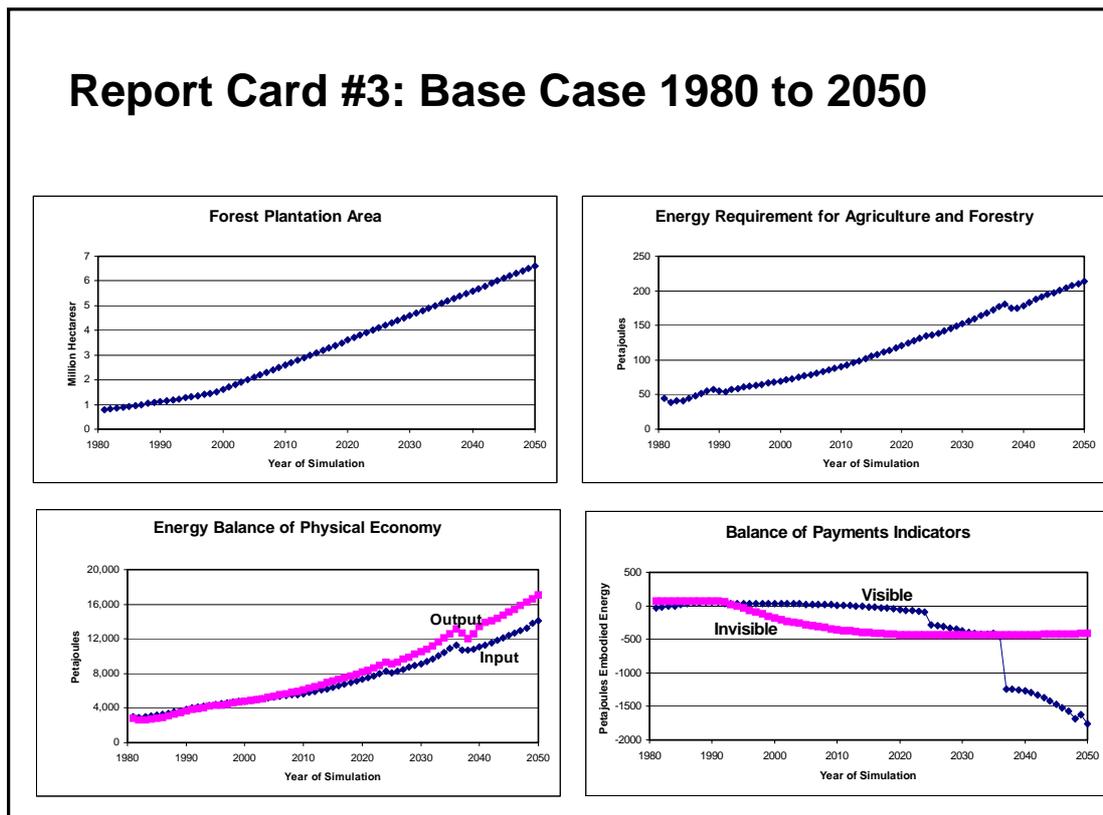


Figure 5.3 Report card #3 for the base scenario showing the biomass plantation area required (top left), the energy requirements for agriculture and forestry (top right), the energy metabolism of the physical economy (bottom left) and indicators of both visible and invisible balance of payments (bottom right)

Scenario 2: Methanol alone

Short abstract

The transition to a methanol production system was set to supply 90% of the total oil requirements. This was judged to be a feasible scenario with indicators of GDP growth rate, per capita affluence, and energy intensity of GDP achieving performance superior to the base case scenario. By 2050 carbon dioxide emissions were approximately 1000 million tonnes per annum, a reduction of 200 million tonnes per annum compared to the base case. More than 31 million hectares of biomass plantation land was required to underpin the methanol production of this scenario and the feasibility of this area being available is questioned. In the past 15 years of the simulation, rebound growth appeared to be occurring where an excess of methanol production was fuelling transport growth, affluence levels and subsequent carbon

dioxide emissions. Subsequent methanol production scenarios aim to bring the rebound under control, while retaining the best functional attributes of this scenario.

Key assumptions

Based on a wide literature review and limited industry consultation, the seven important assumptions underpinning this scenario were as follows:

- The methanol alone scenario would aim to supply 90% of Australia's total oil requirements specifically to meet 100% of the requirements for transportation fuels.
- The feedstock share would be 100% woody material from plantation biomass resources which are currently managed as forests with a 20-year rotation and an average 20 m³ per year mean annual increment.
- Approximately 60% of the woody biomass required is derived as logs and the remainder as branches and waste wood. This assumption relates to the forest growth model which effectively grows the stems or logs. If logs only are harvested then a larger area of biomass plantation will be required.
- The rate of plantation biomass establishment (basically forests) was 400,000 hectares per annum. The cost of establishment of a hectare of biomass plantation was \$2500 in current dollars and regular maintenance was part of the accounting procedure.
- Apart from woody biomass as feedstock, the energy inputs required by methanol production system were 0.08 PJ of external inputs per petajoule of methanol produced. This 0.08 PJ was apportioned 30% for thermal or fuel energy and 70% for electricity.
- The capital cost in constant dollar terms of the methanol plant was \$50 million per petajoule of production capacity and the lifetime of plant was 20 years.
- Job requirements were 50 full-time persons to run the plant, 350 to construct the plant and 150 to supply the biomass feedstocks. Additional regional multipliers to represent flow-on effects were not applied.

Results

The top level indicators in this methanol alone simulation show the following trends (figure 5.4):

- Growth rate in GDP for this scenario tracks with or above the base case for the duration of the simulation. The first drop due to oil depletion is avoided and the second drop due to gas depletion is not as large.
- The per capita affluence measure (gigajoules of embodied energy per capita per year) tracks with the base case until 2030 and then takes a higher trajectory.
- The energy intensity of GDP (megajoules of fossil energy per constant dollar of GDP) is decreased by about 30% (from 8 MJ per dollar to 5 MJ per dollar) by 2050.
- The emissions of carbon dioxide from the energy sector diverge from the base case after 2005 and rise gradually to 1000 million tonnes per annum by 2050, a reduction of 200 million tonnes per year compared to the base case.

Report Card #1: Methanol (0) 1980 to 2050

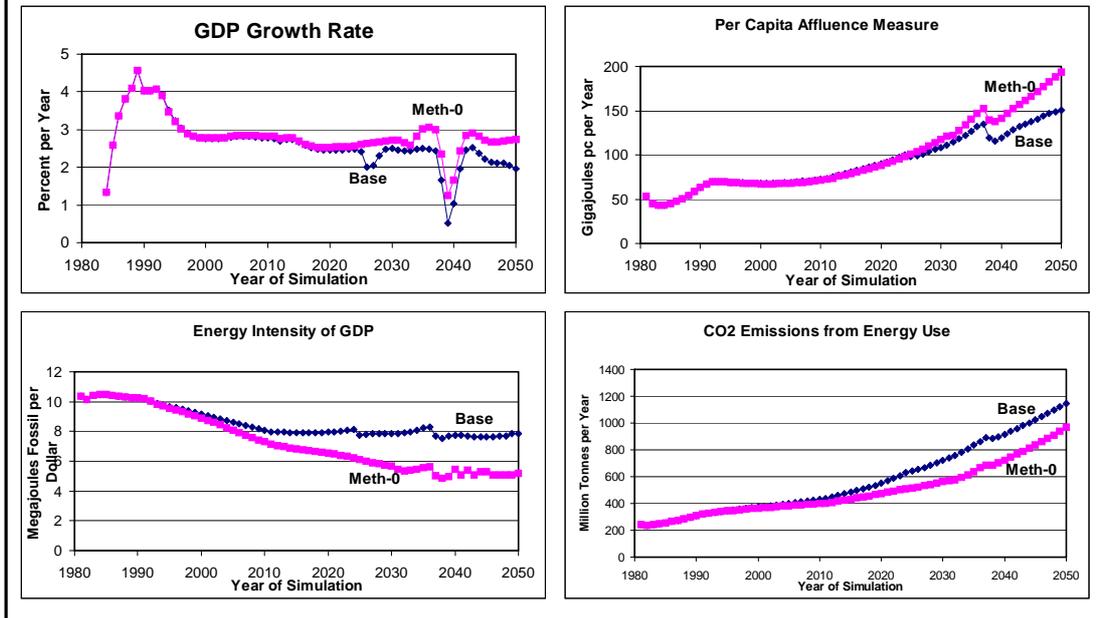


Figure 5.4 Report card #1 for the methanol alone scenario (Meth-0) compared to the base case (Base) showing growth rate in GDP (top left), per capita affluence index (top right), energy intensity of GDP (bottom left) and carbon dioxide emissions from energy use (bottom right)

The success of this methanol alone scenario in changing the key fossil energy parameters of the physical economy is reasonable and this is shown in figure 5.5.

- The depletion date of domestic oil stocks is extended by six years by this fuel substitution scenario.
- Oil and methanol demand increases in line with the base case to 2030 and climbs at a higher rate thereafter. Oil imports are limited to about 500 PJ throughout the duration of the scenario.
- The rate of production of methanol crosses over the domestic oil production in 2018, 12 years ahead of the depletion time for domestic oil stocks, which is extended by the fuel substitution strategy. Total methanol production climbs to more than 6000 PJ per year by 2050 and it is possible that this is stimulating consumption growth rather than meeting functional requirements of the physical economy. It is possible to constrain this production by altering the level of oil replacement required in the scenario.
- Growth rate in energy use by transport generally tracks at higher levels than the base case.

Report Card #2: Methanol (0) 1980 to 2050

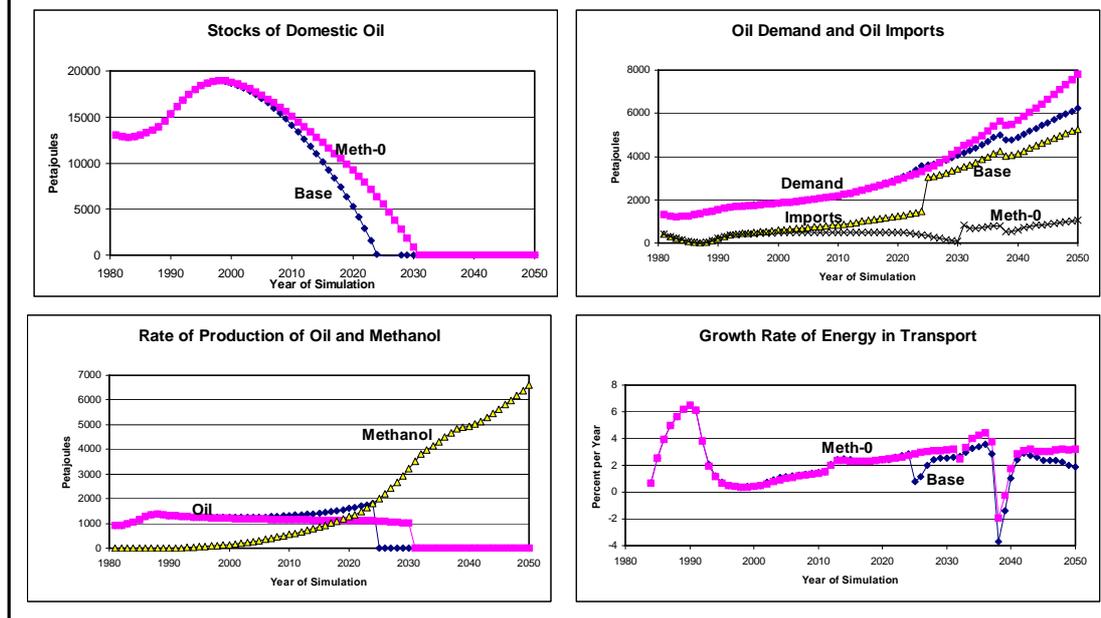


Figure 5.5 Report card #2 for the methanol alone scenario (Meth-0) compared to the base case (Base) showing stocks of domestic oil (top left), oil demand and oil imports (top right), rate of production of domestic oil and ethanol (bottom left) and the growth rate of energy use by transport (bottom right)

The biomass requirements for the methanol alone scenario are considerable and some of the details are shown in figure 5.6.

- By 2050 nearly 31 million hectares of biomass plantation are required to retain a positive wood balance for the entire physical economy compared to 6 million hectares in the base case. At 2020 the requirement is around 15 million hectares.
- By 2050 a total of 500 million tonnes of biomass is required per year to maintain the methanol production of approximately 6000 PJ. The freight task involved in the transport of biomass material could be 20 billion tonne kilometers or about 20% of the current national freight task.
- The energy ratio (available fuel produced in relation to fossil energy used in the production system) increases from 4:1 to 5:1 during the time frame of the simulation. The decline to an energy ratio of 3:1 around the year 2010 is due to the large initial investment in biomass plantations and processing plant which have to be fuelled from fossil sources. The energy ratio begins at a higher level as biomass harvesting is able to utilise and established plantation resource. This drops as the full investment in a biomass based fuel system starts to accelerate.
- The extra energy required by the agriculture and forestry sector climbs to around 450 PJ per year by 2050 compared to a base case of around 200 PJ. This is due to land being excised from high rainfall pasture lands for biomass plantations, which provides two stimulants to energy use. The first is the direct investment in large areas of biomass plantings and the second is the decreasing area of higher rainfall pasture land, which forces more intensification of production to maintain export volumes and therefore more energy is used by the sector.

Report Card #3: Methanol (0) 1980 to 2050

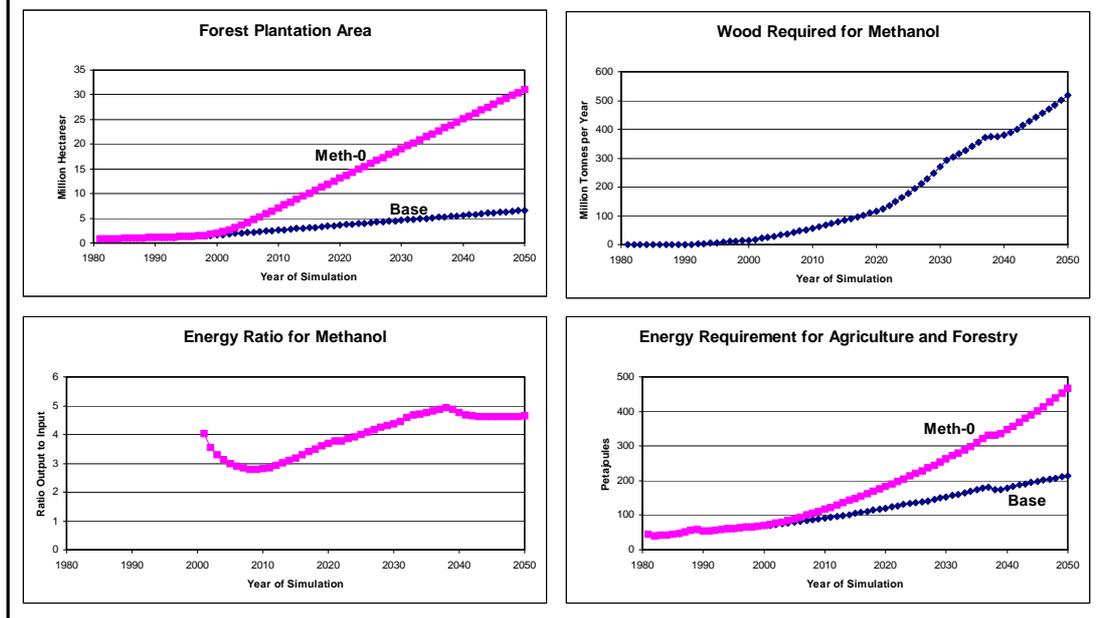


Figure 5.6 Report card #3 for the methanol alone scenario (Meth-0) compared to the base case (Base) showing the biomass plantation area required (top left), the tonnes of feedstock required (top right), the energy ratio of the whole ethanol production system (bottom left) and the energy requirements for agriculture and forestry (bottom right)

Other report cards not shown on this scenario note the following points:

- The direct jobs required by the alcohol fuel cycle climb to more than 200,000 by the year 2025 and more than 500,000 by the year 2050.
- By 2025 all of the transport energy required is being met from the methanol fuel cycle.
- By 2050 the overall fossil energy metabolism of Australia's physical economy has decreased from 14,000 PJ per year to 10,000 PJ per year, an overall drop of 4000 PJ. For the methanol alone scenario, the separation between energy input and energy output has increased to 6000 PJ per year compared to 2500 PJ for the base case.
- The visible balance of payments indicators have improved in comparison to the base case.

Discussion

The methanol alone scenario gives substantial improvements over the base case scenario. It improves indicators of GDP growth rate particularly for the human generation living beyond the year 2025. In addition it decreases carbon dioxide emissions and the energy intensity of GDP, a key functional measure of the energy metabolism of a modern economy. There are three aspects of the scenario which could be improved as follows:

- After the year 2035 there appears to be positive feedback where over-production of liquid fuels stimulates more per capita affluence, more transport usage and more land under plantation biomass.

- The net outcome is that carbon dioxide emissions accelerate after relatively moderate rates of increase.
- These effects are known as rebound (a positive feedback loop) and can be brought under control by a combination of whole-economy measures implemented over long time periods.

The advantages of this scenario and the areas which require attention will form the basis of further scenario development in the following sections. Specifically the scenario design will be improved to further decrease the energy intensity of GDP, thereby decreasing the emissions of carbon dioxide from the energy sector. The cogeneration of electricity will be introduced to supply the requirements of the methanol production system and to use the surplus feedstocks and energy which are not digested by the current process.

Scenario 3: Methanol plus electricity cogeneration

Short abstract

The methanol alone production system from the previous scenario was augmented with biomass-fired electricity generation. Compared to the base case, this scenario improved a number of overall functions in the physical economy. It reduced the energy intensity of GDP to one-quarter the level of the base case, and by 2050 it reduced by 400 million tonnes per year the generation of carbon dioxide emissions from the energy sector. The same area of plantation biomass (31 million hectares) as the methanol alone scenario was required to supply electricity generation plant and methanol feedstocks, but due to a lower requirement for liquid fuels, the amount of methanol-specific feedstock was substantially reduced. The ratio of energy output to energy input rose to 5:1 by the end of the scenario and energy requirements for the agriculture and forestry sector increased by 200 PJ per year in comparison to the base case. Because of the scale of investment required, indicators describing yearly growth rate in GDP and per capita affluence tracked at slightly lower levels than either the base case or the methanol alone scenario.

Key assumptions

This scenario uses the same assumptions as the methanol alone scenario, but includes in addition the following assumptions:

- The desired level for biomass-fuelled electricity generation increases to 80%. This ensures that most new electricity plant will be biomass fuelled, although the 80% target is never reached within the time span of the simulation.
- The biomass electricity plant increases its thermal efficiency from 20% currently to 35% by 2025.
- The biomass electricity plant is 1.5 times the capital cost of traditional thermal electricity plant to account for the implementation of new biomass use technologies.

Results

The top level indicators in the methanol plus electricity cogeneration scenario show the following trends (figure 5.7):

- Growth rate in GDP for this scenario tracks below the base case by approximately 0.5% for the years 2005 to 2020 and then increases to track at the same level as the base. The dip in

growth rates is caused by the increased requirement for capital expenditure for the biomass electricity plant.

- The per capita affluence measure (gigajoules of embodied energy per capita per year) is stabilised at 1990 levels until 2030 and then climbs to equal the base case level by 2050.
- The energy intensity of GDP (megajoules of fossil energy per constant dollar of GDP) is decreased by about 75% (from 8 MJ per dollar to 2 MJ per dollar) by 2050, a notable success in the decarbonisation of economic growth
- The emissions of carbon dioxide from the energy sector start to diverge from the base case from the 2010 onwards. By the end of the simulation they have reached 800 million tonnes per annum compared to nearly 1200 million tonnes per annum for the base case, a drop of 400 million tonnes per annum or roughly equivalent to the current carbon dioxide emissions from the energy sector.

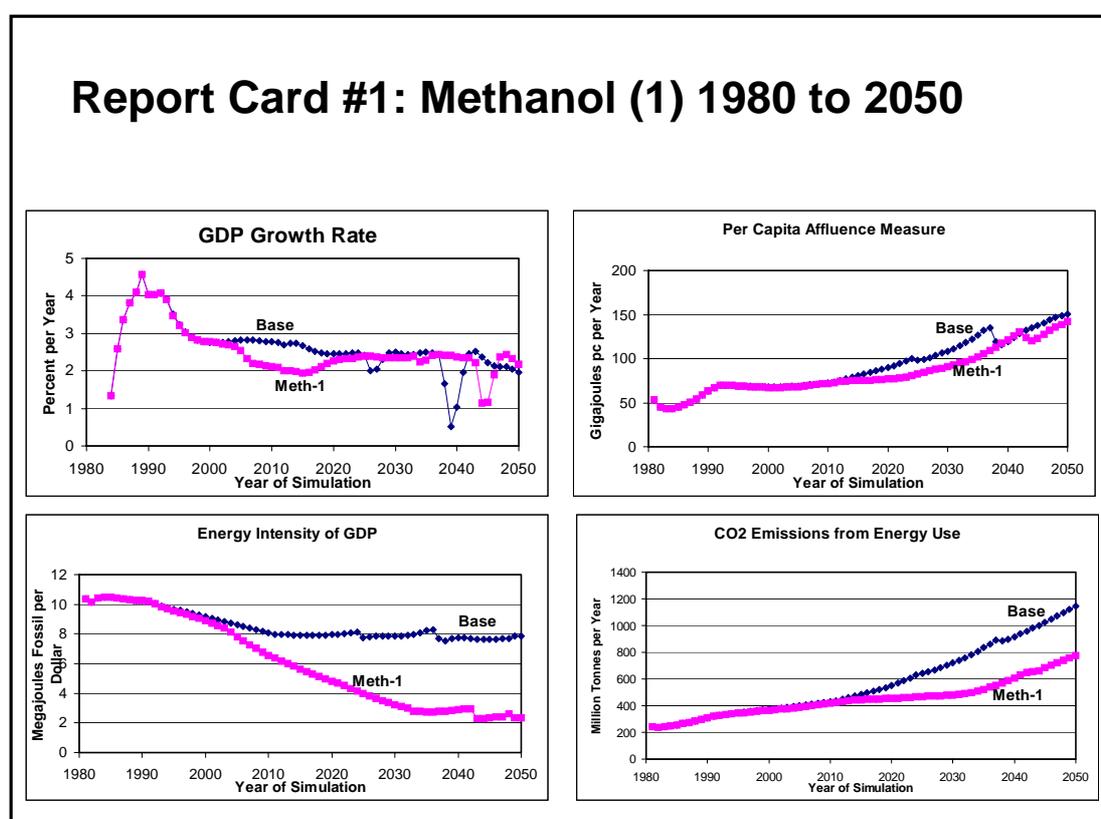


Fig. 5.7. The report card #1 for the scenario of 'methanol plus cogeneration' (Meth-1) compared to the base case (Base) showing growth rate in GDP (top left), per capita affluence index (top right), energy intensity of GDP (bottom left) and CO2 emissions from energy use (bottom right).

The success of this methanol plus electricity cogeneration scenario in changing the key fossil energy parameters of the physical economy is slightly better than the methanol alone scenario and this is shown in figure 5.8.

- The depletion date of domestic oil stocks is extended by eight years by this fuel substitution scenario compared to six years for methanol alone.
- The requirement for oil is similar to the base case although it rises slightly above it for the years 2020 to 2040. The requirement for oil imports, the difference between overall demand

and the combined production of oil and methanol, is kept below 800 PJ per year from 2025 to 2050.

- The rate of production of methanol gradually rises to 5000 PJ per year by 2050 as the fuel replacement strategy is implemented. This is less than the level in the methanol alone scenario due to slightly lower rates of physical activity in the physical economy. The crossover period between oil production and methanol production is around 2020.
- The growth rate in energy use by transport is slightly lower than in the base case particularly in the heavy capital investment period between 2010 and 2020.

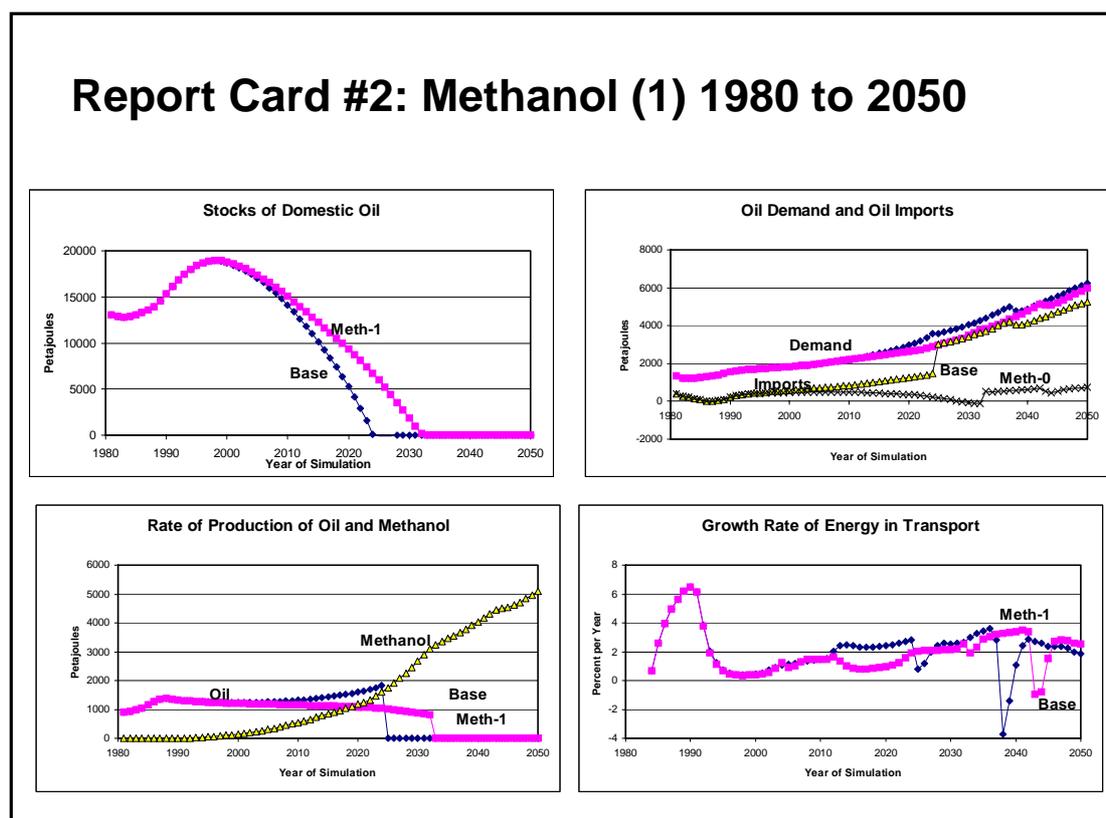


Figure 5.8 Report card #2 for the methanol plus electricity cogeneration scenario (Meth-1) compared to the base case (Base) showing stocks of domestic oil (top left), oil demand and oil imports (top right), rate of production of domestic oil and ethanol (bottom left) and the growth rate of energy use by transport (bottom right)

The biomass requirements for the methanol plus electricity cogeneration scenario have changed in comparison to the methanol alone scenario due mainly to lower levels of transport fuels being required by the whole physical economy. These are shown in figure 5.9.

- Approximately 31 million hectares of biomass plantation are required to retain a positive wood balance for the entire physical economy, similar to the methanol alone scenario.
- Because of lower requirements for liquid fuels from the physical economy (heavier investment, less transport, slightly lower growth rate of GDP, less per capita consumption) the demand for wood for methanol is less (400 versus 500 million tonnes per year), although additional wood is required to fuel the biomass electricity capacity.

- The energy ratio (available fuel produced in relation to fossil energy used in the production system) peaks around 5:1 in the year 2040.
- The extra energy required by the agriculture and forestry sector climbs to 400 PJ per year by 2050 which is 200 PJ per year more than the base case, but a little less than the methanol alone scenario.

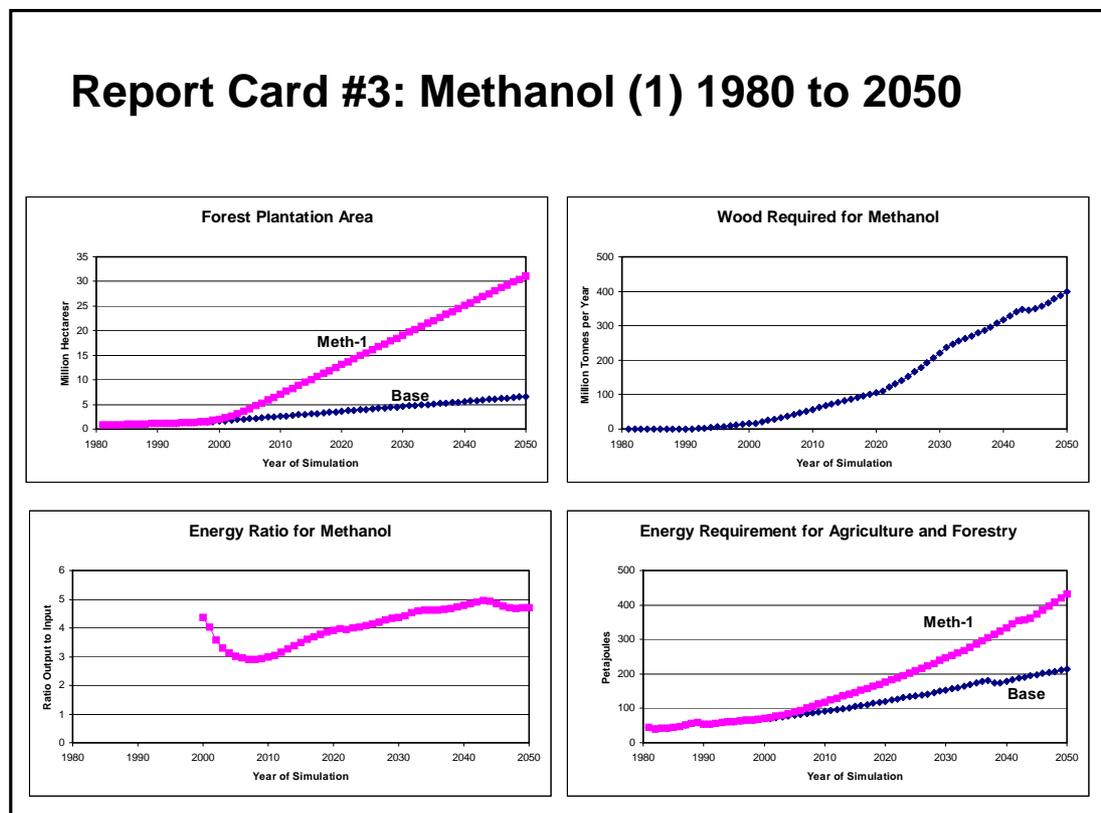


Figure 5.9 Report card #3 for the methanol plus electricity cogeneration scenario (Meth-1) compared to the base case (Base) showing the biomass plantation area required (top left), the tonnes of feedstock required (top right), the energy ratio of the whole ethanol production system (bottom left) and the energy requirements for agriculture and forestry (bottom right)

Other report cards not shown on this scenario display the following points:

- The direct jobs required by the alcohol fuel cycle climb to around 100,000 by the year 2025 and to 400,000 jobs by 2050. In general these are new jobs generated by harvesting and delivery of biomass, the construction of biofuel plants and the running of these plants. Jobs from oil refineries, petroleum exploration and production and associated activities would gradually be lost during the 25 years of phase-in of the methanol fuel cycle, and the phase-out of the hydrocarbon-fuel cycle.
- By 2025, all of the transport energy required is being met from the methanol fuel cycle.
- The overall fossil energy metabolism of Australia's physical economy has by 2050 decreased from 14,000 PJ per year in the base case to 4000 PJ per year, an overall drop of 10,000 PJ. The separation between fossil energy input and embodied energy output within the scenario is 10,000 PJ in 2050, a substantial improvement on the base case and a significant decarbonisation of the physical economy.

- An improvement in the negative balance of the visible balance of payments indicators is shown similar to that detailed in the methanol alone scenario.

Discussion

The methanol plus electricity cogeneration scenario improves substantially on the methanol alone scenario in a number of indicators describing the overall physical economy.

- Carbon dioxide emissions from the energy sector depart from the base case trajectory around 2010 and are 400 million tonnes per year less than the base case by 2050.
- The indicator describing the fossil energy intensity of GDP declines to one-quarter the level of the base case (2 MJ per dollar versus 8 MJ per dollar) by the year 2050.
- Domestic oil stocks are extended by a further two years and the requirements for oil imports are kept relatively low for the duration of the simulation.
- The potential depletion of natural gas stocks is delayed by seven years.

The scenario is still affected by the problem of the rebound effect, which causes carbon dioxide emissions to rise rapidly after 2035. An attempt will be made to manage this rebound in the final scenario of the methanol series. This scenario attempts to control the rebound effect by a radical approach to constraining the size of the physical economy, by altering the nature of international monetary flows and their stimulatory effect in enabling expansion to take place.

Scenario 4: Methanol plus radical economy

Short abstract

The nature of the nation's international monetary arrangements was radically changed in a simulated attempt to manage the rebound effect that stimulates energy use and greenhouse gas emissions in the previous two methanol scenarios. The strategies of ceasing international borrowing, repaying international debt and investing overseas were successful but produced a radically different economy. Greenhouse gas emissions were stabilised and brought to below 1990 levels for the duration of the scenario and the energy intensity of GDP was reduced to one-quarter of the base case strategy. The downsides were that GDP growth rate fluctuated around the 1% per annum level for the duration of the scenario and per capita affluence levels (a physical measure of consumption) stabilised and then declined. Overall it is concluded that this scenario is too radical for the contemporary economic, social and political situation but that it gives some insights for a future, more sustainable energy system.

Key assumptions

This scenario uses assumptions similar to the methanol alone and methanol plus electricity cogeneration scenarios plus the following assumptions, designed to radically transform the nature of international monetary flows. This restricts the rate at which the physical economy grows and specifically aims to control the rebound effect, which was judged to be a problem in the two previous methanol scenarios presented.

- International borrowing was ceased by the year 2010, after which the balance between personal affluence and capital investment in productive purposes had to be sourced from within the physical economy.

- From the year 2000 onwards, international debt was repaid at the rate of 10% of the remaining principle per year, leaving Australia debt-free in international terms from around 2030.
- The balance between capital investment and per capita consumption was biased towards capital investment.
- From 2020 onwards, major capital flows were directed outwards from Australia and long-term investments were made in the physical economies of other nations. In time, this produced a steady flow of investment income without requiring added physical transactions within Australia's physical economy. The global ethics of this strategy are difficult to justify, but it might be modified into a strategic overseas aid approach.
- Lower requirements for electricity and liquid fuels reduced the total planting rate for plantation biomass to 300,000 hectares per year.

Results

The top level indicators in the methanol plus radical economy scenario show the following trends (figure 5.10):

- The growth rate in GDP for this scenario is substantially lower than the other methanol scenarios and the base case. After 2005 it averages about 1% per annum for the duration of the scenario and dips to zero in the period 2030 to 2040, when the availability of investment capital is constrained.
- The per capita affluence measure (gigajoules of energy embodied in personal consumption per capita per year) declines after 2010 to one-third of the base case level by 2050. It should be emphasised that this is a physical measure of consumption and does not represent a quality of life measure.
- The energy intensity of GDP (megajoules of fossil energy per constant dollar of GDP) is decreased by 75% (from 8 MJ per dollar to 2 MJ per dollar) by the year 2035.
- The emissions of carbon dioxide from the energy sector are stabilised for the period to 2010 and then fall back to late 1980s levels of 270 million tonnes per annum, less than that required by the Kyoto negotiations. This is a reduction of 900 million tonnes per annum compared to the base case scenario.

Report Card #1: Methanol (2) 1980 to 2050

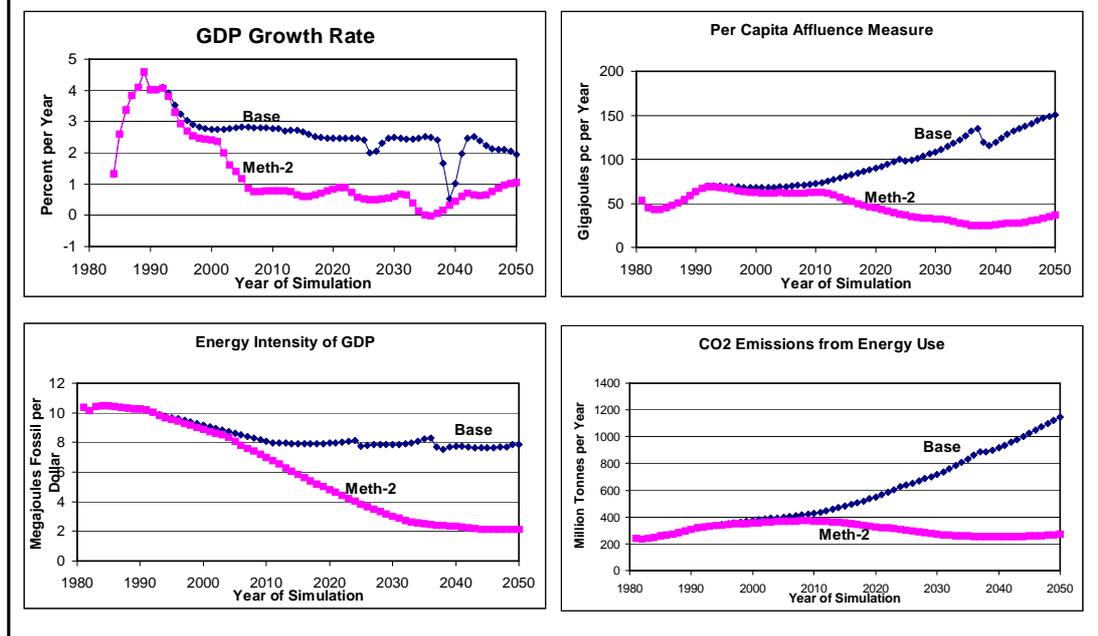


Figure 5.10 Report card #1 for the methanol plus radical economy scenario (Meth-2) compared to the base case (Base) showing growth rate in GDP (top left), per capita affluence index (top right), energy intensity of GDP (bottom left) and carbon dioxide emissions from energy use (bottom right)

This methanol plus radical economy scenario is extremely successful in transforming the energy metabolism of Australia. This is shown in figure 5.11.

- The depletion date of domestic oil stocks is extended by 25 years beyond 2050 by a radical decrease in liquid fuel requirements.
- The requirement for oil departs from the base case from the year 2005 and then stabilises at around 1500 PJ per year for the duration of the simulation period. Oil imports, however, fluctuate around zero for most of the simulation period. There is a 20-year period from 2020 to 2040 when it is possible to achieve complete self sufficiency and even some exports. The modelling uses the concept of net exports and there would still have to be trade in Australian light crudes for heavier oils for lubricants and bitumens.
- The rate of production of the alcohol fuels gradually rises as the fuel replacement strategy is implemented and stabilises at around 1200 PJ per year in 2030. The extension of the depletion date means traditional oil remains in use throughout the simulation period, although it is less than 200 PJ per year by 2050. The crossover between alcohol fuels and traditional oil occurs around 2020. It is possible that this scenario could cease using oil all together which is probably more in sympathy with philosophical approach behind the scenario.
- The growth rate of energy use for transport is negative for the years 2010 to 2040 as the physical economy stabilises or even contracts. It rises to around the same levels as the base case from 2040 onwards as returns from the overseas investment strategy begin to stimulate growth in GDP.

Report Card #2: Methanol (2) 1980 to 2050

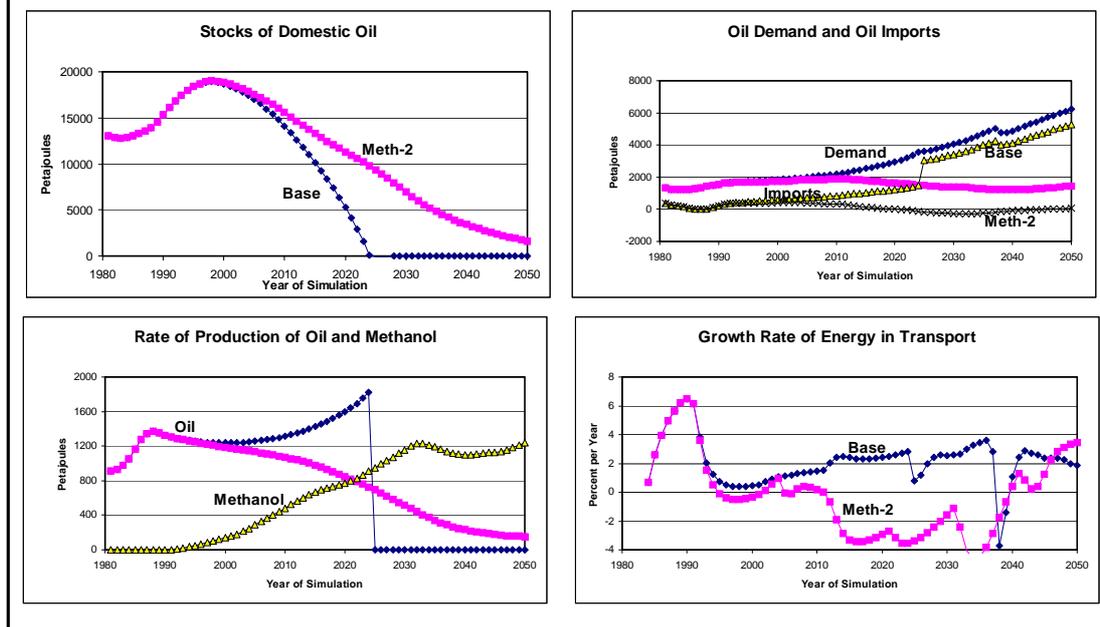


Figure 5.11 Report card #2 for the methanol plus radical economy scenario (Meth-2) compared to the base case (Base) showing stocks of domestic oil (top left), oil demand and oil imports (top right), rate of production of domestic oil and ethanol (bottom left) and the growth rate of energy use by transport (bottom right)

The biomass requirements for the methanol plus radical economy scenario increase the demand for biomass feedstocks to a moderate level in line with moderate levels of demand for liquid fuels. These are shown in figure 5.12.

- More than 8 million hectares of biomass plantation are required to underpin the wood requirements of this scenario by 2020. By 2050, 16 million hectares are required, compared to 6 million hectares in the base case and 31 million hectares in the other two methanol scenarios.
- Methanol production requires 100 million tonnes of wood by 2030 and wood for biomass electricity requires a further 60 million tonnes per annum by 2050.
- The energy ratio of the methanol fuel system (available fuel produced in relation to energy used in the production system) gradually climbs to around 5:1 by the year 2030.
- No extra energy is required by the agriculture and forestry sector compared to the base case. This is driven by a number of factors but mainly a link to the per capita affluence measure where protein consumption in the human diet increases with affluence levels. This is analogous to the diet shifting towards vegetarianism. Lower physical affluence levels in this scenario mean process energy use by agriculture declines, even though stocks of high rainfall pasture land are being reduced by the establishment of biomass plantations.

Report Card #3: Methanol (2) 1980 to 2050

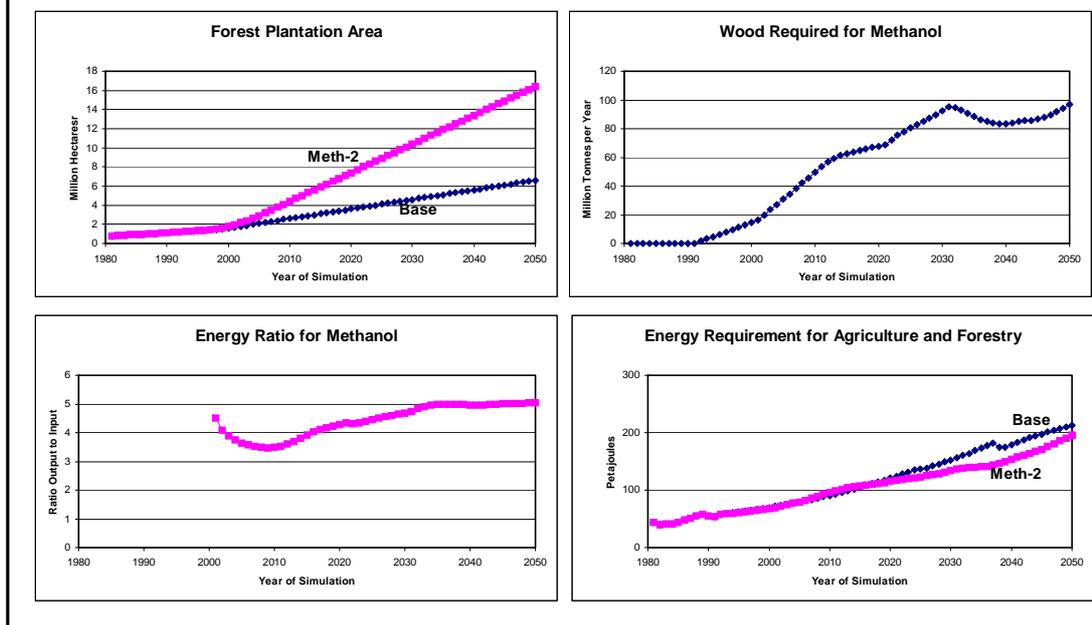


Figure 5.12 Report card #3 for the methanol plus radical economy scenario (Meth-2) compared to the base case (Base) showing the biomass plantation area required (top left), the tonnes of feedstock required (top right), the energy ratio of the whole ethanol production system (bottom left) and the energy requirements for agriculture and forestry (bottom right)

Other report cards not shown for this scenario display the following points:

- The direct jobs required by the alcohol fuel cycle climb to around 100,000 by 2030.
- By 2025 all of the transport energy required is being met from the alcohol fuels cycle although domestic oil is still available.
- By 2050 the overall fossil energy metabolism of Australia's physical economy has decreased from 14,000 PJ to less than 2000 PJ per year. The gap between fossil energy input and embodied energy output in this scenario is 3000 PJ (input 2000 PJ, output 5000 PJ). This is approximately the same difference as the base case but comes from a much lower overall energy metabolism.
- Indicators for the visibles and invisibles balances of payments are in positive balance by the end of the simulation period. The saving of energy imports while maintaining the activity in most commodity export areas maintains a positive balance for the visibles from 2010 onwards. The invisibles sector is kept in negative balance until 2040 in spite of ceasing international borrowing and repaying international debt. This effect is due to large investments offshore in an attempt to restrain internal growth and the rebound effect that it causes.

Discussion

The methanol plus radical economy scenario is probably not a feasible option within the current set of economic, political and social attitudes. The concept that growth rates in GDP would average around 1% would be seen as a failure in policy and leadership and an electorate faced with a stable or declining physical affluence over a 50-year period would not continue to elect governments who imposed such a world on them.

However, the scenario is the one example in the range of options tested in this set which starts to approach some concepts of sustainability while maintaining and enhancing national policies now in place (such as population growth, the Forests 2020 Vision, the Greenhouse Challenge and commodity exports). The key advantages of the scenario are:

- Stabilisation and then sustainable reduction of carbon dioxide emissions from the fossil energy sector to below 1990 levels.
- Retention of the concept of a growth economy – although at one-third to one-quarter the levels that are considered acceptable in a contemporary economic and political setting.
- Transformation of the fossil energy metabolism of the physical economy and reduction of the energy intensity of GDP to 2 MJ per constant dollar.
- Diversification of the options in the supply of liquid transport fuels and development of a new biofuels sector while retaining the traditional sources of oil to 2050 and beyond.
- Production of 100,000 direct new jobs in the biofuels sector, most of them in rural and regional Australia.
- Provision of a productive rationale for the establishment in time of 16 million hectares of perennial deep-rooted biomass plantations within Australia's traditional farming zone.
- Transformation of Australia's international monetary arrangements and possible increased resilience in regard to international debt and balance of payments positions.

The methanol plus radical economy scenario, while judged to be physically feasible in this study, lacks perhaps the political and social feasibility enabling it to be considered within the focus of this particular study. However the deeper implications embedded within the scenario are supported by a growing, although somewhat alternative literature, worldwide.

Scenario 5: Ethanol alone

Short abstract

The transition to an ethanol production system was set to supply 40% of the total oil requirements. Beyond this level there was difficulty after 2030 in maintaining the supply of biomass feedstocks. By 2025 approximately 2000 PJ of ethanol was produced, enough to make the Australian transportation system self sufficient. Overall measures of the economy such as GDP growth rate, per capita physical affluence and energy intensity of GDP were in line with the base case to 2025 and then declined relative to the base case. Carbon dioxide emissions from the energy sector diverged from the base case after 2035 and declined by 300 million tonnes per annum relative to the base case by 2050. The energy ratio for ethanol production was initially around 6:1 as easily obtainable biomass feedstocks were used, but then declined to

2:1 as higher volumes of purpose-grown feedstocks were delivered from the agricultural sector. Energy use by the agricultural sector rose over the simulation period to eight times the level of the base case by 2050. The advantages and disadvantages of the particular production system simulated are used for further refinement and development in subsequent ethanol production scenarios.

Key assumptions

Based on a wide literature review and a limited amount of industry consultation, the eight important assumptions are:

- The ethanol alone scenario would aim to supply 40% of Australia's total oil requirements specifically to meet 100% of the requirements for transportation fuels.
- The feedstock share would be 50% cellulose from agricultural cropping systems, 25% from wood and 25% from waste streams particularly household, food processing and industrial waste.
- The conversion ratio of dry feedstock to ethanol was 25% for crop feedstock, 16% for wood feedstock and 28% for waste feedstock. Over time these would rise to 33%, 20% and 30% respectively.
- Apart from feedstocks, the energy inputs required by ethanol production system were 0.08 PJ of external inputs per petajoule of ethanol produced. This 0.08 PJ was apportioned 30% for thermal or fuel energy and 70% for electricity.
- The capital cost of ethanol plant was \$50 million per petajoule of production capacity and the lifetime of plant was 20 years.
- The job requirements were 50 full-time persons to run the plant, 350 to construct the plant and 150 to supply the biomass feedstocks. Further regional multipliers were not used.
- Some 60% of the wood requirement would be met from logs and the rest from branches and forest waste.
- The rate of plantation biomass establishment (basically forests) was 200,000 hectares per annum and they operated on a 20-year rotation with a 20 m³ per hectare per annum mean annual increment. The cost of establishment of a hectare of biomass plantation is \$2500 (in current dollars) and regular maintenance is part of the accounting procedure.

Results

The top level indicators in this ethanol alone simulation are shown below and in figure 5.13.

- The growth rate in GDP tracks above the base case by approximately 0.5% for the first 25 years after 2000, before dropping to a level 1% below the base case for the rest of the period to 2050. As will be shown in later report cards, the initially higher levels are due more to stimulation of the fuel supply in the physical economy than to increasing efficiency and decarbonisation.
- The per capita affluence measure (gigajoules of embodied energy per capita per year) tracks slightly below the base case until 2035 and then stabilises at around 100 GJ per capita per year after the gas depletion period.

- The energy intensity of GDP (megajoules of fossil energy per constant dollar of GDP) is decreased by about 25% (from 8 MJ per dollar to 6 MJ per dollar) by 2050.
- The emissions of carbon dioxide from the energy sector for this simulation track along the base case until 2035 and then diverge, achieving a 300 million tonne per year decrease by 2050. This is due to the combined effects of a slightly lower energy intensity of GDP, but due mainly to much lower rates of growth in GDP.

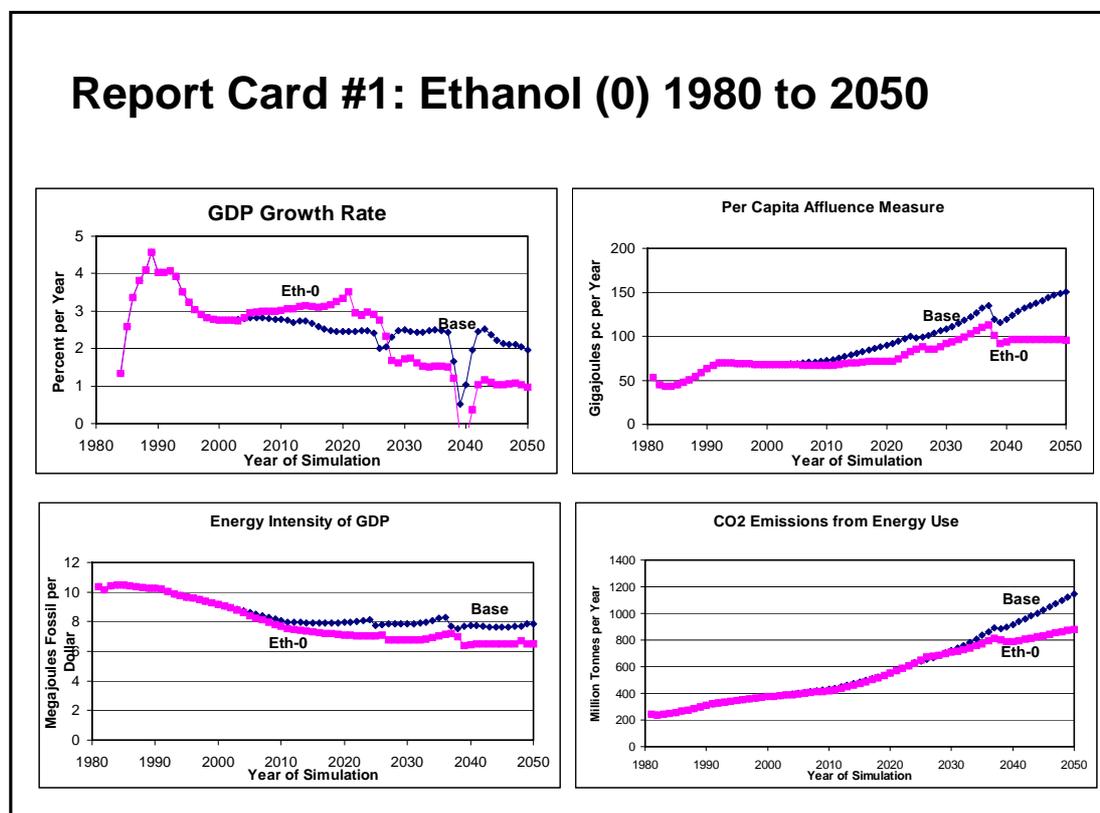


Figure 5.13 Report card #1 for the ethanol alone scenario (Eth-0) compared to the base case (Base) showing growth rate in GDP (top left), per capita affluence index (top right), energy intensity of GDP (bottom left) and carbon dioxide emissions from energy use (bottom right)

The success of this ethanol alone scenario in changing the key fossil energy parameters of the physical economy is only moderate and this is shown in figure 5.14.

- The depletion date of domestic oil stocks is only extended by two years.
- The rate of demand increases for the period 2015 to 2045 in comparison to the base case, due mainly to the fossil fuel inputs required by the biomass production system. This will be detailed in a later report card. Imports of oil under the ethanol alone scenario are lower than in the base case. The levelling off after 2040 is caused more by a drop in economic growth rate and subsequent drop in transport requirement, rather than the magnitude of the fuel substitution effect.
- The rate of production of ethanol crosses over the domestic oil production about three years ahead of the rapid drop-off caused by depletion. Under market mechanisms this transition would be more gradual. The abrupt change in oil production in the simulation is due to a switching mechanism which stops production when oil extraction parameters exceed a level of physical difficulty.

- Growth rate in energy use by transport generally tracks at lower levels than the base case, initially because of the energy demanded by the feedstock production system, and then after 2025 due mainly to the GDP growth rate effect.

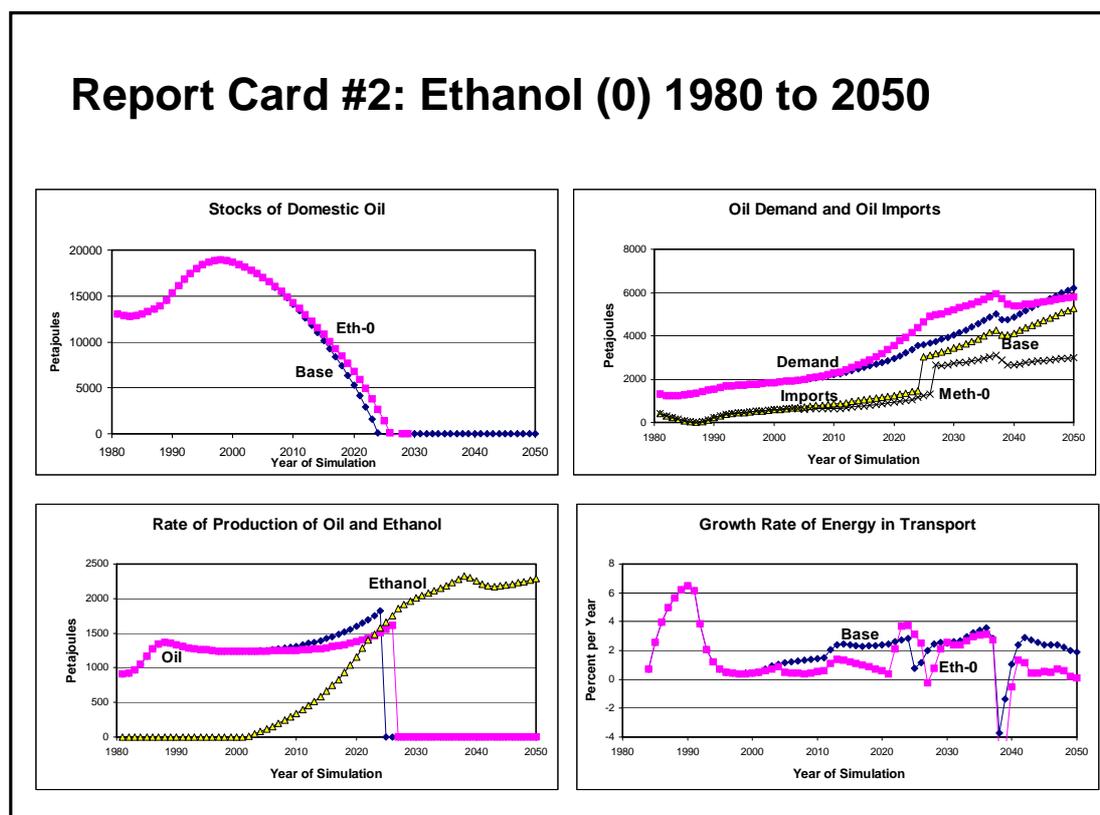


Figure 5.14 Report card #2 for the ethanol alone scenario (Eth-0) compared to the base case (Base) showing stocks of domestic oil (top left), oil demand and oil imports (top right), rate of production of domestic oil and ethanol (bottom left) and the growth rate of energy use by transport (bottom right)

The biomass requirements for the ethanol alone scenario are considerable and some of the details are shown in figure 5.15.

- Nearly 12 million hectares of biomass plantation are required to retain a positive wood balance for the entire physical economy compared to 6 million hectares in the base case. It is assumed that the crop biomass required for ethanol feedstock (traditional forage biomass and standing crop residues) is sourced from the present stocks of ploughed land or pasture land. The perennial biomass plantation land could occupy cleared land which is either perennial pasture or annually cropped. No virgin land is cleared.
- By 2040, 240 million tonnes of biomass is required per year to maintain ethanol production of approximately 2000 PJ. This is made up of 100 million tonnes of crop biomass, 80 million tonnes of wood biomass and 60 million tonnes of waste. This yearly requirement represents an immense set of physical transactions but should be viewed against the 3400 million tonnes of physical movements (excluding water) which currently keep Australia's physical economy functioning.
- The energy ratio (available fuel produced in relation to fossil energy used in the production system) reaches a peak of around 6:1 by 2010 and then declines to 2:1 by 2020. The initial hump is due to the initial availability of relatively free biomass feedstocks. When these

feedstocks have to be supplemented by purpose-grown biomass (particularly the high cellulose forage types), additional energy input is required.

- The extra energy required by the agriculture and forestry sector climbs to around 1600 PJ per year by 2030 compared to a base case of around 200 PJ. This result is questionable and good design and management should be able to reduce the extra energy required to perhaps 1000 PJ or about the same amount used by the transport sector today. The result is also dependent on the assumptions that biomass feedstock is sourced from presently managed and cleared landscapes and that no ‘wild harvesting’ is available. While details might vary, the key point remains that high outputs of biomass feedstock from most Australian landscapes will require high inputs of fossil energy for the maintenance of growth and for harvesting.

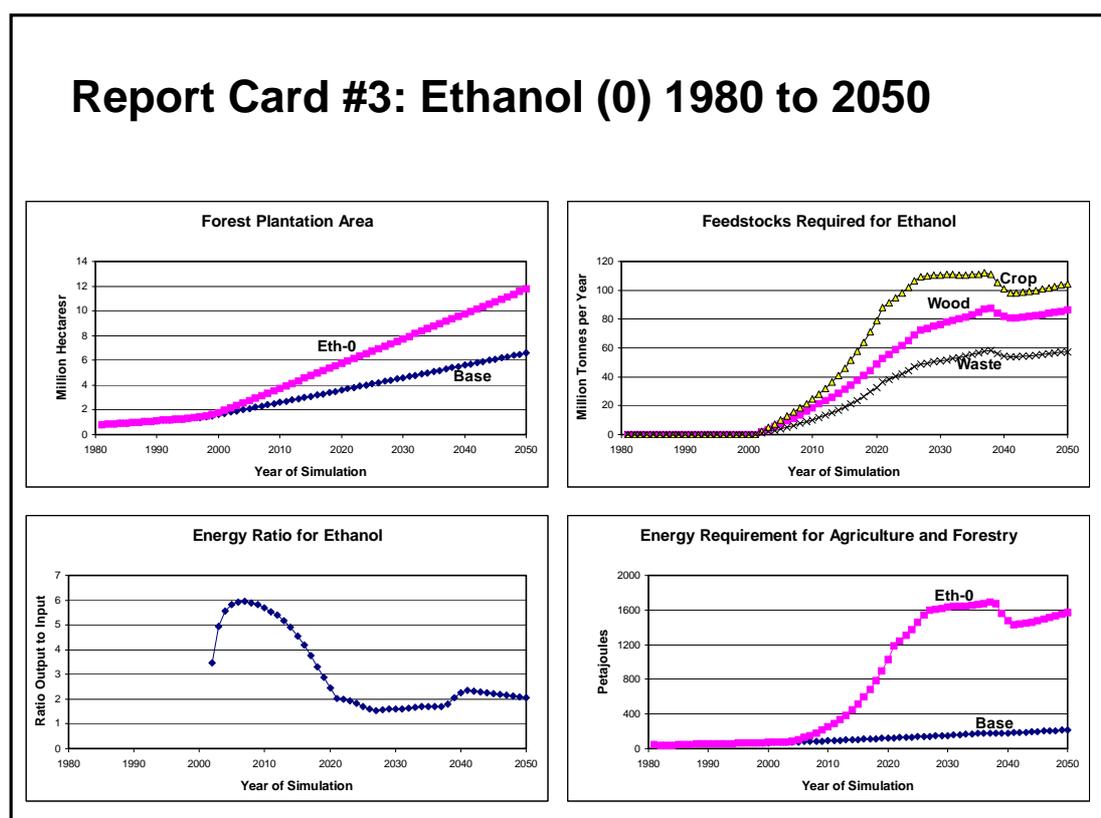


Figure 5.15 Report card #3 for the ethanol alone scenario (Eth-0) compared to the base case (Base) showing the biomass plantation area required (top left), the tonnes of feedstock required (top right), the energy ratio of the whole ethanol production system (bottom left) and the energy requirements for agriculture and forestry (bottom right)

Other report cards not shown note the following points:

- The direct jobs required by the alcohol fuel cycle climb to more than 160,000 by the year 2025. The current assumptions are that 50 persons are required to run an ethanol plant producing 1 PJ of ethanol per year, 350 persons are required to construct the plant and 150 persons are required in the production, harvesting and delivery of biomass to the plant. Regional employment multipliers which gain leverage from the sum total of this activity are not included.
- By 2025 all of the transport energy required is being met from the ethanol fuel cycle.

- By 2050 the overall fossil energy metabolism of Australia's physical economy has decreased from 14,000 PJ per year to 9000 PJ per year. However, in the separation between energy input and energy output the ethanol alone and the base case scenario are similar at about 2500 PJ per year. This means that very little advantage has been gained in decarbonising the physical economy because of the requirements for ancillary fossil energy inputs.
- An advantage has been shown for the visible balance of payments indicators in comparison to the base case. This is partially an artefact of the modelling procedures for the farming sector where large increases in biomass feedstock have been accompanied by large surpluses in vegetable protein available for export. A liberal interpretation of these indicators might note that this transition into the hi-tech carbohydrate economy, which is central to this scenario, might indeed liberate many by-products which could contribute to a non-fossil-fuel-based export surplus.

Discussion

The ethanol alone scenario has four key advantages but, in its current form and implementation, falls down on five main requirements. The four advantages are:

- it can use a wide range of feedstocks, both virgin and waste;
- it creates 160,000 jobs in rural Australia;
- it maintains GDP growth rate and physical affluence for the next human generation; and
- it supplies all the liquid fuels for transport from 2025 onwards.

The five areas where the ethanol alone scenario falls down are:

- carbon dioxide emissions from the energy sector do not fall compared to the base case until after 2035;
- it requires high energy inputs to maintain the biomass feedstock production system;
- it does not appreciably extend the lifetime of Australia's domestic oil stocks;
- it does not much alter the requirements for oil imports for various non-transport requirements; and
- the eventual energy ratio (of outputs to inputs) of around 2:1 represent a less efficient production system than might have been expected.

These advantages will form the basis of further scenario development in the following sections. Specifically the scenario design will be improved to further decrease the energy intensity of GDP, thereby decreasing the emissions of carbon dioxide from the energy sector. The cogeneration of electricity will be introduced to supply the requirements of the ethanol production system and to use the surplus feedstocks which are not used by the current technological settings.

Scenario 6: Ethanol plus electricity cogeneration

Short abstract

The ethanol alone production system from the previous scenario was augmented with biomass-fired electricity generation. Compared to the base case, this improved a number of overall functions in the physical economy: it halved the energy intensity of GDP and reduced by 500 million tonnes per year the generation of carbon dioxide emissions from the energy sector by 2050. A larger area of plantation biomass (20 million hectares) was required to supply electricity generation plant and ethanol feedstocks but, due to a lower requirement for liquid fuels, the amount of ethanol-specific feedstock was substantially reduced. The ratio of energy output to energy input improved from 2:1 to 3:1 and energy requirements for agriculture were reduced to 1200 PJ per year, by the year 2050, a drop of 400 PJ compared to the previous scenario. The scale of investment required meant indicators describing yearly growth rate in GDP and per capita affluence tracked at lower levels than in the base case and the ethanol alone scenarios.

Key assumptions

This scenario uses the same assumptions as the ethanol alone scenario plus:

- The desired level for biomass-fuelled electricity generation is increased from 20% in the base case scenario to 80%. This ensures that most new electricity plant will be biomass fuelled, although the 80% target is never reached within the time span of the simulation.
- The biomass electricity plant increases its thermal efficiency from 20% currently to 35% by 2025.
- The rate of plantation biomass establishment (basically forests) is increased from 200,000 to 300,000 hectares per annum to ensure that a positive wood balance is maintained.

Results

The top level indicators in the ethanol plus electricity cogeneration scenario show the following trends (figure 5.16):

- The growth rate in GDP tracks approximately 0.5% below the base case for the first 25 years after 2000, before dropping to a level 1.5% below the base case for the rest of the period to 2050. This drop is caused by the increased capital expenditure on electricity cogeneration plant at the same time as ethanol production plant is being constructed.
- The per capita affluence measure (gigajoules of embodied energy per capita per year), is stabilised at 1990 levels for the duration of the simulation and is 50% of the base case level by 2050. This effectively halves the physical embodiment of fossil fuel in what might be called discretionary expenditure in economic terms and represents a very different economic structure and function than the current one. However, it need not be interpreted as flattening quality of life. Rather it could represent a different version of economic and social structures where affluence is partially separated from flows of fossil energy and materials.
- The energy intensity of GDP (megajoules of fossil energy per constant dollar of GDP) is decreased by about 50% (from 8 MJ per dollar to 4 MJ per dollar) by 2050. This is an indicator of success in the de-jouling or decarbonisation of economic growth.
- The emissions of carbon dioxide from the energy sector start to diverge from the base case from 2020. By the end of the simulation they are 700 million tonnes per annum compared to nearly 1200 million tonnes per annum for the base case. This represents a reduction of 500 million tonnes per annum or 125% of current carbon dioxide emissions from the energy sector.

Report Card #1: Ethanol (1) 1980 to 2050

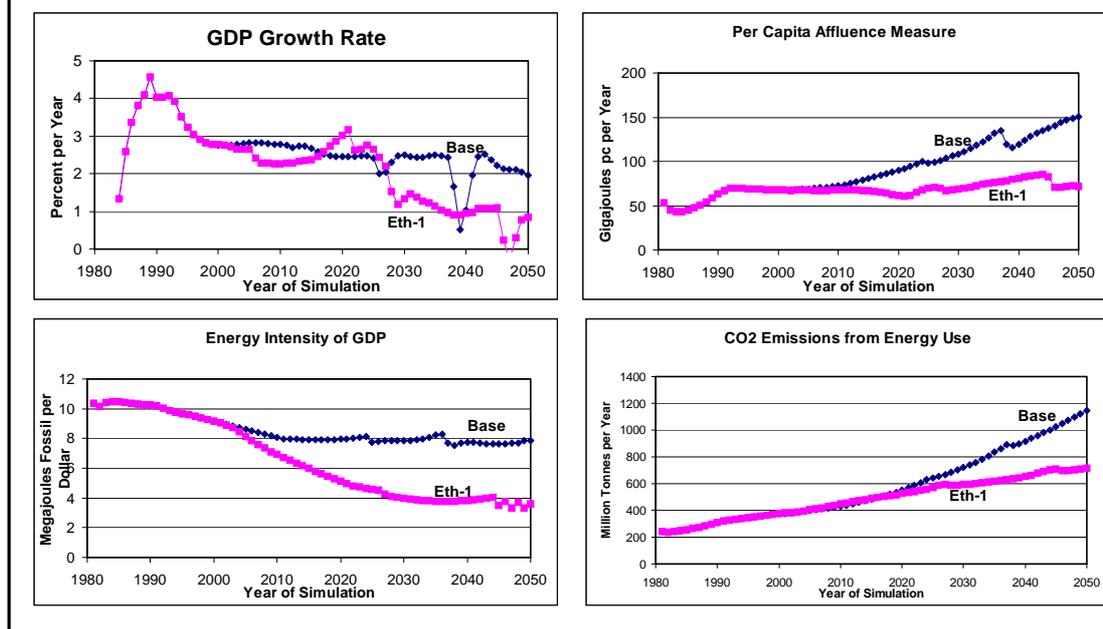


Figure 5.16 Report card #1 for the ethanol plus electricity cogeneration scenario (Eth-1) compared to the base case (Base) showing growth rate in GDP (top left), per capita affluence index (top right), energy intensity of GDP (bottom left) and carbon dioxide emissions from energy use (bottom right)

The success of this ethanol plus electricity cogeneration scenario in changing the key fossil energy parameters of the physical economy is slightly better than the ethanol alone scenario and this is shown in figure 5.17.

- The depletion date of domestic oil stocks is extended by two years, much the same result as for ethanol alone.
- The rate of demand for oil is similar to the base case until 2025 and then flattens and is more or less constant at around 4000 PJ per year. The required oil imports (that is, the difference between overall demand and the combined production of oil and ethanol) then stabilises at around 2000 PJ per year from 2025 to 2050.
- The rate of production of ethanol gradually rises as the fuel replacement strategy is implemented and stabilises at around 1600 PJ per year after 2030. This is less than the level in the ethanol alone scenario due mainly to lower requirements demanded in response to slightly lower rates of physical activity in the overall physical economy. The crossover period between oil production and ethanol production is around 2025.
- The growth rate of energy use for transport is generally 2% lower than in the base case and it is probable that this is driven more by industrial activity than consumer requirement, compared to the base case and ethanol alone scenarios.

Report Card #2: Ethanol (1) 1980 to 2050

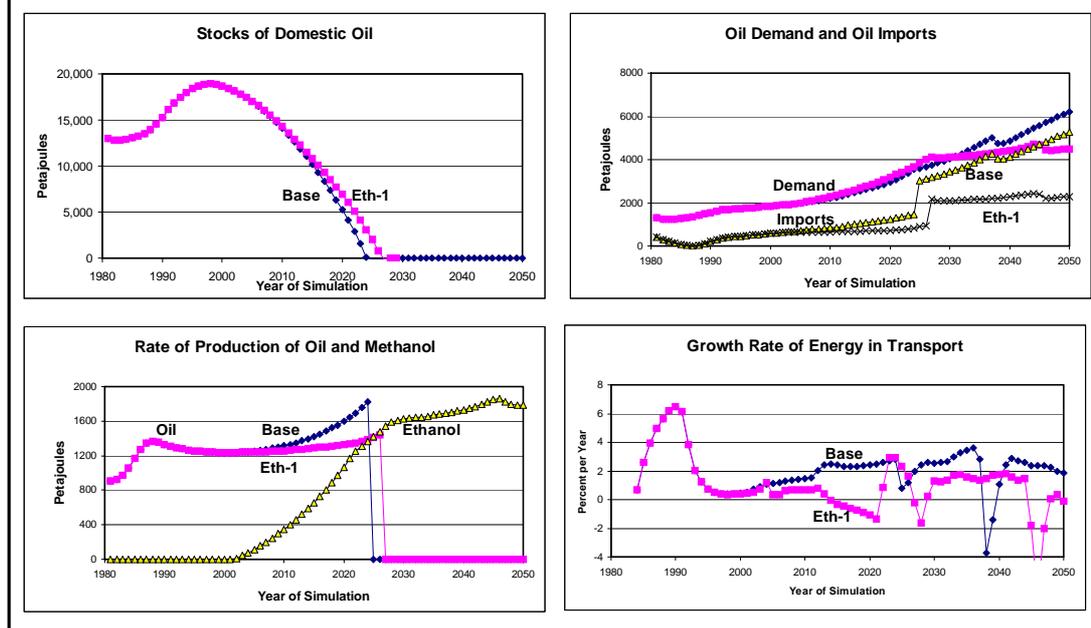


Figure 5.17 Report card #2 for the ethanol plus electricity cogeneration scenario (Eth-1) compared to the base case (Base) showing stocks of domestic oil (top left), oil demand and oil imports (top right), rate of production of domestic oil and ethanol (bottom left) and the growth rate of energy use by transport (bottom right)

The biomass requirements for the ethanol plus electricity cogeneration scenario have changed in comparison to the ethanol alone scenario due mainly to lower levels of transport fuels being required by the whole physical economy. These are shown in figure 5.18.

- Nearly 20 million hectares of biomass plantation are required to retain a positive wood balance for the entire physical economy compared to 6 million hectares in the base case and 12 million hectares in the ethanol alone scenario.
- The transition from coal-fired to biomass-fired electricity plant increases the demand for wood. The requirement for each of the ethanol feedstocks (crop, wood and waste) has stabilised at a level approximately 20 million tonnes per year lower than the ethanol alone scenario. A total of 180 million tonnes of feedstock is required for ethanol production, one-third of which is assumed to be available for electricity cogeneration purposes. A further 160 million tonnes of wood is required specifically for electricity generation by biomass.
- The energy ratio (available fuel produced in relation to fossil energy used in the production system) peaks a little lower at 5.8:1 compared to the ethanol alone scenario, but stabilises at around 3:1 after 2035 due to assumed improvements in process efficiency, the effect of cogeneration and lower requirements for feedstock availability.
- The extra energy required by the agriculture and forestry sector climbs to around 1200 PJ per year by 2030 which is 400 PJ per year lower than the ethanol alone scenario.

Report Card #3: Ethanol (1) 1980 to 2050

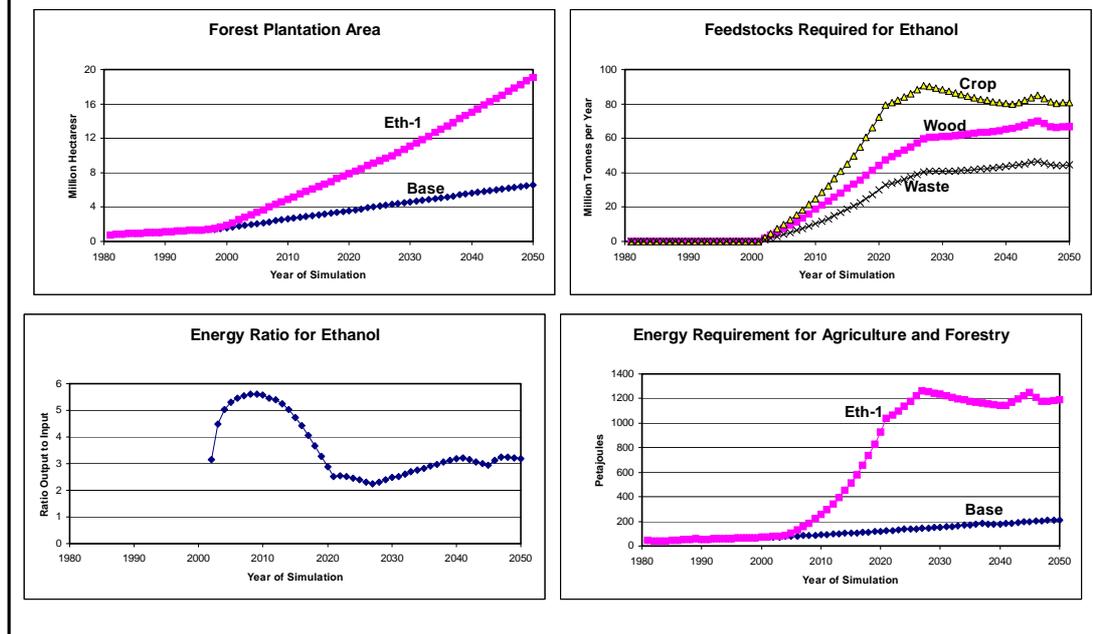


Figure 5.18 Report card #3 for the ethanol plus electricity cogeneration scenario (Eth-1) compared to the base case (Base) showing the biomass plantation area required (top left), the tonnes of feedstock required (top right), the energy ratio of the whole ethanol production system (bottom left) and the energy requirements for agriculture and forestry (bottom right)

Other report cards display the following points:

- The direct jobs required by the alcohol fuel cycle climb to around 140,000 by the year 2025, about 20,000 jobs fewer than in the ethanol alone scenario, due mainly to lower levels of overall liquid fuel requirement.
- By 2025 all of the transport energy required is being met from the ethanol fuel cycle.
- By 2050 the overall fossil energy metabolism of Australia's physical economy has decreased from 14,000 PJ per year to 9000 PJ per year. In addition, fossil energy input and embodied energy output have separated substantially compared to the base case and ethanol alone scenarios, showing a significant dejouring of the physical economy.
- There is an advantage in the visible balance of payments indicators, similar to that detailed in the ethanol alone scenario.

Discussion

The ethanol plus electricity cogeneration scenario improves substantially on the ethanol alone scenario in a number of indicators describing the overall physical economy:

- Carbon dioxide emissions from the energy sector depart from the base case trajectory around 2020 and are 500 million tonnes per year lower by 2050.

- The indicator describing the fossil energy intensity of GDP declines to half the level of the base case (4 MJ per dollar versus 8 MJ per dollar) by 2025.
- While it does not extend the lifetime of domestic oil stocks, it does stabilise the requirements for oil imports at 2000 PJ per year to 2050.

However the scenario lowers the long run growth in GDP indicator to 1% from 2025 onwards, compared to the base case which varies from 2.5% to 2% in the same period. The per capita affluence indicator remains stable at 1990 levels, signifying a changed structure in the economy rather than a stable or declining quality of life. The jobs generated by this approach to ethanol generation total 20,000 less than in the ethanol alone scenario, although the supply of wood to biomass electricity plants would generate significant jobs to balance this reduction.

In their present formulation, the ethanol scenarios are inherently limited by the moderate yield of ethanol per unit of biomass feedstock. Over the scenario time frames, these yields are increased in line with the technological developments anticipated by the National Renewable Energy Laboratory in the United States and a wide range of current scientific literature. The scenarios are also affected by the treatment of crop biomass growth within the model. This crop treatment could be improved by detailed modelling of different production systems that are designed for each location.

The final scenario attempts to make the best of both world by supplementing the ethanol production systems in this scenario with methanol production from wood.

Scenario 7: Ethanol plus methanol

Short abstract

The scenario combined both ethanol and methanol into a joint alcohol fuels strategy. The energy intensity of GDP was reduced from 8 MJ to 2 MJ per constant dollar, giving some theoretical underpinning to the Factor 4 concept, where economic productivity can be achieved at one-quarter the level of physical transactions. Carbon dioxide emissions were 700 million tonnes per annum at 2050, a reduction of 500 million tonnes per year on the base case. Domestic oil stocks were extended by 10 years to 2035 and 400,000 direct jobs were created by the end of the simulation period. However, the GDP growth rate was still below the base case after 2025 and the indicator of per capita affluence still tracked below the base case trajectory. Overall this combined scenario met most of the strategic requirements, the main questions centring on the feasibility of establishing 27 million hectares of biomass plantations by the year 2050.

Key assumptions

This scenario uses the same assumptions as the ethanol alone and ethanol plus electricity cogeneration scenarios plus:

- supplying 50% of the yearly oil requirement with methanol from wood to augment the 40% already supplied by the ethanol process; and
- increasing the rate of plantation biomass establishment (basically forests) from 200,000 or 300,000 hectares to 500,000 hectares per annum, to ensure that a positive wood balance is maintained.

Results

The top level indicators in the ethanol plus methanol scenario show the following trends (figure 5.19):

- The growth rate in GDP maintains a similar track to the ethanol plus electricity cogeneration scenario up to 2025, after which it maintains a track which lies between the base case and the ethanol plus electricity cogeneration scenario.
- The per capita affluence measure (gigajoules of embodied energy per capita per year) is stabilised at 1990 levels to 2020 and then grows gradually to 2040, when it stabilises on a level two-thirds of the base case.
- The energy intensity of GDP (megajoules of fossil energy per constant dollar of GDP) is decreased by 75% (from 8 MJ per dollar to 2 MJ per dollar) by the end of this simulation. This result is an example of the Factor 4 concept where economic productivity can be achieved at one-quarter the level of physical transactions.
- The emissions of carbon dioxide from the energy sector take a slightly different track than in the ethanol plus electricity cogeneration scenario, being relatively stable to around 2030 before rising to achieve the same end result of 700 million tonnes per annum by 2050. This pattern suggests that a set of new initiatives (in different sectors of the physical economy) planned for implementation in that period might have success in maintaining economic and affluence indicators, while flattening and decreasing carbon dioxide emissions.

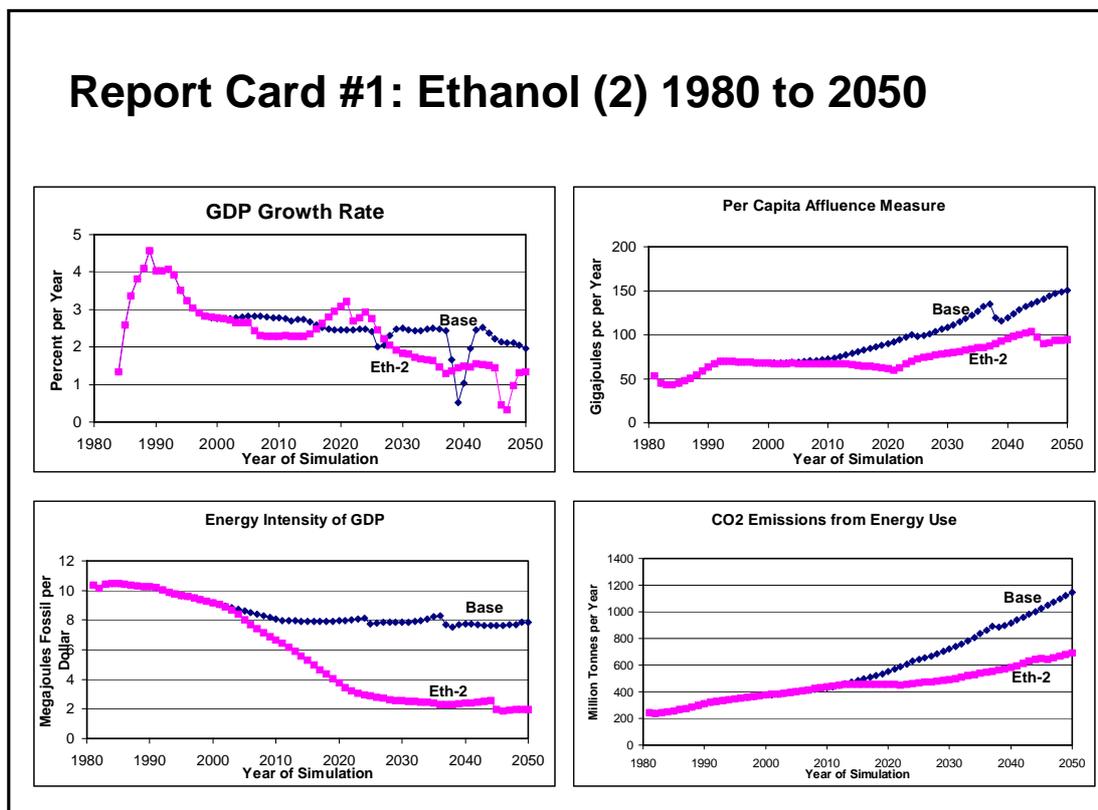


Figure 5.19 Report card #1 for the ethanol plus methanol scenario (Eth-2) compared to the base case (Base) showing growth rate in GDP (top left), per capita affluence index (top right), energy intensity of GDP (bottom left) and carbon dioxide emissions from energy use (bottom right)

The ethanol plus methanol scenario is relatively successful in transforming the energy metabolism of Australia (figure 5.20).

- The depletion date of domestic oil stocks is extended by 10 years to 2035.
- The requirement for oil is similar to the base case throughout the simulation period. However, oil imports are kept at around 500 PJ per year for most of the simulation period. There is a 10-year period from 2020 to 2030 when it is possible to achieve complete self sufficiency and even some exports.
- The rate of production of the alcohol fuels gradually rises as the fuel replacement strategy is implemented and stabilises at around 2500 PJ per year in 2045 for each fuel, giving a total of 5000 PJ. The requirement for domestic production of oil is moderated by the production of substitute fuels and it declines after 2010 but remains until 2035. The crossover between alcohol fuels and traditional oil occurs around 2015.
- For the period 2000 to 2020, the growth rate for energy use by transport is generally 2% lower than in the base case. After 2020, however, the growth rates in transport energy use are broadly comparable.

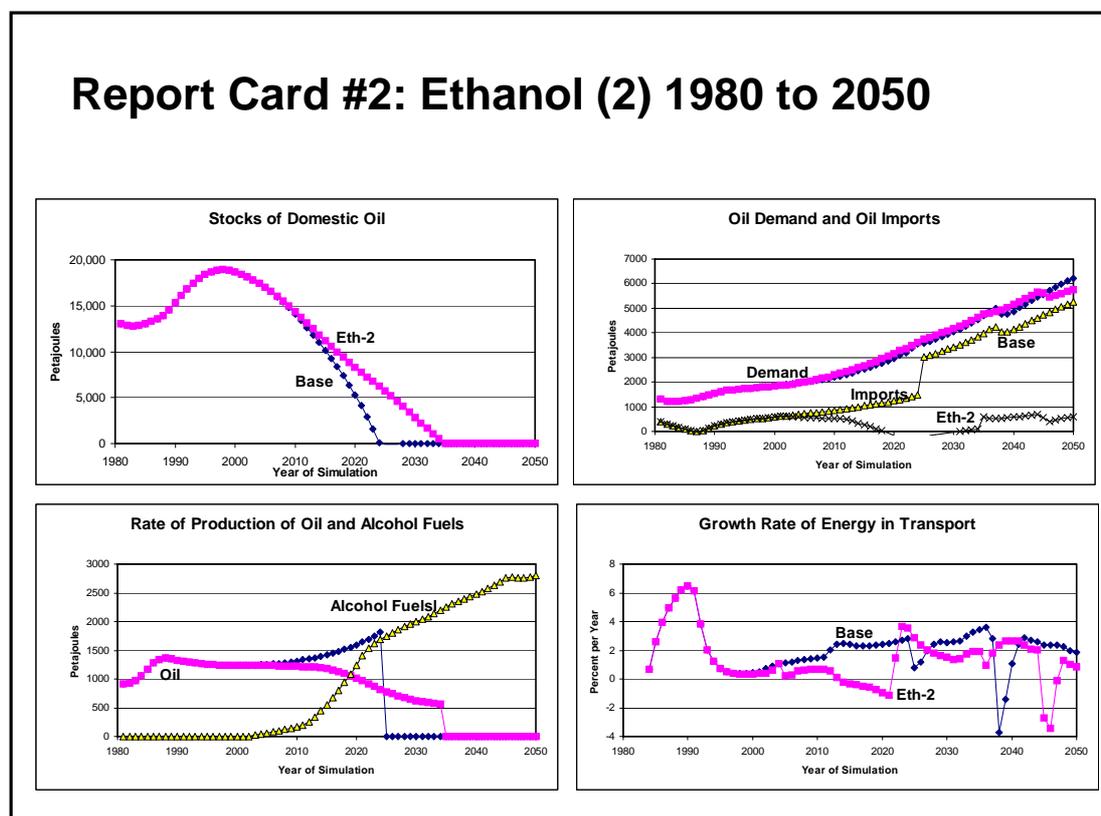


Figure 5.20 Report card #2 for the ethanol plus methanol scenario (Eth-2) compared to the base case (Base) showing stocks of domestic oil (top left), oil demand and oil imports (top right), rate of production of domestic oil, ethanol and methanol (bottom left) and the growth rate of energy use by transport (bottom right)

The biomass requirements for the ethanol plus methanol increase the demand for biomass feedstocks to a high level (figure 5.21).

- An area of more than 27 million hectares of biomass plantation is required to retain a positive wood balance for the entire physical economy, compared to 6 million hectares for the base case and 20 million hectares in the ethanol plus electricity cogeneration scenario.
- Methanol production requires 200 million tonnes of wood by 2040 and ethanol production a similar total made up of crops, wood and waste.
- The energy ratio (available fuel produced in relation to energy used in the production system) for ethanol declines eventually to around 2:1, while methanol climbs to around 6:1. The differences in modelling dynamics between the two energy ratios in the graphs suggest a competition for feedstock. In practice, capital expenditure in plant would be lagged to meet availability and continuity of biomass feedstock supplies.
- The extra energy required by the agriculture and forestry sector climbs to around 1600 PJ per year by 2030, which is similar to the level required in the ethanol alone scenario.

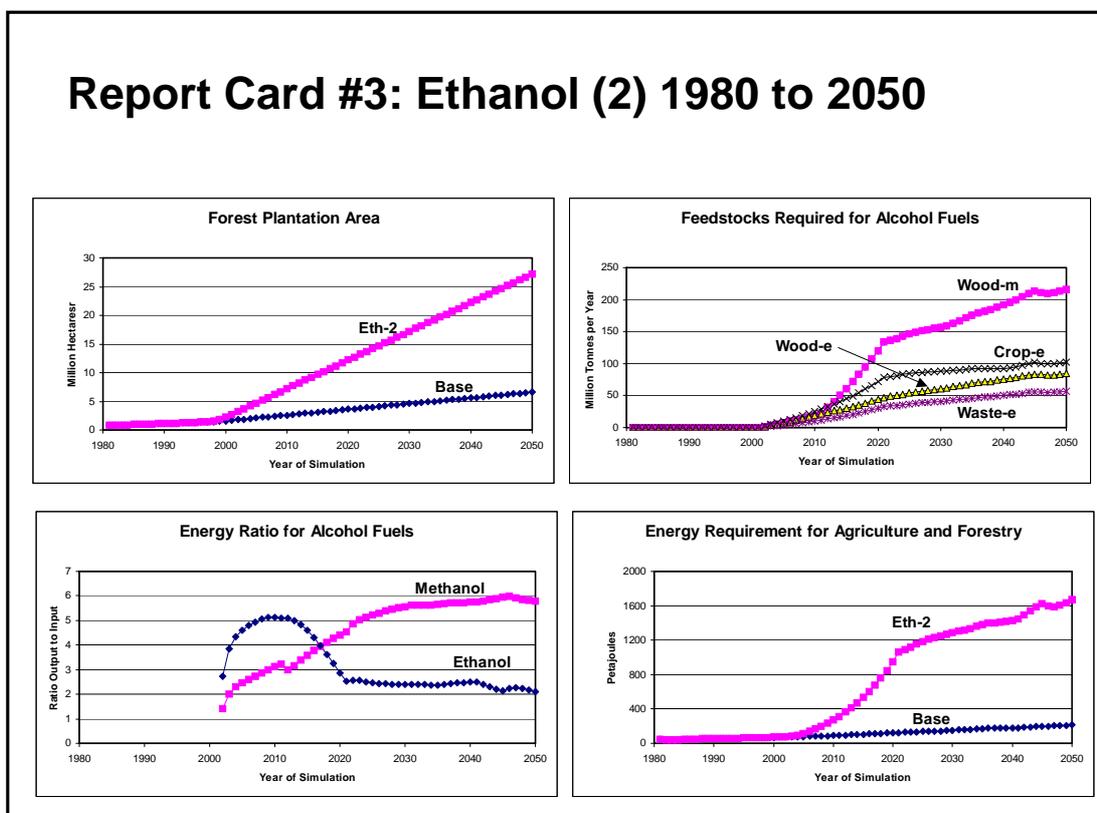


Figure 5.21 Report card #3 for the ethanol plus methanol scenario (Eth-2) compared to the base case (Base) showing the biomass plantation area required (top left), the tonnes of feedstock required (top right), the energy ratio of the whole ethanol and methanol production system (bottom left) and the energy requirements for agriculture and forestry (bottom right)

Other report cards display the following points:

- The direct jobs required by the alcohol fuel cycle climb to around 400,000 by the year 2040.
- By 2016, all of the transport energy required is being met from the alcohol fuels cycle and there is a substantial capacity to replace oil in a variety of petrochemical applications.
- By 2050 the overall fossil energy metabolism of Australia's physical economy has decreased from 17,000 PJ per year to 12,000 PJ per year. In addition, the gap between fossil energy

input and embodied energy output has widened to 9000 PJ, indicating a significant removal of fossil energy from the physical economy.

- There is an advantage in the visible balance of payments indicators, similar to that detailed in the ethanol alone scenario.

Discussion

The ethanol plus methanol scenario uses key facets of both processes to substantially alter the physical economy over the next 50 years, or two human generations. In particular it has the following advantages:

- Carbon dioxide emissions from the energy sector remain relatively stable to 2020 and then rebound more rapidly, but are still 500 million tonnes per year lower than the base case by 2050.
- The indicator which describes the fossil energy intensity of GDP declines to one-quarter the level of the base case (2 MJ per dollar versus 8 MJ per dollar) by the year 2040, thus giving a theoretical underpinning to the concept of the Factor 4 economy.
- The scenario extends the lifetime of domestic oil stocks from 2025 to 2035 and stabilises the requirements for oil imports at around 500 PJ per year out to 2050.

There are a number of disadvantages, two of which (lowered rates in growth of a nominal GDP and lower per capita affluence in comparison to the base case) have been discussed in previous sections.

A third factor is the feasibility of supplying this amount of biomass feedstock on a continuing basis. There are three important facets in examining this issue. The first is land availability, which will be analysed briefly in the next chapter. A recent Australian Bureau of Agricultural and Resource Economics (Burns et al., 1999) publication estimated that there were approximately 20 million hectares of cleared pasture land available for plantations and market-driven carbon credit schemes. Stewart et al. (1979) suggest that 70 million hectares were available for biomass production. It is feasible therefore that the 27 million hectares required by this scenario is available. The second issue is one of biomass plantation productivity. We have made a simplifying assumption based on a 20-year rotation and a 20 m³ per year mean annual increment. Plantations in areas with poor soils and in marginal rainfall zones will not achieve these rotation periods or production rates. It is reasonable, however, to assume that selection and breeding of biomass plant types and development of integrated production systems will allow practical and economically viable systems to be developed which maintain biomass flows. The last issue is whether this scale of establishment of biomass plantations will substantially affect the hydrology of the farming zones and dry up streams and rivers. The focus of this study is to do just that with deep-rooted plant production systems that tap elevated water tables and perched accumulations of mineral nutrients. The spatial strategy of how 27 million hectares of biomass plantations might be located while enhancing biodiversity values, visual amenity, social values and normal expectations of agricultural production is beyond the scope of this document.

OVERALL DISCUSSION

The entry point into choosing which strategy to implement at a national level is a difficult one, and depends as much upon world view and sectoral interest as it does on the numbers and graphs that form the centre of the analytical outputs from the simulation of the different scenarios. There is also the problem of time frames. The scenarios tested in this study are focused on intergenerational time frames of 25 to 50 years. The insights from the modelling suggest that in that time frame, domestic oil and gas stocks might become constrained, human population might grow to 25 million in Australia and 10 billion globally and the current size of the economy and its greenhouse gas emissions might triple. Implementing a transition to an alcohol fuels-driven economy can only be achieved over intergenerational time frames. It is probably wise and politic to exploit the current economic structure, the current transport system and domestic stocks of oil and gas, while making long-term plans to change the structure and function of the physical economy. In these time frames of 50 years or more, current management ideologies may change markedly.

For this reason the options for a transition to biomass fuels will be evaluated under three different ideological frameworks or strategic scenarios, which were developed by Cocks (1999) in his book *Future Makers Future Takers*. The three scenarios are built around three core beliefs about how a society seeking high quality of life for all, should respond to four overarching hazards of early 21st century society. These four hazards or challenges are:

- an inappropriate rate of economic growth
- increasing environmental degradation
- increasing social injustice
- declining sociality (social health) mirrored by rising sociopathy (social decay).

Cocks (1999) briefly describes these three strategic approaches or ideologies as follows:

Economic growth

The first set of core beliefs, underpinning an economic growth ideology, is as follows:

While it is true that environmental degradation and social injustice are important impediments to achieving high quality of life, these hazards will be ameliorated without resorting to any serious collective intervention if we move towards a more individualistic form of social organisation focused on the feasible objective of reaching and maintaining a high rate of economic growth. Sociopathy is not a priority problem. The two-pronged strategy proposed for implementing this philosophy is to selectively remove significant barriers to profit-making by entrepreneurs (eg environmental regulations) while focusing a small (by today's standards) government sector on the task of providing business with cost-saving infrastructure such as transport and communications and with productive human capital in the form of a technically educated workforce. Other priority components of this strategy are: population growth; extended property rights; a flexible labour market; and free trade.

Conservative development

The second set of core beliefs, underpinning a conservative development ideology, is as follows:

Environmental degradation and social injustice are important impediments to a high quality of life which will only be ameliorated if they are managed directly within the context of a more hierarchical, reconstructed form of social organisation. Nonetheless, it is desirable, and should be possible, to do this and simultaneously reach and maintain a high rate of economic growth. Sociopathy is a collateral problem rather than a priority problem.

The strategy proposed for implementing this philosophy centres on achieving full employment, this being the best way to address both social injustice and social decay. A Jobs and Incomes Program will be funded by a major tax reform program. Environmental degradation will be addressed by an Environment Management Program which will have a significant 'green jobs' component. Environmental damage is strongly related to energy consumption and to the quantities of raw materials entering the economy as inputs and leaving the economy as pollutants. Regulatory, fiscal and market-based measures will be used to stabilise net materials-use and energy use as rapidly as possible and to cap the rate at which land is converted from low-intensity to high-intensity uses. Other priority components of this strategy are industry support programs, trade management programs and population stabilisation.

Post-materialism

The third set of core beliefs, underpinning a post-materialist ideology, is as follows:

Environmental degradation, social injustice and sociopathy are all important impediments to high quality of life which will only be ameliorated if managed within the context of a more mutualistic form of social organisation. Economic growth is also a priority problem requiring management, but in the sense that it is too high rather than too low, with social and environmental costs exceeding the benefits. The strategy proposed for implementing this philosophy focuses on transforming the economy, redistributing power in society and radically reforming the socialisation system, these being the starting points for ameliorating environmental degradation, social injustice and pervasive social decay.

The socialisation system, assisted by a formalisation of citizens' rights and responsibilities, will concentrate on producing responsible, collaborative and useful community members. Power redistribution will be sought through the widespread development of participatory, non-adversarial institutions and the devolution of State and Commonwealth powers to strong regional governments. A range of tools (eg comprehensive recycling, population stabilisation, decentralisation, import replacement, a cap on personal consumption) will be used to diversify and localise and 'green' the economy and the cities so as to conserve energy, materials and natural systems. Stabilising consumption will facilitate investment in social, human and institutional capital at the expense of 'output-increasing' capital.

Alcohol fuels strategy under an economic growth ideology

Under an economic growth ideology, the success of a transition towards alcohol fuels would be judged primarily on its effect on economic growth rates, the generation of new jobs, success in import replacement and the efficiency of the production system in physical and economic terms.

On these criteria, two methanol scenarios, methanol alone and methanol plus electricity cogeneration, appear to be advantaged compared to the other scenarios (table 5.1). Both scenarios generate indicators that describe equal or higher rates of growth in GDP than the base case. Because of the double load of investing in methanol plant and biomass-fuelled electricity plant, the simulated GDP growth rate in the methanol plus electricity cogeneration scenario does drop approximately 0.5 percentage points in the period 2005 to 2015, but the trajectories are at similar levels thereafter. In terms of job generation, both scenarios have a requirement for more than 100,000 direct jobs by 2020 and more than 400,000 by 2050. Most of these jobs would be in rural areas that are currently losing population and services.

The effects of the methanol alone and methanol plus electricity cogeneration scenarios on the replacement of energy imports are substantial. By 2010 the requirement for oil imports has flattened and does not rise above 1000 PJ per year for the duration of the simulation. The total saving in energy imports by 2050 is at least 4000 PJ per year which might be priced at \$18 billion dollars in today's currency if oil is priced at US\$25 per barrel. This flows through to produce a better result for the merchandise trade or visible portion of the balance of payments indicator. The efficiency of the production system could be assessed in two ways. The most direct way is the energy ratio which describes the delivery of useable fuel from the production system in relation to the energy inputs (electricity, transport fuels and production inputs). Both scenarios deliver a ratio of five units of

output to each unit of input. A broader description of whole-system efficiency is the energy intensity of GDP described as the units of fossil fuel required to produce a constant dollar of GDP and expressed in megajoules per dollar. In comparison to the base case which stabilises at an energy intensity of 8 MJ per dollar around the year 2020, the methanol alone scenario delivers an energy intensity of 5 MJ per dollar by 2035 and the methanol plus electricity cogeneration scenario delivers 2 MJ per dollar by 2045.

Thus from an economic growth viewpoint an analyst or a decision maker may have to make some difficult trade-offs. The methanol alone scenario produces marginally higher rates of economic growth, jobs generation and per capita affluence. The methanol plus electricity cogeneration scenario produces a substantially lower fossil energy intensity of GDP and resultant lower emissions of carbon dioxide. Both scenarios require approximately 12 million hectares of biomass plantation by 2020 and 30 million hectares by 2050. The requirement for biomass plantation area would need to be balanced against the land requirements for other agricultural production systems and decisions made based on economic criteria. Both scenarios retain a strong similarity to the structure and function of the economic system of today. Given all of these considerations the methanol plus electricity cogeneration scenario might become the preferred alcohol fuels strategy from an economic growth perspective.

Table 5.1 A comparison of six scenarios for alcohol fuel production using key indicators of structure and function within Australia's future physical economy

	Methanol-0	Methanol-1	Methanol-2	Ethanol-0	Ethanol-1	Ethanol-2
Description	Methanol alone	Methanol plus electricity cogeneration	Methanol plus a radical economy	Ethanol alone	Ethanol plus electricity cogeneration	Ethanol plus methanol
GDP growth rate compared to base case	Higher	Same	Lower	Lower	Lower	Lower
Energy intensity of GDP by 2050 (MJ/\$)	5	2	2	6	4	2
Carbon dioxide emissions by 2050 (million tonnes per annum)	1000 200 less than in the base case	800 400 less than in the base case	270 930 less than in the base case	900 300 less than in the base case	700 500 less than in the base case	700 500 less than in the base case
Extension of oil stock (years)	6	8	25-plus	2	2	10
Oil import reduction by 2050 (PJ)	4000	4500	5000	2000	3000	4500
Area of biomass plantation by	31	31	17	12	19	27

2050 (million hectares)						
Energy ratio of alcohol production by 2050	5	5	5	2	3	Methanol 6 Ethanol 2
Direct jobs by 2050	550,000	400,000	100,000	170,000	140,000	400,000
Indicator of per capita affluence	Rising	Rising	Stable then declining	Rising then stable	Stable	Stable then rising

Alcohol fuels strategy under a conservative development ideology

Under a conservative development ideology, the success of a transition towards alcohol fuels would be judged firstly on its effect on a number of key environmental criteria, secondly on the maintenance of reasonable levels of affluence and thirdly in maintaining reasonable levels of economic performance.

On these criteria, the methanol plus electricity cogeneration, ethanol plus electricity cogeneration and ethanol plus methanol scenarios appear to be advantaged (table 5.1). The methanol plus electricity cogeneration scenario produces 800 million tonnes per annum of carbon dioxide emissions by the year 2050, a reduction of 400 million tonnes when compared to the base case. The two ethanol scenarios produce approximately 700 million tonnes of carbon dioxide per annum by 2050. This is 100 million tonnes per annum lower than the methanol plus electricity cogeneration scenario and 500 million tonnes per annum lower than the base case. The reduction of 400 to 500 million tonnes per annum represents the emissions from the energy sector of the current physical economy.

Under the conservative development ideology, the rationale for the transition to biofuels is to re-establish perennial production systems across large areas of Australia's farmed landscapes. The scenarios under examination require between 19 and 31 million hectares of land in biomass plantation and so this criterion is met. The two ethanol scenarios require substantial quantities (80 to 100 million tonnes per annum) of crop biomass as feedstock for the ethanol production process. The success in integrating the land rehabilitation component of perennial plantations with semi-traditional forage cropping systems will determine whether these two ethanol systems are judged to be acceptable on environmental criteria. In both a social and an economic sense, the retention of forage systems which could produce either bioalcohols or meat and fibre pose easier transitions to a structurally different economy. In a spatial sense, whether within a farm, a catchment or a region, more robust and resilient economic and social systems might be enabled if there is a diversity of markets for the same biomass resource.

Both scenarios generate equivalent rates of growth in nominal GDP to 2025. The rates for both scenarios fluctuate around the base case to 2025 (figures 5.16 and 5.19). After this period, which coincides with the depletion of domestic oil stocks, the ethanol alone scenario declines to a 1% yearly growth rate in nominal GDP whereas the ethanol plus methanol scenario declines to approximately 1.5%. The ethanol plus methanol scenario generates more than 400,000 direct jobs

by the year 2050 in comparison to the ethanol plus electricity cogeneration scenario which generates 140,000 jobs. The ethanol plus methanol scenario produces an energy intensity of GDP of 2 MJ per dollar by 2050 whereas ethanol plus electricity cogeneration produces a value of 4 MJ per dollar. There is a similar outcome for the indicator of per capita affluence where the ethanol plus methanol scenario is stable until 2020 but then gradually increases to reach a level 60% of the base case by the year 2050 (figure 5.19). For the ethanol plus electricity cogeneration scenario, the indicator of per capita affluence remains at 1990 levels for the remainder of the simulation.

Thus from a conservative development viewpoint the decisions are not quite as difficult as for the decision maker driven by an economic growth ideology. Both ethanol scenarios under scrutiny produce equivalent reductions in carbon dioxide of around 500 million tonnes per annum less than the base case by the year 2050. The ethanol plus methanol scenario has a higher requirement for land under plantation biomass and would better satisfy the criterion of dryland salinity control at the core of this ideology. In addition, the ethanol plus methanol scenario produces a lower value for the energy intensity of GDP, gives a higher rate of growth in nominal GDP and eventually provides higher levels of per capita affluence.

Given all of these considerations the ethanol plus methanol scenario might be the preferred alcohol fuels strategy from a conservative development perspective.

Alcohol fuels strategy under a post-materialist ideology

Under a post-materialist ideology, the success of a transition towards alcohol fuels would be judged mainly on its ability to moderate and level-off a wide range of trends in the use of resources and the generation of effluent and by-products. Thus lower rates of economic growth and declining per capita affluence would be compatible with this ideology provided that carbon dioxide emissions were declining, landscape problems were receding, oil depletion time frames were extended, transport use was declining and Australia's economic system was becoming more resilient and less dependent on the linkages to the international market place.

The methanol scenario which combines methanol production and biomass-fired electricity with a number of radical macro-economic policies meets many of these criteria. The genesis of the scenario came with the insight that both the methanol alone and methanol plus electricity cogeneration scenarios were, in effect, too efficient in a physical sense. By 2030, when the transition to a biomethanol economy had been achieved, the ease of producing available energy was stimulating the economy rather than retarding it. Thus rising per capita affluence was stimulating more production, and positive growth feedbacks were being generated. The effect of this can be seen in figure 5.7, which describes carbon dioxide emissions for the methanol plus electricity cogeneration scenario. Emissions are constrained to be approximately stable until the year 2030 and then rise gradually as consumption feeds growth and then growth feeds further consumption. In the energy literature this effect is sometimes called the rebound effect (Inhaber, 1997) or the Jevons' Paradox (Jevons, 1865) and there are parallels in public health policy.

Within the modelling protocols used in the OzEcco framework, there are a number of ways in which these positive feedbacks can be brought under control. Most of these approaches have time-lagged effects and need to be implemented well before the growth in consumption is likely to occur. In macro-economics, the use of interest rates to restrain money supply and damp down inflation is an analogous situation. In the physical modelling paradigm, the concept of money allows physical capacity to be borrowed or bought and it does not (in the short term at least) have to be sourced internally from the nation's physical economy. Restraints and constraints in the money supply can be used to restrict the rate at which the physical economy grows and the eventual size it reaches by some time in the future. The strategies used in this scenario were:

- International borrowing ceased by 2010, after which the balance between personal affluence and capital investment in productive purposes had to be sourced from within the physical economy.
- From 2000, international debt was repaid at the rate of 10% of the remaining principle per year, leaving Australia debt-free in international terms from around 2030.
- The balance between capital investment and per capita consumption was biased towards capital investment.
- From 2020, major capital flows were directed outwards from Australia and long-term investments were made in the physical economies of other nations. In time, this produced a steady flow of investment income without requiring added physical transactions within Australia's physical economy. The global ethics of this strategy are difficult to justify, but it might be modified into a strategic overseas aid approach.

After these simulation strategies were implemented the methanol plus radical economy scenario produced many outcomes suitable for the post-materialist ideology. The emissions of carbon dioxide peaked at 370 million tonnes in 2010 and declined to 270 million tonnes by 2050, a reduction in 2050 of 900 million tonnes per annum compared to the base case. The indicator of per capita affluence declined and remained around 1980 levels or a little lower. The indicator of GDP growth rate fluctuated around 1% per annum for the duration of the simulation period and the energy intensity of GDP measure declined to 2 MJ per dollar by 2030. Many of the physical indicators describing the methanol production system were similar to the other methanol scenarios but the requirements were reduced to one-third of the base case levels.

Given all of these considerations, the methanol plus radical economy scenario might be the preferred alcohol fuels strategy from a post-materialist perspective.

Other strategies and ideologies

The comparison of the six options for biomass-alcohol production systems has been deliberately restricted to those options using and requiring large flows of woody and other biomass sourced from perennial plantation vegetation. The rationale for this is to revegetate Australia's farmed landscapes to help control dryland salinity and other problems of landscape function. The additional rationale is to use a future constraint in Australia's domestic oil supplies as the stimulus to developing an economic rationale (import replacement) and a social rationale (job generation and rural renewal) to underpin the enormous physical task to be undertaken in long-term landscape refurbishment and renewal.

There are, however, many strategies within Australia's physical economy that can be explored in an effort to moderate and change many of the modelling indicators used in this study. Eight interesting strategies for exploration are:

- Reduce demand for transport fuels by new car technology, driving less and changing mode to more energy-efficient transport, for example, from cars to urban trains and buses, and from planes to intercity trains.
- Restrict exports of natural gas and make the transition to a gas-fuelled transport fleet in unison with the transport efficiency strategy above.

- Introduce forms of renewable electricity, such as solar photovoltaics, solar thermal and wind power, to decrease carbon dioxide emissions from the energy sector.
- Explore no-carbon electricity alternatives such the use of the nuclear cycle or geothermal ‘hot dry rock’ technology. It should be noted that nuclear technology is on the wane in a number of countries because of a number of community views and well as perceived issues of cost competitiveness when the whole nuclear cycle (mining, fuel enrichment, plant construction and plant decommissioning) is taken into account.
- Reduce the level of consumer demand and increase the longevity of consumer products to help slow down the throughput within the physical economy.
- Reduce the net effects on the physical economy of the inflows of international capital (both longer-term investment capital and shorter-term portfolio capital), thereby increasing resilience of the economy to international shocks and reducing the requirement for increasing exports to pay for increasing imports.
- In combination with the international finance strategy above, gradually reduce the requirement for the export of commodities from challenged farming landscapes and allow a contraction to more robust landscapes and less extractive farming systems.
- In combination with the international finance and farming export strategies above, allow deep-rooted native woody vegetation (eg woody weeds and forest regrowth) to re-establish over large areas of farmland with less-intensive management methods.

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Chapter 6

Locating biomass plantations

ABSTRACT

The simulation analyses in the previous chapters have tested a number of options for developing a biomass-based liquid fuels economy. The main question of physical feasibility hinges on whether there is enough land area on adequate soils, in reasonable rainfall zones, to produce a biomass flow equivalent to the 20-year forest rotation and 20 m³ mean annual increment used in these simulations. The land requirements for the scenarios vary between 6 million and 13 million hectares by 2020, and between 12 million and 31 million hectares by 2050. This chapter examines, in a very simple way, the stocks of land that are currently used intensively in the Australian farming zone. There are 19.4 million hectares of croplands, 17.1 million hectares of intensively managed pastures and a further 56.4 million hectares of managed pastures which are managed less intensively. A simple allocation of all the intensively managed pasture lands to biomass plantation would mean all scenarios would be feasible by 2020, but by 2050 the larger ones would not be. Another strategy of allocating 60% of the total pasture land and 40% of cropping land to biomass produces 21 million hectares, which again enables feasibility of all but the larger scenarios. A third strategy allocates all the crop and pasture land in those statistical divisions where dryland salinity is currently, or predicted to be, a problem. This generates 16 million hectares which again enables feasibility of all but the larger scenarios. A recent Australian Bureau of Agricultural and Resource Economics study detailed 20 million hectares of cleared land available for carbon sequestration, so the rough estimates of this study are of the correct order of magnitude. Further, more detailed investigation is obviously required, specifically focused on the feasibility at a regional level of maintaining biomass flows in perpetuity within a 40 km to 50 km radius of a central biofuels processing plant.

INTRODUCTION AND METHODS

This chapter briefly assesses the availability of land for conversion to biomass plantation. There is an overarching consideration that the biofuel production systems should be located on currently managed land and not venture into state forests, national parks or wilderness land. There are three layers of assessment that could be implemented in a simple manner to test the feasibility of implementing the scenarios:

- with a national view, allocate all the more intensively managed pasture land to biomass plantation;
- within each State allocate 60% of the planted pasture land and 40% of the cropland; and
- within statistical divisions of each State allocate all crop and pasture land in those areas that have a rating of greater than four for the dryland salinity challenge.

The requirements for biomass plantation land in the different scenarios are shown in table 6.1. By 2020 all biofuel scenarios require between 6 million and 13 million hectares of established biomass plantation stock. By 2050 the requirement varies from 12 million hectares to 31 million hectares. In addition, the ethanol scenarios are using established stocks of cropping land to grow crop biomass for digestion.

Table 6.1 Total area of land required for biomass plantation for the base case and six biofuel scenarios in 2020 and 2050 (millions of hectares)

Scenario	2020 biomass land	2050 biomass land
1. Base case	3.6	6.6
2. Methanol alone	13.0	31.0
3. Methanol plus electricity cogeneration	13.0	31.0
4. Methanol plus radical economy	7.4	16.4
5. Ethanol alone	5.7	11.7
6. Ethanol plus electricity cogeneration	7.9	19.0
7. Ethanol plus methanol	12.2	27.2

RESULTS

The national perspective

Australia currently has 36.5 million hectares of intensively managed land made up of 17.1 million hectares of pasture and 19.4 million hectares of cropland (table 6.2). There are sufficient stocks of intensively managed pasture land to accommodate the land requirement for biomass for all scenarios by 2020. The larger scenarios require 13 million hectares and the smaller scenarios 6 million hectares. The larger scenarios would leave only 4 million hectares of intensive pasture land, and this would probably require a sizeable reduction in intensively managed animal groups such as dairy cattle, beef and fat lambs.

Table 6.2 Total area of land in Australia and States, by broad land-use category

	Total Land 000s ha	Farm Land 000s ha	Total Pasture 000s ha	Planted Pasture 000s ha	Total Crop 000s ha
NSW	80,072	61,009	10,810	3,687	4,757
VIC	22,777	12,768	5,237	3,936	2,445
QLD	173,031	149,748	22,232	2,543	2,495
SA	98,409	56,901	4,663	2,008	3,219
WA	252,752	114,521	12,709	4,272	6,419
TAS	6,796	1,949	928	612	75
NT	134,802	68,276	16,899	19	4
ACT	235	50	21	13	0
TOTAL	768,874	465,221	73,500	17,090	19,415

There is, however, a total pasture stock of 73.5 million hectares, much of it less productive, where some of the animals could be relocated. The problem is more acute by 2050 and it is doubtful if the larger scenarios could be accommodated on the intensively managed land. A requirement for

31 million hectares would leave 5 million hectares for intensive crop and animal production. The feasibility of these land requirements would rest on the development of biomass production systems which could access the total pasture land stock of 73.5 million hectares. Approximately 40% of the total 'managed' pasture lands (non-rangeland and non-marginal lands or rough land) would be required to supply the land stock for biomass production. In the absence of a detailed land inventory this could be considered to be physically feasible.

Another approach would be to allocate 60% of the intensively managed pasture land and 40% of the cropland. This would yield 18 million hectares for biomass plantations and make all scenarios feasible in 2020 and three scenarios still feasible in the year 2050.

The State perspective

New South Wales could potentially allocate intensive pasture land (60% of 3.687 million hectares) and cropland (40% of 4.757 million hectares) totalling 3.2 million hectares (table 6.3). However, the threshold rating for the assessment of the dryland salinity problem highlights only the South Eastern NSW division where a total of 1.1 million hectares of crop and pasture land (intensive plus less intensive) is currently available.

Table 6.3 Total area of land in New South Wales, by broad land-use category, referenced to an index of landscape function

Statistical Division	Total Land 000s ha	Farm Land 000s ha	Total Pasture 000s ha	Planted Pasture 000s ha	Total Crop 000s ha	Landscape Functional Ratings			
						Soil Acidify	Dryland Salinity	Irrig Salinity	Soil Struct
Sydney	1,214	88	23	12	8	2	0	0	1
Hunter	3,092	1,510	405	138	51	4	1	0	3
Illawarra	834	130	51	34	2	4	0	0	1
Richmond-Tweed	983	468	100	29	30	4	0	0	3
Mid-North Coast	2,594	965	204	66	13	3	0	0	3
Northern - NSW	9,810	7,318	1,693	602	1,190	3	2	0	6
North Western	19,950	16,627	2,271	428	1,036	1	3	0	5
Central West - NSW	6,304	4,780	1,342	800	848	5	2	0	4
South Eastern - NSW	5,247	2,691	1,017	593	128	7	5	0	4
Murrumbidgee	6,342	5,354	1,253	534	853	5	3	3	5
Murray - NSW	9,017	8,077	1,524	452	591	4	1	3	8
Far West	14,685	13,000	926	0	6	0	0	0	5
TOTAL	80,072	61,009	10,810	3,687	4,757				

Victoria could potentially allocate intensive pasture land (60% of 3.936 million hectares) and cropland (40% of 2.445 million hectares) totalling 3.3 million hectares (table 6.4). However, the threshold rating for the assessment of the dryland salinity problem highlights only the Central Highlands and Loddon Campaspe divisions where a total of 1.1 million hectares of crop and pasture land (intensive plus less intensive) is currently available.

Table 6.4 Total area of land in Victoria, by broad land-use category, referenced to an index of landscape function

Statistical Division	Total Land 000s ha	Farm Land 000s ha	Total Pasture 000s ha	Planted Pasture 000s ha	Total Crop 000s ha	Landscape Functional Ratings			
						Soil Acidify	Dryland Salinity	Irrig Salinity	Soil Struct
Melbourne	780	224	120	85	23	1	0	0	6
Barwon	814	507	293	213	31	4	3	0	7
Western District	2,406	1,749	1,140	930	55	7	1	0	8
Central Highlands	1,264	739	374	291	71	2	4	0	8
Wimmera	3,058	2,292	680	537	806	0	3	0	8
Mallee	4,082	2,576	457	318	1,035	0	3	3	8
Loddon-Campaspe	1,927	966	422	310	240	3	4	4	9
Goulburn	2,336	1,568	782	573	126	7	2	4	5
Ovens-Murray	1,826	663	273	187	36	5	0	0	1
East Gippsland	2,782	1,023	372	251	8	1	1	0	2
Gippsland	1,503	462	325	242	13	2	0	0	2
TOTAL	22,777	12,768	5,237	3,936	2,445				

Table 6.5 Total area of land in Queensland, by broad land-use category, referenced to an index of landscape function

Statistical Division	Total Land 000s ha	Farm Land 000s ha	Total Pasture 000s ha	Planted Pasture 000s ha	Total Crop 000s ha	Landscape Functional Ratings			
						Soil Acidify	Dryland Salinity	Irrig Salinity	Soil Struct
Brisbane	464	152	31	7	9	1	0	0	5
Moreton	1,767	887	143	34	47	3	3	0	2
Wide Bay-Burnett	5,228	3,864	841	154	147	4	4	0	5
Darling Downs - Qld	9,008	7,964	1,080	301	1,151	2	2	0	7
South West - Qld	32,266	30,108	3,291	352	253	0	0	0	3
Fitzroy - Qld	12,335	10,797	1,730	624	414	1	2	0	4
Central West - Qld	37,009	32,659	5,613	105	1	0	0	0	6
Mackay - Qld	6,900	6,212	1,435	433	244	3	1	0	5
Northern - Qld	10,095	9,511	1,172	72	122	2	1	0	2
Far North - Qld	26,831	18,332	1,726	102	106	2	0	0	0
North West - Qld	31,129	29,262	5,169	359	1	0	0	0	5
TOTAL	173,031	149,748	22,232	2,543	2,495				

Queensland could potentially allocate intensive pasture land (60% of 2.543 million hectares) and cropland (40% of 2.495 million hectares) totalling 2.5 million hectares (table 6.5). However, the threshold rating for the assessment of the dryland salinity problem highlights only the Wide Bay-Burnett division, where a total of 1.0 million hectares of crop and pasture land (intensive plus less intensive) is currently available

Table 6.6 Total area of land in South Australia, by broad land-use category, referenced to an index of landscape function

Statistical Division	Total Land 000s ha	Farm Land 000s ha	Total Pasture 000s ha	Planted Pasture 000s ha	Total Crop 000s ha	Landscape Functional Ratings			
						Soil Acidify	Dryland Salinity	Irrig Salinity	Soil Struct
Adelaide	193	47	13	9	13	3	1	0	1
Outer Adelaide	1,195	817	315	211	167	7	2	0	4
Yorke and Lower Nort	1,852	1,699	328	181	785	1	2	0	8
Murray Lands	4,779	3,372	651	442	654	1	2	4	8
South East	2,132	1,710	1,040	814	151	7	5	0	6
Eyre	7,235	4,522	683	289	1,083	3	2	0	6
Northern - SA	81,023	44,734	1,634	62	366	1	1	0	6
TOTAL	98,409	56,901	4,663	2,008	3,219				

South Australia could potentially allocate intensive pasture land (60% of 2.008 million hectares) and cropland (40% of 3.219 million hectares) totalling 2.5 million hectares (table 6.6). However,

the threshold rating for the assessment of the dryland salinity problem highlights only the South East division, where a total of 1.2 million hectares of crop and pasture land (intensive plus less intensive) is currently available.

Table 6.7 Total area of land in Western Australia, by broad land-use category, referenced to an index of landscape function

Statistical Division	Total Land 000s ha	Farm Land 000s ha	Total Pasture 000s ha	Planted Pasture 000s ha	Total Crop 000s ha	Landscape Functional Ratings			
						Soil Acidify	Dryland Salinity	Irrig Salinity	Soil Struct
Perth	538	87	36	24	8	0	0	0	0
South West - WA	2,858	876	488	388	43	0	2	4	1
Lower Great Southern	3,892	2,830	1,160	927	662	5	4	0	8
Upper Great Southern	4,442	3,415	1,096	852	1,202	8	8	0	7
Midlands	11,044	7,205	1,345	935	2,789	7	6	0	4
South Eastern	61,176	17,466	1,407	677	483	4	2	0	5
Central	76,356	43,337	2,443	392	1,224	4	4	0	2
Pilbara	50,538	14,095	2,183	0	0	0	0	0	2
Kimberley	41,908	25,209	2,550	77	6	0	0	0	0
TOTAL	252,752	114,521	12,709	4,272	6,419				

Western Australia could potentially allocate intensive pasture land (60% of 12.709 million hectares) and cropland (40% of 6.419 million hectares) totalling 9.1 million hectares (table 6.7). The threshold rating for the assessment of the dryland salinity problem highlights the Lower Great Southern, the Upper Great Southern, the Midlands and the Central divisions where a total of 11.9 million hectares of crop and pasture land (intensive plus less intensive) is currently available.

Tasmania could potentially allocate intensive pasture land (60% of 0.928 million hectares) and cropland (40% of 0.612 million hectares) totalling 0.8 million hectares (table 6.8). The threshold rating for the assessment of the dryland salinity problem does not highlight any divisions.

Table 6.8 Total area of land in Tasmania, by broad land-use category, referenced to an index of landscape function

Statistical Division	Total Land 000s ha	Farm Land 000s ha	Total Pasture 000s ha	Planted Pasture 000s ha	Total Crop 000s ha	Landscape Functional Ratings			
						Soil Acidify	Dryland Salinity	Irrig Salinity	Soil Struct
Greater Hobart - Tas	136	71	22	15	2	3	0	0	1
Southern - Tas	2,416	667	300	166	15	3	1	0	2
Northern - Tas	1,994	880	433	297	37	3	3	0	5
Mersey-Lyell	2,251	331	172	135	21	2	2	0	0
TOTAL	6,796	1,949	928	612	75				

The Northern Territory has only small stocks of intensively used land and does not show on the assessment ratings for landscape function problems (table 6.9).

Table 6.9 Total area of land in the Northern Territory, by broad land-use category, referenced to an index of landscape function

Statistical Division						Landscape Functional Ratings			
	Total Land 000s ha	Farm Land 000s ha	Total Pasture 000s ha	Planted Pasture 000s ha	Total Crop 000s ha	Soil Acidify	Dryland Salinity	Irrig Salinity	Soil Struct
Darwin	21	0	0	0	0	0	0	0	0
Northern Territory - Bal	134,781	68,276	16,899	19	4	0	0	0	2
TOTAL	134,802	68,276	16,899	19	4				

In the pro rata allocation of managed pasture land (60%) and cropland (40%), a total of 21 million hectares of land could be available for biomass plantations. This figure is dominated by Western Australia with 9 million hectares. When the assessment includes only the pasture and cropland in those statistical divisions where dryland salinity is judged to be a problem now, or potentially in the next 20 years, the total area is 16 million hectares. Thus a finer focus at a State and a statistical division level suggests that the biomass plantation option is broadly feasible for most scenarios, with more investigation required to examine those scenarios requiring 27 million and 31 million hectares of plantation by the year 2050.

Chapter 7

Caveats and uncertainties

ISSUES REQUIRING MORE DELIBERATION

The detailed process analyses in chapters 3 and 4 are not fully included in the simulation modelling reported in chapter 5. There are a wide range of possible architectures for each bioalcohol type and a wide range of possible feedstocks and combinations of same. The world literature suggests that each plant in each region will have highly specific design criteria and a wide range of efficiency possibilities. The key data deliberated upon were the inputs of energy (both electricity and liquid fuels) that were required per petajoule (10^{15} joules) of plant capacity. The median figure used throughout the simulation was 0.08 PJ of energy input per 1 PJ of bioalcohol produced. This amount was allocated 70% to electricity and 30% to liquid fuels. A sensitivity analysis was undertaken using data values which were 25% greater and smaller than the median figures. While differences were discernible, they were not different enough to change the nature of any analytical outcome.

The indicators of economic growth used in the analysis form an important measure of success for any scenario option. The GDP growth rate indicator rests on highly specific assumptions about the relationship between energy consumption in specific sectors and the generation of constant dollars that contribute towards GDP (productivity version). These relationships are based on detailed analyses where input-output tables describing monetary relationships between economic sectors are related to the energy metabolism of the economy, and a relationship developed between the energy used and the dollars generated for each sector. It is likely that these relationships will change over time and so the GDP growth rate indicator must be viewed as just one indicator among many. However, Australian data show the Australian physical economy has become more energy intensive over the past 100, years rather than less energy intensive. Therefore the linkage of greenhouse gas emissions to energy use and economic growth should not come as a surprise.

The production of biomass feedstocks from the forestry module within OzEcco comes from a fairly simplistic treatment of forest growth and it must be better calculated. The current assumption is that forests have a standard rotation sequence of 20 years and a mean annual increment of 20 m³ per year. We assume that good management practices are assured and that technological development and plant selection will enable a wide range forest bandwidth to be 'dialled up' and so a perennial biomass type will be found for any soil type in any rainfall zone. Further analyses should be undertaken with a nested forest model related to 20 biomass zones in Australia. This should be able to accommodate the three-year rotation schedule being developed for the Western Australian oil mallee industry and the 30-year to 40-year rotations with thinnings for some of the pine and eucalypt types. In a similar way, the crop biomass production should be more appropriately modelled.

The modelling framework does not include a complete or comprehensive account of the carbon flows within and around the biofuel production process. When the ethanol process uses crop biomass it is assumed that the carbon is recycled from the point where alcohol fuel is combusted back to capture in photosynthesis by the crop. It is further assumed that only the above ground

component is used and affected (for example, soil respiration and below-ground processes are not positively stimulated). The carbon released by the use of electricity and liquid fuel is counted and included in the 'CO₂ generated from fossil fuel use' account. The use of forest biomass for digestion by microbial action, gasification or as heat fuel for the process is counted and reconciled. In all scenarios, checks were made to ensure that the process was carbon neutral. This entailed relating the 'CO₂ released from wood use' to the 'CO₂ sequestered from new forest plantation growth' and checking that the latter was always greater than the former throughout the scenario. For all scenarios, the balance was always a net positive (that is, no release) to the extent of 10 million to 25 million tonnes of carbon dioxide per year. For the record, the production of 1 PJ of ethanol releases 268,867 tonnes of carbon dioxide (fermentation – 32,646 tonnes; feedstock and fuel wood – 236,221 tonnes). The production of 1 PJ of methanol releases 106,614 tonnes of carbon dioxide from the wood used as feedstock and fuel.

The OzEcco analytical framework is designed to physically account for energy flows that sit under a monetary economy that is designed for, and rests on the concept of, yearly growth. If an economic system grows at 3% to 4% per annum and that system requires large inputs of fossil and renewable energy to underpin its development, then the logic is inescapable that fossil fuel use grows and subsequent emissions of greenhouse gases also grow. The implications of growth in the physical economy over a 50-year time frame is potentially large. Thus the base case scenario, which is used to judge the success in changing the physical economy, has some challenging results particularly in the areas of fossil fuel depletion, greenhouse gas emissions and subsequent effects on the international debt load and balance of payments situation. As noted at the start of chapter 5, this base case scenario should not be viewed as a strong prediction. Rather it should be viewed as the anvil on which we shape and beat future versions of a physical economy into a better and more appropriate shape.

The methanol scenarios refer to the management of the rebound effect. The concept of the rebound effect was first published in the 1800s by leading economist William Stanley Jevons whose analysis noted that the more efficient the use of coal, then the more coal was required and used over the long term. Within the context of the OzEcco modelling methodology, and indeed in the management of the real economy, the management of the rebound effect is an inexact science. In the biofuel scenarios, the build-up of a surplus of energy efficiency (which eventually causes rebound if it is not managed) is restricted by stripping the excess 'energy profits' out of the system before the rebound effect can accelerate. The particular strategy selected was to invest all surplus capital in an undefined overseas nation. This represented a loss of investment capital for the Australian economy, so restricting the ability of the internal physical economy to expand. This outflow was eventually rewarded when returns from the overseas investment started flowing back into the invisibles portion of the balance of payments sector.

The OzEcco modelling methodology treats exports and imports, both physical (for example, computers, jumbo jets and earth moving machinery) and monetary (for example, short-term portfolio investment and longer-term infrastructure and productive investment) in the opposite way to which monetary transfers are normally conceived. This is done specifically for accounting purposes in tracking the flows of embodied energy (the energy embodied in goods and services). Physical goods that are exported from the physical economy are seen as a loss of embodied energy in the short term, because these flows restrict the capacity of the physical economy to grow in an immediate sense. Imports of monetary capital are seen as a stimulus to growth in the physical economy, since these flows expand our ability to undertake more physical transactions and so expand the potential for growth. The stock of debt built up, however, eventually requires the repayment of interest on capital which then restricts the ability of the physical economy to grow.

The assumptions about future discoveries of oil and gas are critical to the maintenance of future trajectories of growth for Australia's physical economy. This is particularly so under the trajectory imposed on the development of a biofuels economy with reference to the depletion of domestic oil and gas reserves. We take the 50% probability estimates from the Australian Geological Survey Organisation which allow the inclusion of the present economically available resources, those amounts that are not yet considered economic, plus oil and gas locations that have not yet been discovered. This results in a reasonably optimistic view of when domestic oil and gas reserves might be depleted. There is often surprise at the relatively early date for the depletion of natural gas in Australia. This is caused (in the modelling assumptions) by the free market expansion of natural gas exports, which deplete domestic reserves more quickly but contribute to the balance of payments position in the visibles or merchandise part of that account. There is a counter effect later in the simulation period when natural gas has to be imported and so has negative impacts on the visibles balance of payments.

The capital cost of ethanol and methanol plant is a key uncertainty in these sets of analyses, since most scaled-up costs of pilot plant are available for United States examples where the costs of construction and capital are less. The current capital cost of biofuel plant has been set at A\$50 million per petajoule of yearly production capacity. A range of literature searches has located this as a reasonable estimate for Australian conditions, but with uncertainty bounds extending out to \$100 million per petajoule of production capacity. An optimistic assumption has been made that the lower bound of capital cost is a reasonable one, particularly when 250 to 500 plants might need to be constructed over a 50-year period. It is possible to undertake a range of sensitivity analyses to ascertain the effect of the capital investment required to produce biofuels and these will be appropriate when a limited number of biofuel scenarios are selected for further exploration.

Deciding on the superiority of the ethanol or the methanol process has been avoided in this report because of its preliminary nature. The political process in the United States is well on track to choose ethanol as the biomass-alcohol of preference but this is set within a much broader agenda. In a budget initiative (Clinton, 2000), US\$249 million was devoted to 'making biomass a viable competitor to fossil fuels as an energy source and chemical feedstock. Its efforts will be concentrated on developing biorefineries, integrated systems for processing feedstocks simultaneously into a variety of products such as fuels, chemicals and electricity'. Parallel to these developments, and not directly linked, is a process which aims to replace a methanol derivative, MTBE (methyl tertiary butyl ether) with ethanol as an octane enhancer for unleaded petrol (Ethanol Renewable Fuels Association, 2000).

MTBE is an oxygenate added to petrol to promote cleaner burning. It decreases emissions of carbon monoxide and ozone precursors and has been added to petrol since the late 1970s as an octane booster to replace lead and such toxic aromatic compounds as benzene, toluene etc. (Andrews, 1998). MTBE is produced through the reaction of isobutene with methanol to produce a substance with relatively low volatility, complete miscibility with petrol and a number of improved handling characteristics relative to methanol (Ancillotti and Fattore, 1998). Leakage of petrol containing MTBE from storage tanks has led to widespread ground and surface water contamination with the substance being the second most widespread contaminant in a national water quality survey in the US (Chang and Last, 1998). Some estimates of human health risk (Stern and Tardiff, 1997) note 'virtually no health risks are associated with chronic or sub-chronic exposures to MTBE in tap water', although health issues in the past half century have repeated the lesson of caution in the release of industrial products to the environment. A much wider review of the toxicological effect of petrol and its constituents (Caprina and Togna, 1998), led to the conclusion that 'the problem of potential toxicity of gasoline is still open, even though it is clear that modern unleaded gasolines present less risk to human health due to lower quantities of benzene and lead'. In relation to MTBE the authors note an increase in a range of reported symptoms when MTBE was introduced in

specific areas, but that controlled testing and experimentation has not yet revealed significant negative results. Controlled tests with ETBE (the ethanol derived equivalent of MTBE developed by reacting ethanol with isobutene) showed a number of symptoms similar to those reported for MTBE but were assessed to have no clinical significance (Nihlen et al., 1998).

While the environmental health and toxicological literature are important components on the decisions relation to the production of biomass-ethanol or biomass-methanol, much of the lobbying effort in the US relates to the effects of the compounds ETBE and MTBE derived from ethanol or methanol, rather than to the direct effects of combustion of the pure alcohol fuels in internal combustion engines or their use in fuel cells. A limited literature review produced no conclusive evidence either for, or against, ethanol or methanol. In a number of controlled laboratory tests as well as vehicle tests Taylor et al. (1999) reported a number of advantages of methanol over ethanol when both alcohols were combusted under conditions ideal for each alcohol fuel. A comparison of 20% blends of both methanol and ethanol with petrol gave equivalent ozone producing potential (Zervas et al., 1999).

A possible outcome of the ethanol versus methanol debate is that a biomass-alcohol economy will probably be better served by providing both ethanol and methanol depending on the end uses and likely areas of production and types of feedstock. Several authors (eg Claassen et al, 1999) make the point that the ethanol and the fermentation route promise to provide a wide and diverse source of products, the totality of which will be necessary to bridge the gap between production volumes, market penetration and cost per litre. The methanol route might better serve markets and production areas where simpler more assured process provides liquid fuels, heat and limited number of by-products. Methanol is seen as a suitable energy carrier in parts of Europe, particularly for the direct methanol fuel cell along with ethanol from biomass for the polymer electrolyte fuel cell. Both ethanol and methanol show a high degree of energy density with adequate handling properties and currently available infrastructure (Hohlein et al., 1999).

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Appendix 1

The OzEcco embodied energy model of Australia's physical economy

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ABSTRACT

Within the broader context of a population-development-environment project focused on Australia's environmental futures to 2050, we have developed an embodied energy model (OzEcco) of the country's energy metabolism based on the ECCO approach first developed by Malcolm Slessor. The model has aggregated descriptions of the main sectors which physically transform natural resource stocks, such as coal, oil, natural gas, minerals, water and agricultural soils, into useful goods and services for domestic consumption and export. The influence on national energy metabolism of a globalised economic and trading system is included with aggregated descriptions of key international trade and monetary flows as well balance of payments and international debt. This research project of two main parts sits within an environmental division of CSIRO, which is a government-funded national research organisation. The first is a context-setting and more qualitative part, where possible future options are explored through the development of scenarios which include political, social, economic, technological and environmental components. The second part is more quantitative and focused on dynamic models and analytical frameworks which analyse the larger and more important physical transformations which underpin the functioning of the national socioeconomic system.

The OzEcco model is built and calibrated on the national physical and financial accounts for the period 1981 to 1993. During that period approximately 11 MJ of primary energy were transformed within the physical economy to produce one constant Australian dollar of GDP. This calibration produces very close agreement between real data and modelled data for all the key energy-using sectors. An iterative approach has been used for model development to achieve a more competent modelling framework that can deal with topical technological issues. The current operating version is the eleventh iteration. Model development is guided by the population, lifestyle, organisation and technology (PLOT) approach where policy issues on these matters can be assessed either individually (other factors being held constant) or in more complex and holistic combinations to mimic the national scenarios developed in the more qualitative part of the project.

There are four insights, important in a national context, so far developed from a wide range of OzEcco simulation studies:

1 In a post-Kyoto greenhouse context, Australia's physical economy could triple its carbon dioxide from energy use from 340 million tonnes per year currently to around 1000 million tonnes per year by 2050.

2 The run-down of Australia's domestic supplies of oil and natural gas around 2020 could, through feedbacks from the balance of payments and international debt areas, cause a slowdown in the ability of the physical economy to grow. Annual rates of growth of 3% to 4% could decline to 1% and this could signal a large change in political, economic and social systems that rely on growth for their *raison d'être*.

3 Transitions to renewable energy economies have been tested which stabilise and then reduce carbon dioxide emissions while maintaining national infrastructure and indices of gross domestic production. The pressure of investment also stabilises a per capita physical measure of discretionary income to 2050.

4 The use of embodied energy analysis in a dynamic simulation model gives many counter intuitive results over the long term to 2050. These results may challenge strongly held paradigms in science and policy circles where in-depth knowledge in focused sectors is the norm and where the integration of complex outcomes is usually performed qualitatively by policy experts.

INTRODUCTION

The OzEcco modelling approach described in this paper is one component of a broad approach to future environmental quality in Australia within the context of population-development-environment studies. Attempts to develop quantitative studies on such a broad front are difficult for technical and political reasons. The scientific difficulties of how to integrate, which numeriare to use and how to describe and model complex socioeconomic systems are the topic of this workshop. The political difficulties are well described by Choucri (1994):

This paradox is salient in modern societies, in which undeniable benefits are derived from applications of technology, energy in various forms, and other natural resources are increasingly balanced against consequent ecological debits. Each increment of growth and development appears to exact costs in resource depletion, pollution, and other forms of degradation. Conversely, serious efforts undertaken to protect the environment are perceived as threats to agricultural and industrial production, commercial enterprises, employment, and the general welfare as it is conventionally defined.

This work started initially from an environmental quality perspective with a desire to contribute scientifically to Australia's national population policy. As the definition of the problem became more complex three insights developed. The first was that the problem was complex and intertwined and required a systems approach. The second revealed that precise definition of a particular problem was not particularly useful in policy terms. Instead we were required to develop a range of solutions for a complex set of nested problems. The third is that integrated analysis with a futures focus can be viewed as doubtful and dangerous science especially when it challenges current policy paradigms.

These insights led to a research program with qualitative and quantitative themes. The qualitative theme sets the context for the work by documenting a wide range of social, economic and political drivers and developing future scenarios. These can be seen as political options for Australia to the year 2050 and beyond. The quantitative theme seeks to test the national scenarios for physical feasibility in a whole-system sense. It can also test the effect of individual policies (for example, renewable electricity) on the whole system. The search for analytical paradigms and approaches led to the development two 'stocks and flows' approaches. A top down approach using the ECCO paradigm of Slessor (Slessor, 1992, 1997; Crane, 1996; Noorman, 1995) in a system dynamics framework (Pugh Roberts, 1986) was developed by Crane (1995) into the OzEcco model of Australia's physical economy (Foran et al., 1997). A highly disaggregated bottom up approach was implemented in the *Whatif* simulation language (Robbert Associates, 1998) into the *Australian Stocks and Flows Framework* (Poldy and Foran, 1998). The choice of two analytical frameworks for integrated assessment of a physical economy was needed to cover the range of modelling paradigms noted by Janssen (1998) as well as the aggregated and disaggregated nature of the advice potentially required in national policy discussions. This paper describes the development of the OzEcco embodied energy model and its analytical application to a number of studies of Australia's physical economy in a futures context to the year 2050.

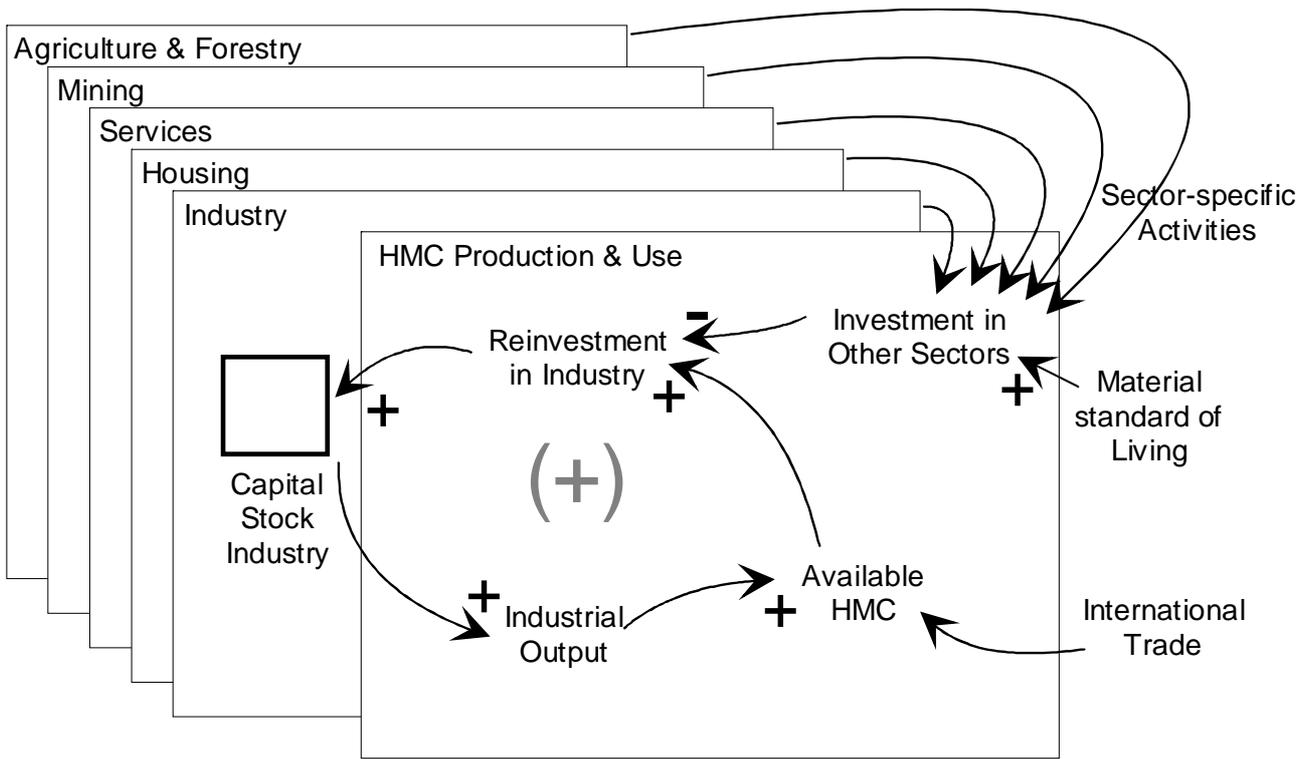
METHODOLOGY

Design and operation

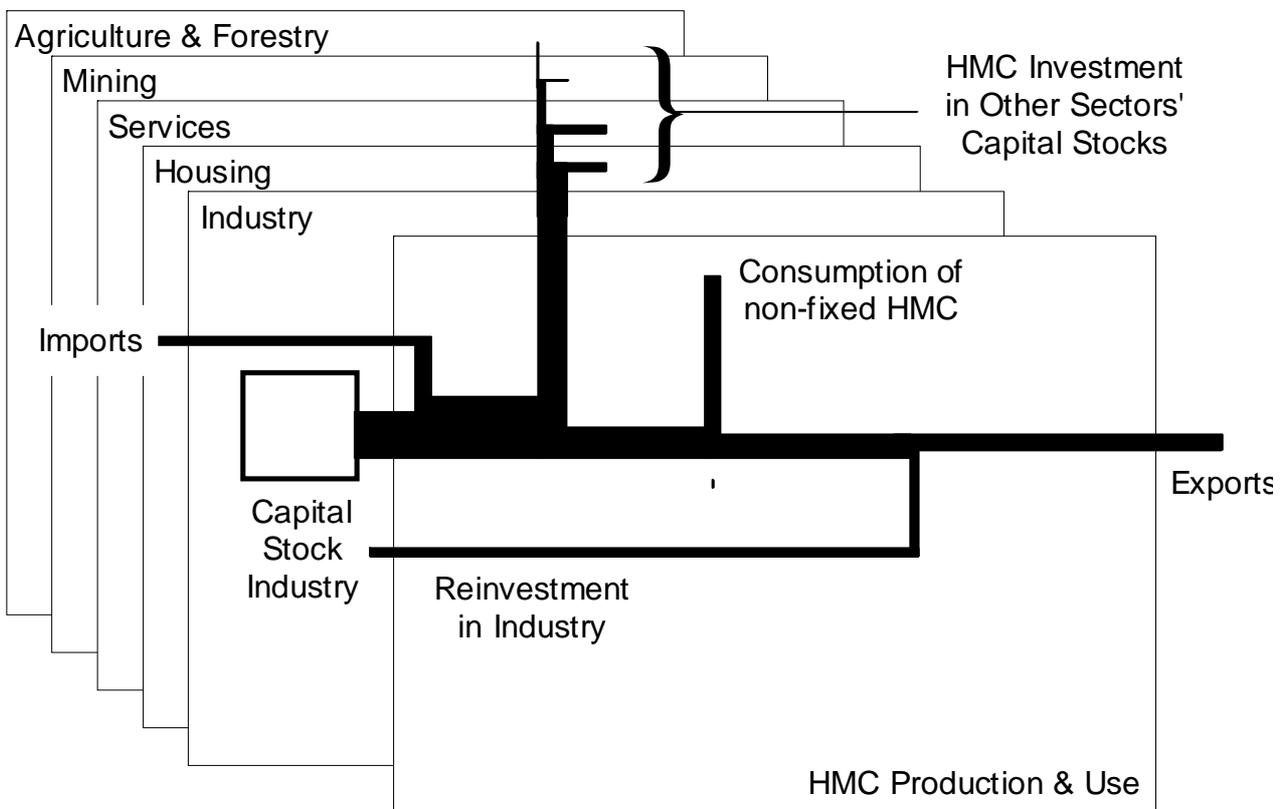
The OzEcco model is designed to integrate the driving forces of population, lifestyle, organisation and technology and explore their possible effects on the environment within the context of Australia's physical and economic structure. It is a systems dynamics representation of Australia's national function based on the philosophy of embodied energy analysis. The structure of the national economy and the energy accounts have been integrated so that capital stocks are expressed in terms of petajoules of embodied energy. The activities within the economy have been expressed as energy flows, again in petajoules. In this way economic activity has been converted to physical activity which is consistent with the first and second laws of thermodynamics. All economic transactions are represented by the physical transformations which underpin them. This representation is consistent with the long-term physical processes which are central to the functioning of any modern economy.

Conceptually, the model has five broad components: natural resource stocks, the transformation sectors, consumption activities, pollution generation and whole system indicators. The core modelling concept is that access to, and transformation of, energy (typically stocks of fossil fuel) are the determinants of physical growth in a modern industrial economy. Thus all goods and services are seen in terms of their embodied energy content. Some sectors such as domestic housing act as long-term accumulators of fixed capital (expressed in embodied energy terms), whereas personal consumption, for example, dissipates embodied energy quickly. The concept is shown in figure A1. The capital stock of industry is a node which creates human capital through its contribution to other sectors such as agriculture (for example, fertiliser and machines) and domestic housing (for example, bricks, carpets and stoves).

The rate at which industry can grow is limited by its contributions to other sectors and the consumption activities of the population at large (both negative feedbacks). The effects of international finance can be both positive and negative. Exports are negative in that they reduce the amount of physical capital (embodied energy) that can be applied nationally. Imports and capital inflows are positive in that they increase a nation's ability to perform physical work. All of these factors are linked in a systems dynamics framework and the system is set to grow as fast as physically feasible (the first and second laws of thermodynamics) in a physical economy which is constrained by the availability of energy, the requirement to maintain national infrastructure and personal consumption activities. Global monetary flows (for example, balance of payments and international debt) can override the capacity of the physical economy in the short term.



(a) Primary Influences on human-made capital creation and use



(b) Primary flows of human-made capital

Figure 1. A diagram of the central growth-determining loop in the OzEcco model, with the aggregated industrial sector depicted here as the core resource on which growth depends. The processes of fixed or human-made capital are

depicted as: (a) an influence diagram, illustrating the main causative features represented in the model; and (b) a flow diagram illustrating the sources and sinks of human-made capital. (Black lines indicate human-made capital flows into, out of and through the economy, with flow rate being represented by line thickness. The total human-made capital available is the sum of imports and native production. The ordering of flows from left to right here does not imply any temporal ordering of events.)

Validation and model testing

The OzEcco model is designed and calibrated on the structure and data for the Australian physical system for the period 1981 to 1993. In assessing whether the model functions in a plausible and valid manner (that is, the validation and model testing process) we have used a range of quantitative criteria. This judgment on the relative accuracy and validity must always be linked back to the design objective of the model, that is, it is structured to test technology and policy options for the physical functioning of the Australian system to the year 2050.

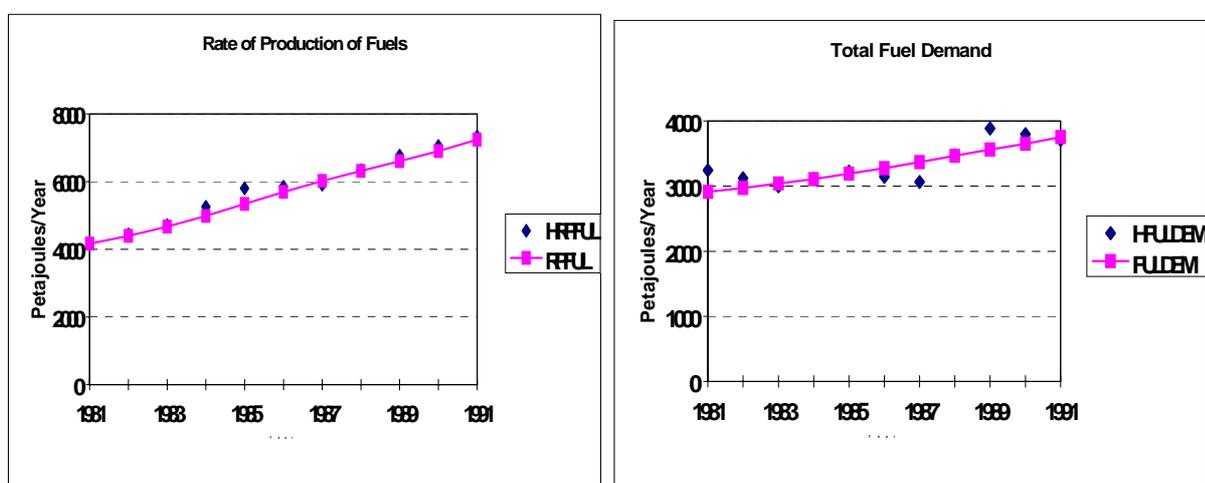


Figure 2. A comparison of historical and modelled data for rate of production of fuels (HRFUL, RPFUL), total fuel demand (HFULDEM, FULDEM)* Points are historical data and lines are modelled data.

Within those criteria, the design and calibration process has produced good results, that is, the model is judged to have validity. Over the period 1981 to 1993, the modelled data agree well with the historic data in the important energy using sectors (figure 2). Growth in capital stocks is maintained at close to historic values (figure 3) and the overall energy use and fuel mix of the economy agrees well with published data. The modelled emissions of carbon dioxide concur with greenhouse gas accounting data (figure 4). In addition, the function of the model is believable when policy or technological variables are set within reasonable bounds. The model is not fail safe in cases where some policy options force large changes in the structure of the economy. While it is always possible to suggest that many sectors of the model can be developed to more detail and disaggregation, the current model version is judged to be a valid one for exploration of Australia's physical future. This statement rests within the belief that the paradigm of a physical world is important, along with the concept of embodied energy flows and accumulation of embodied energy stocks which underlie the functioning of any modern economy.

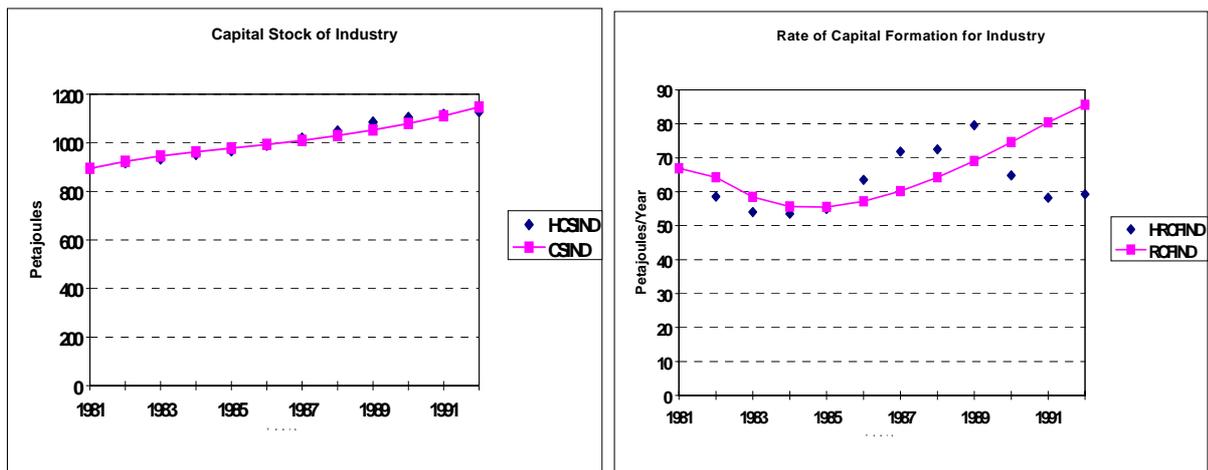


Figure 3. A comparison of historical and modelled data for capital stock of industry (HCSIND, CSIND) and rate of reinvestment in industry (HRCFIND, RCFIND)* Points are historical data and lines are modelled data.

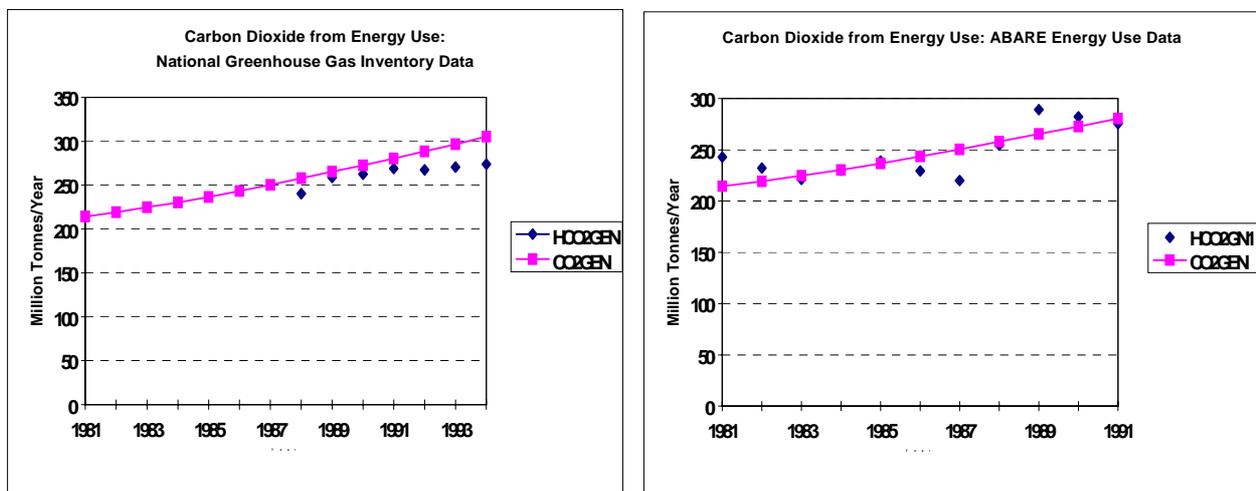


Figure 4. A comparison of historical data from greenhouse gas accounts and energy accounts (HCO2GEN, HCO2GN1) and modelled carbon dioxide (CO2GEN)* Points are historical data and lines are modelled data.

Selected results

Three scenarios

Within the context of global greenhouse gas policies and the agreement at Kyoto by developed economies to limit emissions, OzEcco was used to examine options for altering future production of greenhouse gas from energy use. Three scenarios were developed, the base case or ‘business as usual’, a ‘high-tech transition’ to renewable electricity and ‘another Australia’ which actively reduced consumption in sympathy with the Factor 4 concept (von Weisacker et al., 1997). In order to implement these scenarios, a range of control variables were altered over the simulation period from 1995 to 2050. A number of these are shown in table A1. The business as usual scenario simulates the physical economy as it is structured in the calibration period. There are a wide range of modest technological improvements to 2050, but current industries and industrial growth are maintained, personal consumption grows and there is no large change in the nation’s international financial arrangements.

Table 1. A selection of policy instruments (model control variables) used to implement three scenarios for Australia's physical economy to 2050

Control variable	Business as usual or the base case	High-tech transition	Another Australia
Oil discovery	All potential oil discovered to 50% probability level	Same as BAU	Same as BAU
Gas discovery	Same as oil	Same as BAU	Same as BAU
Gas exports	Grow linearly	Cease by 2000	Cease by 2000
Efficiency of thermal electricity plant	34% over the total fuel cycle to 2050	Increase to 46% by 2050	Increase to 46% by 2050
Population	Grows to 26 million by 2050	Same as BAU	Same as BAU
Renewable electricity	Hydro and biomass are maintained at present level; minimal solar and wind	6000MW of solar and wind renewables installed per year	Increase from 2000MW per year in 2000, to 5000MW by 2050
Transport	Personal vehicles saturate at 500 per 1000 of population; vehicles for industry grow in line with capital stocks	Personal vehicles saturate at 400 per 1000 of population; all new vehicles powered by natural gas	Same as BAU except that slowdown in the economy slows down personal and industrial vehicle use
Forestry plantations	Expand to 4 million hectares by 2050	Expand to 38 million hectares by 2050	Expand to 30 million hectares by 2050
Repayment of debt	Interest only at 6% per annum	From 2000 repay outstanding balance at 15% per year	Same as BAU
International borrowings	Maintained at \$12 billion to 2050	Same as BAU	Cease all international borrowings from 2000 onwards

BAU = business as usual

By contrast, the high-tech transition scenario seeks to maintain national productivity in GDP terms, but radically transform Australia's electricity production system, replacing coal-fired thermal plant with solar and wind renewables. Trade and international financial arrangements are altered, there is massive reforestation and transport use is capped. The another Australia scenario seeks to lower the throughput of the physical economy by reducing industrial output, changing trade and finance and taking a moderate investment approach to renewable electricity. It does not seek to maintain national productivity in GDP terms and opts for a slower-growing physical economy which is a

slower moving target for the infusion of new technologies. The results of the three simulation experiments are shown below.

The business as usual or base case scenario

A look ahead to 2050 for Australia under a business as usual scenario suggests a mixture of good and not so good outcomes. On the positive side, the economy is strong in a physical sense, underpinned by abundant coal and less abundant hydrocarbon reserves. Most modern economies rely for their growth on transforming fossil energy into useful goods and services. Thus the Australian economy can continue to grow to 2050 and beyond. The GDP and physical output could multiply two-and-a-half times by 2050 (figure 5). Less positively, carbon dioxide emissions from energy use may grow from 340 million tonnes currently to more than 950 million tonnes per year by 2050, and per capita emissions may rise from 17 tonnes to 37 tonnes. A rundown in hydrocarbon stocks around 2030 could increase the import bill for oil. Together, a number of factors, such as hydrocarbon imports, interest on international debt and maintenance of national infrastructure, could constrain the economic and the physical economy. Per capita physical affluence could start to decline. Anticipations of this nature more often than not produce a policy and management response long before they come to pass. These anticipations may therefore be assumed to be fragile from the start, or their final effect to be at least muted. In carbon dioxide emissions terms they represent a possibility rather than a prediction.

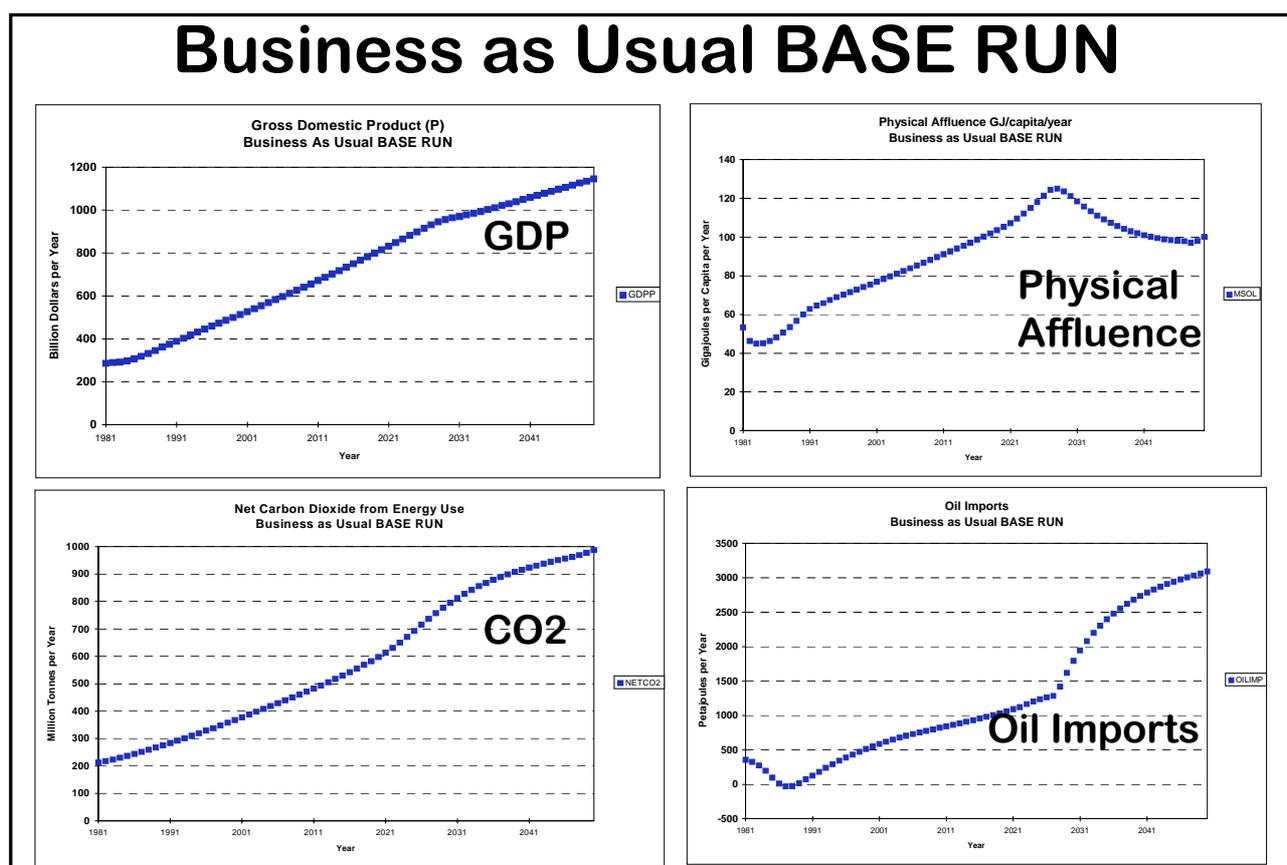


Figure 5. Report card for the business as usual scenario to 2050. This portrays GDP in constant 1989–90 Australian dollars, the energy embodied in discretionary personal expenditure or physical affluence (gigajoules per capita per year), the carbon dioxide emissions from energy use in million tonnes per year and oil imports in petajoules per year.

The high-tech transition scenario

A transition to a renewable electricity economy was tested and found to be feasible within the assumptions and constraints of the OzEcco embodied energy model. In order to manage this complex transition, it required that at least six sets of policy insights from other detailed simulations be integrated over time (table A1). Investment into renewable electricity generation took place at 6000MW per year with an assumed cost of \$4 per installed watt in constant 1989–90 Australian dollars. Thermal electricity production decreased its usage of coal to zero by 2020 and used natural gas as the substitute. Over the transition period, thermal efficiency was gradually increased to average 46% by 2050. International borrowings were stopped and from 2000 international debt was repaid at the rate of 15% of debt per year. Vehicle usage was capped and all new cars from 2000 were powered by compressed natural gas. Carbon scrubbing technology was applied to all thermal electricity plant from the year 2020. Plantation forestry at the rate of 1 million hectares per year was established for 40 years to stimulate the forestry industry, repair inland hydrology and sequester carbon.

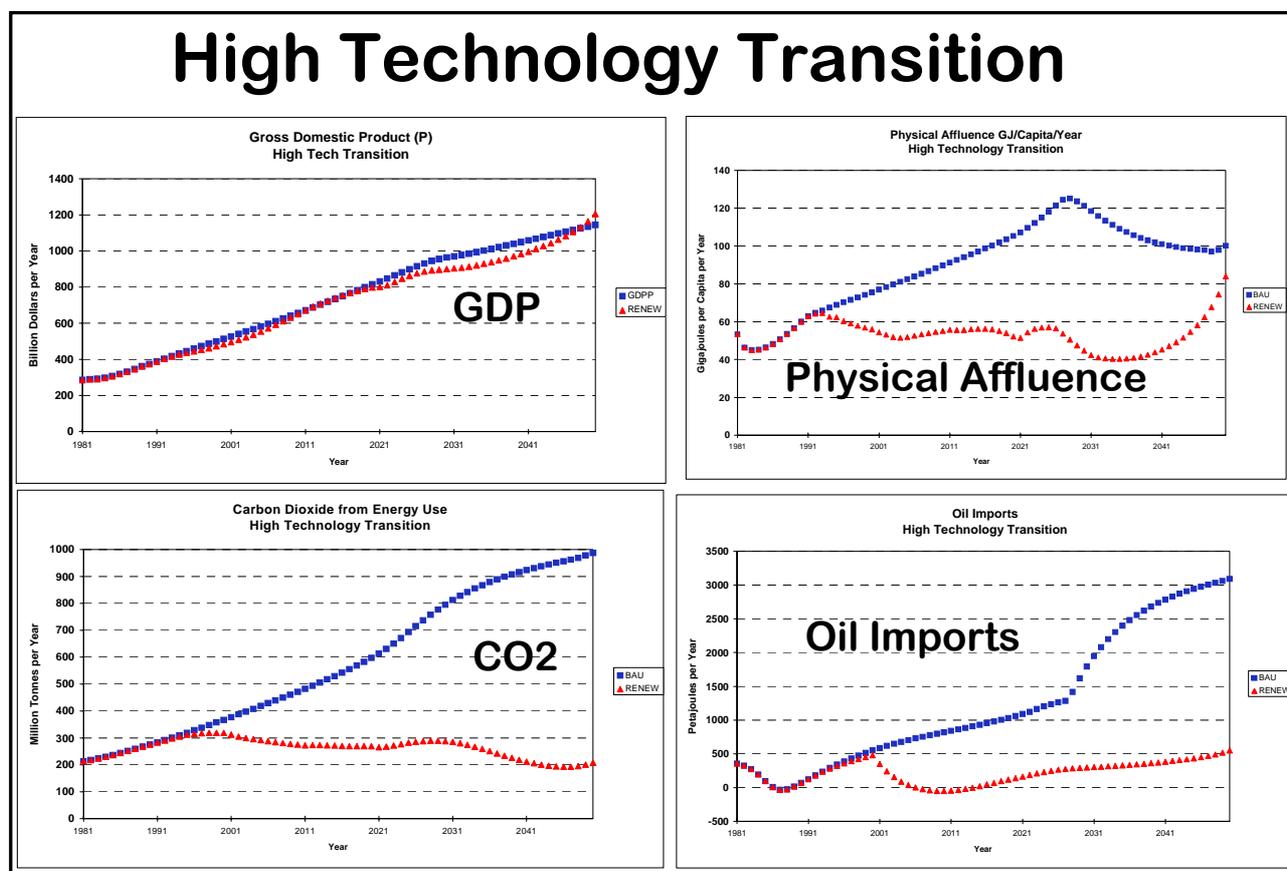


Figure A6 Report card for the high-tech transition scenario compared to the business as usual scenario to 2050. This portrays GDP in constant 1989–90 Australian dollars, the energy embodied in discretionary personal expenditure or physical affluence (gigajoules per capita per year), the carbon dioxide emissions from energy use in million tonnes per year and oil imports in petajoules per year. The high-tech transition scenario is the lower graph in all cases.

These policies together allowed the stabilisation of carbon dioxide emissions from energy use at 300 million tonnes per year until 2030 and then a decline to 200 million tonnes per year by 2050 (figure A6). By comparison, the business as usual scenario produced more than 950 million tonnes per year of carbon dioxide from energy use by 2050. In the mid-period of the transition, the pressure of this investment decreased a surrogate measure of GDP by up to 7% (900 vs 963 billion dollars in 2030), but by 2050 the situation had reversed. A measure of per capita physical affluence was stabilised for 40 years during the transition, compared to the business as usual scenario where it

continued to rise until 2030 and then declined gradually. While this transition is judged to be physically feasible, it needs to be further tested in other arenas for its feasibility in meeting Australia's medium-term and long-term social, political and economic goals.

The another Australia scenario

A transition in this scenario aims to substantially decrease the physical transactions underpinning the economy. It is found to be physically feasible within the assumptions of the OzEcco model (figure 7). This simulation is successful in stabilising carbon dioxide emissions from energy use at about 300 million tonnes per year for 30 years and then decreasing them to 175 million tonnes per year by 2050. This emission loading is 80% lower than those for the business as usual scenario at the end of the simulation. Electricity demand and supply is stabilised at around 300,000 gigawatt hours per year and by 2050 all of this comes from renewable sources. The use of natural gas is stabilised at around 500 PJ per year and, with a policy of retaining gas stocks for use in Australia, this provides natural gas supplies sufficient to last until 2100. A lighter economy of physical transactions gives embodied energy outputs of both the industrial and services sectors that are approximately equal by 2050.

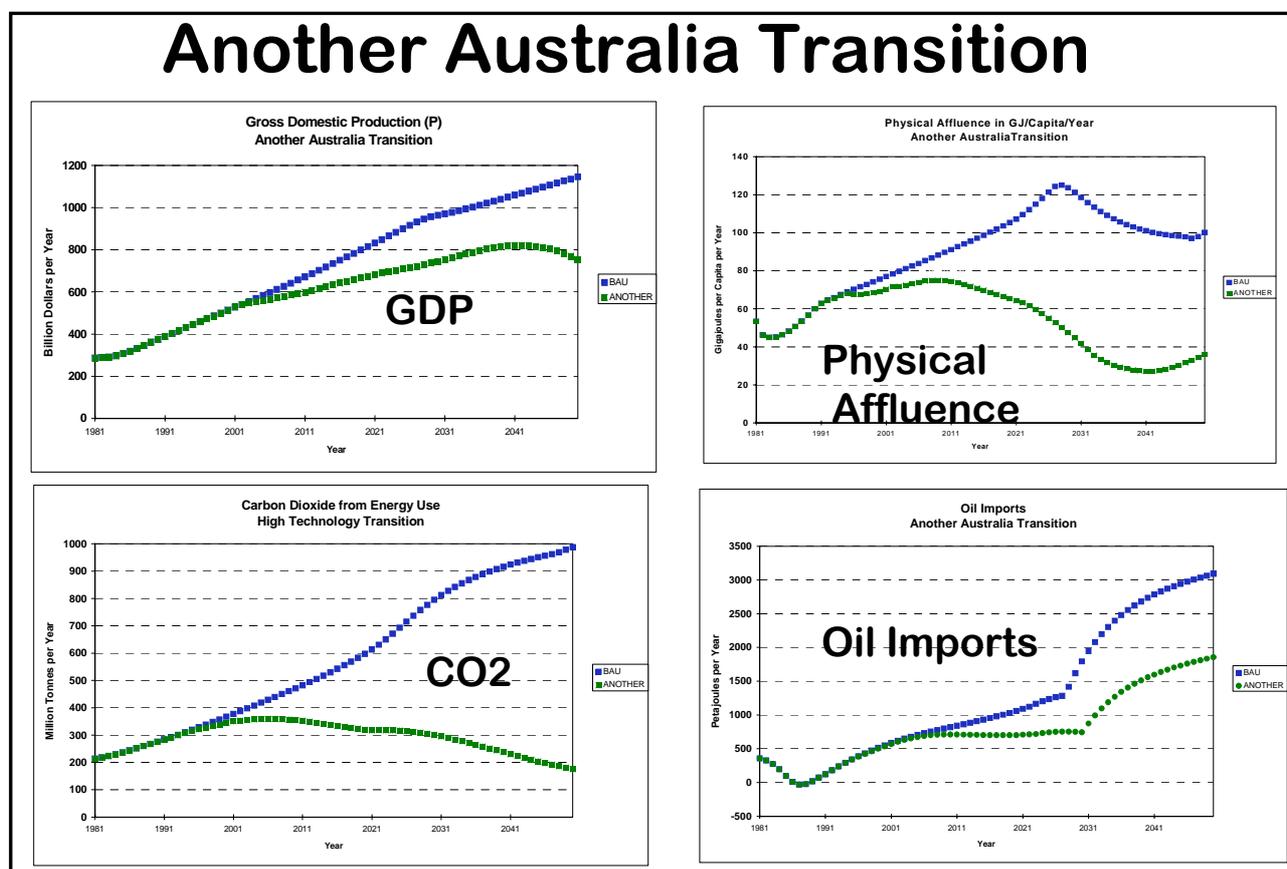


Figure 7. Report card for the another Australia scenario compared to the business as usual scenario to 2050. This portrays GDP in constant 1989–90 Australian dollars, the energy embodied in discretionary personal expenditure or physical affluence (gigajoules per capita per year), the carbon dioxide emissions from energy use in millions of tonnes per year and oil imports in petajoules per year. The another Australia scenario is the lower graph in all cases.

There are some negative aspects to this scenario. The surrogate measure of GDP is 34% lower than in the business as usual scenario in constant dollar terms by 2050. By 2050 the per capita physical affluence indicator, a measure of the energy embodied in the goods and services purchased with discretionary income, is at 40 GJ per capita per year in this scenario compared to 100 GJ in the

business as usual scenario. With 100 constant dollars equating to 1 GJ of embodied energy within the modelling calibration, this is the difference between 4000 and 10,000 constant dollars worth of personal consumption per year. These results portray a very uni-dimensional view of the system changes needed to implement a radical approach to sustainable energy usage. Nevertheless there is a considerable intellectual development already published by other authors to suggest that similar views to this, of a vastly different Australia in both physical and social terms, are worth further investigation.

Petroleum resources

Previous simulations using the business as usual scenario highlighted a potential slowdown in the physical economy after 2020 caused by a number of factors, but particularly by a rundown in the stocks of domestic oil and gas (Foran et al., 1997). While both industry and the community acknowledges that oil stocks have peaked, there is little published long-term policy evaluation of the flow-on effects. There is an expectation that rising oil prices will spur technological innovation and make non-traditional hydrocarbon sources such as oil shale or coal bed methane economically competitive. Simulation results indicating that gas stocks might run down earlier than expected have been greeted with disbelief which may represent a static view by policy evaluation.

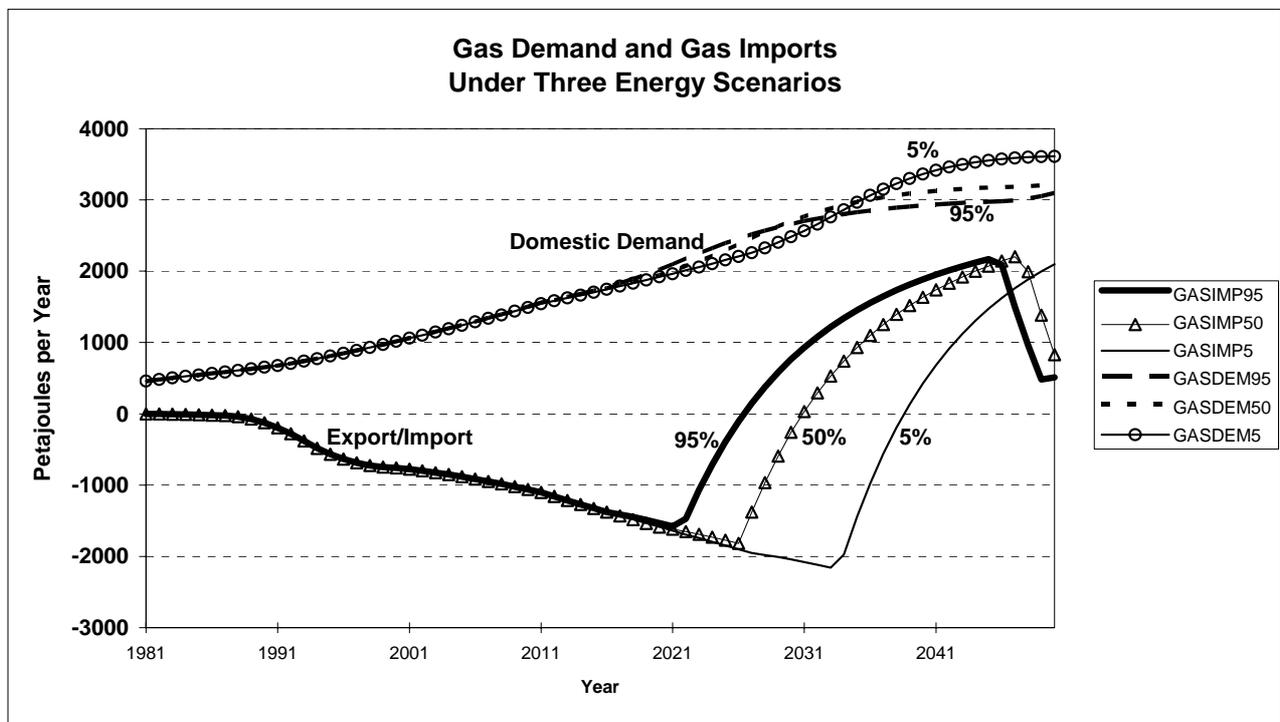


Figure 8. Simulated domestic and export demand for natural gas and liquid petroleum gas to 2050 under three scenarios of oil and gas discovery rates. Units are petajoules per year. Exports are represented as negative values and imports as positive values.

In an attempt to place uncertainty bounds around these possible events, this simulation examines different levels of exploration success from the high probability level (95% sure but lower stocks), to average probability (50% sure) and low probability (5% sure but higher stocks) (figures 8 and 9). On the demand side, oil requirements may range from 5000 PJ to 5800 PJ per year for the high (95%) and low probability (5%) finds at 2050, while domestic gas demand may stabilise around 3000 PJ per year in the same year. Gas exports could reach around 2000 PJ per year before declining rapidly in the face of domestic demand and low stock levels. The length of cover for domestic gas stocks may be interpreted as low as 30 years because both domestic and export

demand will expand in a growing economy. Under the 5% (higher stocks) probability, indicators of national activity such as industrial productivity, GDP and carbon dioxide emissions may be 8% to 10% higher than the 50% probability. Under the 95% (lower stocks) probability, the measures could be 4% to 6% lower.

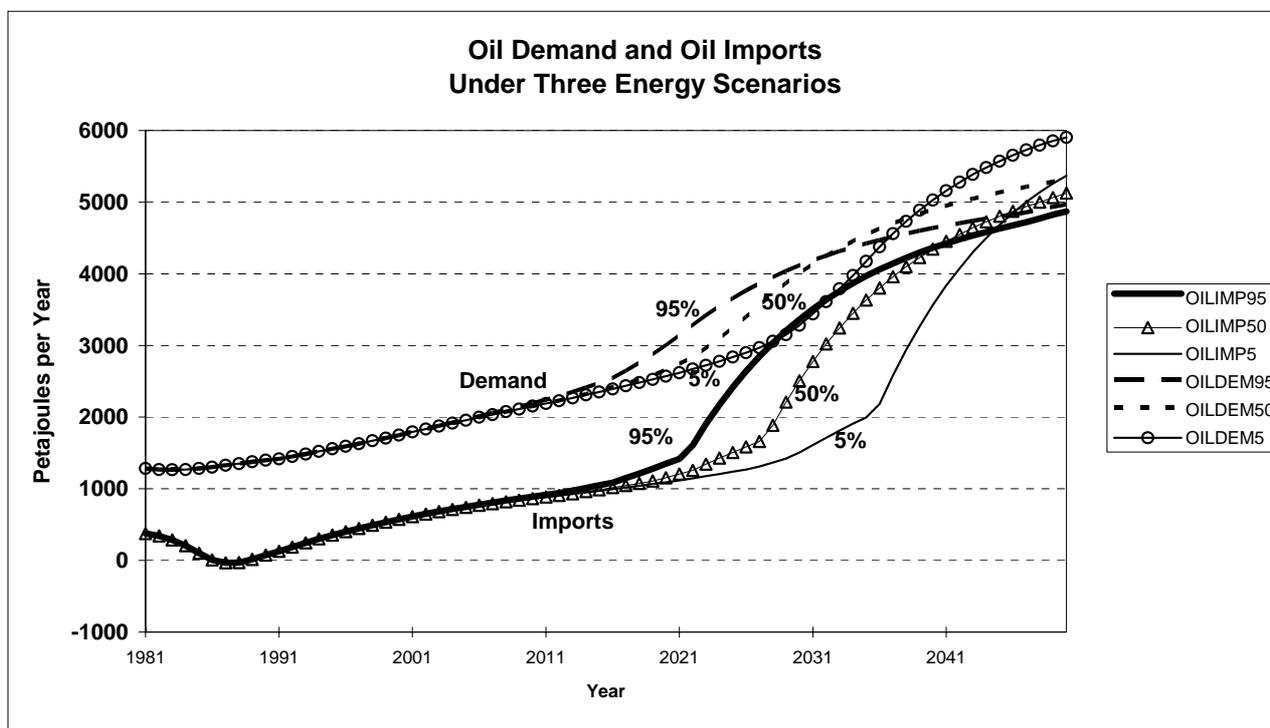


Figure 9. Simulated domestic demand and requirements for imports for oil and condensate to 2050 under three scenarios of oil and gas discovery rates. Units are petajoules per year.

There are some interesting dynamics portrayed by these OzEcco simulations as petroleum stocks decline. As oil and gas stocks decline, capital is released from the oil and gas exploration and production sector. This may cause an increase in growth of the physical economy, even as oil and gas imports are increasing. After 10 years, the pressure of petroleum imports cause a number of constraints on what is effectively a business as usual physical economy. These constraints might suggest a physical economy that cannot grow as developed economies have been used to doing under readily available and relatively cheap oil supplies. Rather than a prediction, the physical insights offered by these simulations of future petroleum stocks should be interpreted as some early warning signs for policy deliberations. Without complementary analyses from longer-term economic and social studies, this restricted physical view of the future may miss a number of key innovations that lie outside the physical economy. Technological and marketplace innovations are obvious examples of these. It is, however, difficult to ignore some of the physical realities imposed by the rundown in domestic oil and natural gas stocks, especially in a country as large as Australia. If the domestic and export transportation structure is to remain functional into the future, then policy responses may have to accommodate the possibility of less oil, higher prices and a substantial change to the physical nature of transport infrastructure.

DISCUSSION

The OzEcco model

Acceptance

For a number of reasons, acceptance of the OzEcco approach by the science and policy communities has not been assured. The use of a numeriare such as embodied energy is difficult for scientists outside the field of energy analysis to accept and perhaps comes from the ‘summing apples and oranges’ problem. However, recent news reveals that another energy research group in our organisation will now collaborate with us in developing energy supply and demand scenarios for a 10-year Kyoto protocol period and a 100-year period to 2100. This follows a difficult year in which the environmental, climate change and industrial groups in a large government research organisation have found it difficult to come to some agreement, or even speak the same language, around a topic entitled ‘sustainable energy policy’. National policy fora are likewise becoming more sensitised to the concept of a physical economy and the different analytical paradigms which are becoming available. While OzEcco was not able to contribute to national policy discussions in the pre-Kyoto period, some of the policy advice resulting from econometric approaches to energy integration were found wanting. The post-Kyoto period might provide an opportunity for physical modelling to complement these econometric approaches which will remain the dominant method for national integration and policy advice in most developed countries.

Further development

A recent review of the research project of which the OzEcco model is part suggested that the model development be stabilised and effort be spent on developing client-led analyses. As part of the completion of this development and testing phase, we have decided to introduce nuclear power plants, nuclear fuel reprocessing and the production of liquid transportation fuels from biomass. Given recent developments in our research organisation, further work might stress a more rigorous description of the fossil fuel cycle and prospective new technologies therein. There is always a temptation to include more disaggregation of population cohorts, vehicle fleets, building types and the industrial sector. However, as noted in the introduction, the OzEcco model has been deliberately developed with a more aggregated view to examine behaviour of the whole physical economy in a more macro-economic manner. The bottom-up *Australian Stocks and Flows Framework* (Poldy and Foran, 1998) is well disaggregated and is able to provide those detailed analytical insights.

There are a number of improvements which could be made to the simulation environment in the OzEcco model. The design and testing of any individual technology or fully integrated scenario, as discussed above, inevitably involves many sequences of simulation runs until physically feasible solutions are found which minimise some system indicators (for example, carbon dioxide emissions) and maintain others (for example, per capita physical affluence). At one level this involves considerable learning on the part of the operator, particularly around the dynamics of a complex physical economy. However, there may also be need for automated searching and simulation which may reveal some policy settings and sequences previously unrecognised because they lie outside conventional knowledge. In addition there is scope to infuse the concepts of adaptation, learning and agent-based modelling (Janssen, 1998; Epstein & Axtell, 1996) into the simulation experiments.

Whole system properties

Initial use of the OzEcco model (Foran et al., 1997) involved eight simulation experiments, four of which have been reported briefly in this paper. While the individual experiments are interesting there are also diffuse properties of the system, perhaps hypotheses of system behaviour, which are becoming evident. When these are tested, distilled and refined they may form the rules of thumb which energy analysis might take back to the policy table. Some insights are presented below:

- An economy may be on a trajectory that could lead to some future problem arising (for example, fossil fuel use leads to depletion of stocks and increasing carbon dioxide emissions). Where this is the case, the rate at which it consumes resources is not particularly important since the problem will be encountered sooner or later in a 50-year time frame. The key question is the timeliness of the response strategy, for example bridging strategies to other trajectories developed well in advance, and trust in technological progress or preparing to manage the crisis when it happens.
- The stabilisation (or reduction) of physical affluence on a per capita basis may be a central part of the complex transitions so far simulated for the physical economy. The implications of this in a growth-based economy could be challenging to conventional economic thinking and the current organisations of markets.
- Inefficiency in energy use can be viewed as not completely bad as it retards the capacity of the system to accelerate growth in physical transactions. Large and rapid increases in energy efficiency release resources to the consumption sector which in turn restimulate all of the primary resource sectors. Resource use and emissions may then increase over the long term in free market situations. Simply put increased energy efficiency stimulates physical growth and physical throughput.

Energy analysis: The way ahead

The ECCO approach to energy modelling has proven resilient through time and is beginning to gain acceptance in some policy circles. In this application it uses national databases and those central to economic theory and policy. The concept of converting monetary stocks and flows to embodied energy stocks and flows is a difficult one to conceptualise and this is one of the challenges of the discipline. Much of the analysis underlying the global greenhouse concerns is couched in the same language and analytical paradigms that underlie the ECCO approach. This is cause for optimism.

The concept of eMergy (Odum, 1996) has intuitive appeal and the bridge between embodied energy and eMergy must be built. Long-term sustainability issues are better based in ecosystem theory and functional reality with the eMergy concept. In policy terms, however, eMergy may face tougher barriers of acceptability than does embodied energy, which is well accepted in the life cycle analysis and industrial ecology areas. However, since eMergy collapses geological and human time scales into a single accounting framework and bypasses the intricacies of a dynamic analysis, it may be well suited to the policy table in providing an essentially static view for policy makers.

The paper by Giampietro and Mayumi (1998) is timely in the challenge it poses to the energy analysis discipline. The OzEcco model is a complex systems model and it portrays a number of behavioural characteristics which are sometimes difficult to explain and more difficult to control. Chief among these is the intersectoral rebound effect or Jevons' paradox. However, the model cannot yet be called a 'complex adaptive systems' model as there is no facility for learning and adaptation similar to those used by Janssen (1998) in his 'battles of the perspectives'. Being able to explain and defend the results of simulation analyses to a policy forum is the first step in changing policy. The formulation and development of complex adaptive models of national energy systems is a large enough challenge. A bigger challenge will be to find ways in which these can be explained and understood by harried and focused policy experts.

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Appendix 2: Cost Estimates for Ethanol and Methanol

COMPARISON OF THE COSTS OF ALTERNATIVE ALCOHOL FUELS (1999 A\$) (PREPARED BY CHRIS MARDON)

COST PER TONNE ALCOHOL

Fuel	Feedstock	Scale '000 tpa (PJpa)	Capital Cost, \$m	Labour Required	Raw Material Cost, \$/t	Operating Cost, \$/t	Capital Charges, \$/t	Total Cost, \$/t	c/L	
Methanol	Wood	100	(2.24)	172	248	426.4	256.6	344.4	1027.4	81.3
Methanol	Wood	16.5	(0.37)	30	38	328.0	237.9	361.8	927.7	73.4
Methanol	Wheat Straw	100	(2.24)	152	225	114.3	226.4	305.0	645.8	51.1
Ethanol	Wood	115	(3.37)	387	277	1390.7	360.3	673.1	2424.1	191.0
Ethanol	Wheat Grain	120	(3.52)	161	274	543.8	211.9	267.9	1023.6	80.8
Ethanol	Sugar Cane	119	(3.49)	216	274	508.0	245.1	363.9	1117.0	88.0
Micro-EtOH	*Sugar Beet1	0.47	(0.014)	1.1	9	883.7	742.9	457.8	2084.3	165.0
Micro-EtOH	†Sugar Beet2	0.47	(0.014)	1.1	9	1378.2	742.9	457.8	2578.8	204.0
Micro-EtOH	*Sugar Beet1	1.19	(0.035)	1.7	10	883.7	347.1	279.4	1510.2	119.0
Micro-EtOH	†Sugar Beet2	1.19	(0.035)	1.7	10	1378.2	347.1	279.4	2004.8	158.0

* Irrigated dairy area, beet yield 70 t/ha roots, tops used as cattle feed.

† Non-irrigated area, beet yield 50 t/ha roots, no value allowed for tops.

In both cases, no value has been allowed for soil from beet washing or beet fibre as a feed supplement.

If sawdust or other wood residues were available as fuel for the cost of collection and delivery, that could reduce the cost of ethanol to a minimum of \$1/L from the micro-ethanol plant. The quantity of fuel required is small.

COST PER PJ OR GJ

Fuel	Feedstock	Scale PJpa	Capital Cost, \$m/PJ	Labour per PJ	Raw Material Cost, \$/GJ	Operating Cost, \$/GJ	Capital Charges, \$/GJ	Total Cost, \$/GJ
Methanol	Wood	2.24	76.8	111	19.04	11.45	15.38	45.86
Methanol	Wood	0.37	81.1	103	14.64	10.62	16.15	41.42
Methanol	Wheat Straw	2.24	67.9	100	5.10	10.11	13.62	28.83
Ethanol	Wood	3.37	114.8	82	47.46	12.30	22.97	82.73
Ethanol	Wheat Grain	3.52	45.7	78	18.56	7.23	9.14	34.94
Ethanol	Sugar Cane	3.49	61.9	78	17.34	8.37	12.42	38.12
Micro-EtOH	*Sugar Beet1	0.035	47.4	286	30.16	11.85	9.54	51.54

* Note high labour usage. Raw material cost would drop to \$20/GJ and total cost to \$41/GJ if sawdust used as fuel.