Wednesday, 1 April 2009

Committee Secretary
Senate Select Committee on Climate Policy
PO Box 6100
Parliament House
Canberra ACT 2600
Australia

Senate Select Committee on Climate Policy

Dear Senators,

I represent the discipline of biophysical economics where all economic and social functions are judged first by their physical impacts and are thus constrained by the physical laws of thermodynamics and mass balance. *In biophysical economics there are no free lunches!*

My submission first makes ten points relevant to Australia's transition to a low carbon economy and then briefly addresses your Committee's terms of reference. My knowledge is based on 25 years experience in biophysical economics within CSIRO, and my ongoing research in the energy metabolism of Australia's economy.

1. Physics first: effectiveness before economic efficiency
Global climate disruption is first a physical problem and economic function must therefore bend to physical realities and laws. Most of the essential outcomes of the Garnaut Review, the Government's CPRS White Paper and the Treasury modelling behind them have very little physical reality i.e. they are a virtual house of cards. My 'Balancing Act' report for CSIRO details the production chains behind every sector of the economy and shows the carbon, water and land implications of each dollar spent. A national aspiration of doubling or tripling our per capita wealth generation by 2050 while transitioning to a low carbon economy where water and land systems are in good condition, is not physically feasible.

2. Only a rapid rollout will work
Such is the size of the physical transition to a low carbon economy, only a rapid rollout of today's low carbon technologies will meet the challenging goals that will be set for developed countries. Considerable inertia in replacing the 'physical stocks' means that current infrastructure must be overwhelmed by 'off the shelf' low carbon machines. It is economically and physically feasible to have 80% low carbon electricity by 2030 made up of equal portions of wind, solar photovoltaic, solar thermal, biomass and hot rocks. Institutional constraints (lawyers, planners, technicians etc.) only start to show when the expansion rate exceeds 25% per year.

3. Materials and manufacturing must come from Australia
The economy will maintain a 2.2% growth rate ongoing if most of the manufacturing and fabrication takes place in Australia. The physical challenged posed by 80-90% reduction in net carbon emissions is immense and will require many new economy jobs. The perverse reality is that a low carbon economy is a less efficient generator of energy services per unit of capital stock compared to high carbon and energy dense sources. It thus requires higher skills and more physically involved workers than a fossil fuel economy, where the energy density of oil, gas and

coal substitutes ‘energy slaves’ for real people. The transition will revitalise Australian manufacturing and potentially generate large export opportunities in both integration skills and energy machines.

4. Energy growth drives economic growth and value adding

In a modern complex economy, energy transactions drive value adding and thus economic growth. A century long analysis by Robert Ayers of the USA’s real economic growth shows that 85% of its real growth can be attributed to ‘quality corrected’ energy consumption, thus revealing the sham of the ‘multifactor productivity’ indicator much used by economic researchers. Because of the interdependence between production chains in the economy (each chain doing its own value adding and contributing partially to aggregate GDP), a focus on ‘efficiency alone’ may even slow economic growth. The focus must first be on the decarbonisation of production chains, and secondly on reining in the profligate consumption of energy for activities that are marginally useful.

5. A border tax on carbon is required

A modern globalised economy is sourced from the cheapest point using basic filters for product certification and labour practices. Thus the cheapest and most physical production chains have market advantages allowing OECD countries to outsource most carbon metabolism to developing countries. Were carbon accounting based on country of consumption rather than country of production, it would show that the USA and EU-27 are responsible (historically and currently) for the carbon pollution challenge now facing the globe. Affluent consumers are thus consuming the earth’s fundamental processes. Ignoring this trade reality will penalise domestic producers who implement low carbon production chains, while low price emissions continue to be stimulated in unregulated economies. Trade’s next ‘level playing field’ must therefore rest on ‘lowest carbon’ rather than ‘lowest price’. A border tax on carbon is required to restrain free-traders from free-riding. While the Government’s CPRS White Paper opines this to be ‘infeasible’, the carbon content of every production chain in the world will soon be available from the University of Sydney.

6. Widespread CCS will not underpin a growing economy

The analytical and political dependence on coal combustion with CCS to maintain energy growth domestically and globally, can only be justified for a specific technical window (See Attachment 1). Because of the parasitic load imposed on traditional thermal electricity generators by carbon scrubbing with CCS, economic grow slows because of the tight dependence of economic growth on electricity growth. Perversely, this can slow carbon emissions in a similar way to a global recession, but does not meet generally accepted growth goals of policy. CCS will only function effectively in a macroeconomic sense when it is applied to generators with a greater than 60% (fuel to electricity) thermodynamic efficiency. Modern coal generators will not exceed 49% efficiency on 30 years time and thus expectations for coal combustion continuing in a low carbon world are not justified physically. Only advanced gas turbines and carbonate fuel cells have the excess efficiencies to implement CCS technologies while providing growing electricity to a growing market. Since they are fuelled by natural gas, most domestic gas resources should be retained for high efficiency generators with CCS. Thus a continuing expansion of gas exports is not in Australia’s long term strategic interest, nor in its aspiration to become a low carbon economy.

7. Transport fuels must transition to wood-based bio-alcohols

A previous Senate enquiry became bewitched by the chimera of ‘more oil out there’ from GeoScience Australia and ‘coal from liquids’ from the fossil-fuelled ABARE. The issue of ‘peak oil’ is conveniently avoided by both major parties as dependence on oil imports passed $10 billion recently, and will grow to $20 billion by 2020. The impact on our trading balance will be substantial as will be the physical disruption on the many production chains that underpin social wellbeing and economic productivity. My current energy work has proved the feasibility of a transition to wood-based alcohols replacing 90% of petroleum fuels by 2030 (reports available on request). This transition replaces petrol by methanol and diesel by dimethyl ether to give carbon neutral transport outcomes where the flow of carbon molecules circulate from exhaust to tree plantation and back again. By 2050 this part of the carbon neutral transition will require in excess of 500 regional processing plants providing fuel, electricity, biochar and green feedstocks. The refurbishment of the landbase and social opportunity for Australia's regions will be immense.

8. The renewable energy economy has simpler supply chains

The financial and physical investment required for the low carbon economy changes Australia's economy from a consumption-based to an investment-led one. This has profound implications for current lifestyle settings (see Point 9) and will catalyse big changes in perceptions of wealth and macroeconomic resilience. The critical understanding is that 'once in place', a mostly renewable energy economy has shorter supply chains and runs on wind, sun and geothermal heat except for the biomass component. Generally, regions and suburbs will be at least 50% energy self sufficient and utilities owned by cooperatives that return profits as improved levels of service. The distributed nature of supply means that higher maintenance requirements (from much larger but less productive infrastructure stocks) will require local labour giving high regional multipliers. From 2040 onwards, the low carbon but self centred economy could be so buoyant that it will require large 'future fund' extracts to rein in inflationary consumption levels.

9. Physical affluence must reduce to 1980 levels

To invest in and sustain the large infrastructure stocks required for a low carbon economy (the investment-led one from Point 8) will require that the per capita physical affluence (specifically the embodied energy in the goods and services of discretionary spending) drift back to levels experienced in Australia in the early 1980s. This does not mean 'a return to the cave' suggested by many media commentators but does require that today's 'consume fast and throw-away' lifestyle will become a thing of the past. The physical reality of achieving this transition is at odds with the main analytical conclusions of the Garnaut Report and the Government's CPRS White Paper. Based on treasury modelling, both reports promise a doubling or tripling of per capita wealth in dollar terms, even with high rates of population growth. This reality need not be at odds with Garnaut and the CPRS but promises large changes in lifestyle orientation. For example one dollar spent on education, health or culture has half the embodied energy of a dollar spent in shopping or in the café culture. Biophysical economics tells us we can't get something for nothing i.e. there are no free lunches.

10. Bio-sequestration is a buffer to, not a source of permanent carbon reductions

Both the Garnaut Report and the CPRS White Paper make only modest attempts at carbon mitigation relying on coal combustion with CCS (which does not work: see my Point 6 plus Attachment 1) and bio-sequestration to soak up the carbon emissions from an essentially unchanged economy that proceeds along business-as-usual lines. This conventional wisdom uses bio-sequestration as a 'get out of jail free card' allowing semi-permanent inaction until a magical carbon extractor appears in 2066 when the carbon prices passes a threshold. My own rough calculations suggest that an optimistic 34 million tonnes of carbon per year out to 2050 can be sequestered on 26 million hectares of measured and monitored landscape. At most, this accumulates to 20% of our likely carbon emissions to 2050 under the assumptions of both Garnaut's and the Government's assumed economic structure. Four physical realities are critical before bio-sequestration land can be used in realistic mitigation efforts. First is that trees must be harvested and buried, or turned to biochar, to lock up the carbon on a semi-permanent basis. The second is that bio-sequestration capacity saturates with most landscapes having at most 35 years left of active takeup capacity. The third is that future climate and changed fire regimes mean that much of the sequestration land may become a source of carbon emissions, rather than a carbon sink. The fourth is that the measurement required to certify carbon storage on a legal long term basis is substantial and could soak up nearly half of monies raised by carbon taxation. For all of these physical realities, bio-sequestration at best offers a medium term carbon buffer rather than a long term solution.

Given these ten points, my short comments in relation to the Committee's terms of reference are as follows:

(a) the choice of emissions trading as the central policy to reduce Australia's carbon pollution, taking into account the need to:
(i) reduce carbon pollution at the lowest economic cost,
(ii) put in place long-term incentives for investment in clean energy and low-emission technology,
(iii) contribute to a global solution to climate change;

In the absence of a physically based plan for a low carbon transition, the political and bureaucratic soul searching on trading scheme architecture or levels of carbon taxation suggest a decision making mindset that is dangerously removed from physical realities. The current global financial disruption is ample proof of what biophysical economics has known all along: the 'market' is a dunce when it comes to long term substantive issues. If an aggressive carbon transition plan (a blueprint for physical infrastructure and household consumption) is developed which allows investor security as well as the capacity to change technological horses at say 2020 and 2040, then an ETS or a carbon tax should be designed to move both investors and consumers quickly into a low carbon activities. The concept of 'lowest economic cost' should be replaced by 'optimal carbon outcome' as dollars saved by least cost in a macroeconomic sense, will slosh into consumption activities. This will stimulate more emissions domestically, or in the factories of our trading partners, principally China and Japan.

(b) the relative contributions to overall emission reduction targets from complementary measures such as renewable energy feed-in laws, energy efficiency and the protection or development of terrestrial carbon stores such as native forests and soils;

These are minor sideshows compared to the principal task of decarbonising an affluent carbon-intensive economy. 'Feed-in laws' will help shift the investment burden to households but 10 Star regulations for homes and commercial buildings (each unit to generate its own energy at near carbon neutrality on a yearly basis) would be more effective. 'Energy efficiency' is good but only in the context that energy per end user is tightly capped and regulated to meet yearly (reducing) targets. Most policy seems to be oblivious of the inter-sectoral rebound effect (The Jevon's Paradox) where efficiency lowers cost and thus allows the consumption of more overall, not necessarily in the same consumption category, hence 'inter-sectoral'. 'Terrestrial carbon stores' are okay as a buffer or resilience factor (see my Point 10) and should be used as Australia's global contribution to climate safety, rather than reducing our moral and strategic obligations for rapid and sustained carbon mitigation efforts.

(c) whether the Government's Carbon Pollution Reduction Scheme is environmentally effective, in particular with regard to the adequacy or otherwise of the Government's 2020 and 2050 greenhouse gas emission reduction targets in avoiding dangerous climate change;

The current CPRS design and intent is dangerously inadequate for three reasons. Firstly, a rapid revolution of infrastructure and lifestyles requires substantial and sustained changeover of physical assets (buildings, transport, machines, processes). A low 2020 target and a high 2050 shifts an impossibly large physical burden to subsequent generations, given that we have 'off the shelf' low carbon solutions ready to be implemented now. Secondly, the proposed compensation for polluting and trade exposed sectors rewards commercial inactivity, political corruption (The Carbon Mafia) and immoral misinformation programs. Perverse rewards such as these promised by the current

Government thus restrain the innovation and investment central to any modern economy wishing to be part of a vital 21st century. Thirdly, the reliance on silver bullet solutions (CCS on thermal coal plants, bio-sequestration, atmospheric carbon extractors etc.) are simply end-of-pipe solutions historically derived from the coal-driven industrial revolution. These marginal add-ons are the physical equivalent of financial derivatives, collaterised debt instruments and toxic bonds that caused the current financial crisis. To endure in four human generations time, modern economic structures must transition from linear to the circular flows, now common in industrial ecology designs.

(d) an appropriate mechanism for determining what a fair and equitable contribution to the global emission reduction effort would be;

It is physically self evident that current climate disruption is 90% due to carbon emissions from the industrial revolution that has mostly advantaged the current developed world. This developed world must reduce its yearly carbon flows, in parallel to sustained increase in energy services for the developing world that allows those countries and communities reasonable lifestyles, health, education and aspirations. Note that I have use the words ‘energy services’ for the developing world because they need not walk the same high carbon path which has led the globe to the current climate uncertainty. The political and moral high ground requires that the developed world decrease its physical affluence while that of the developing world increases. This means a global equality on a per capita basis for CO2-equivalent emissions by 2050. Australia has no ‘special case’ on which to plead, apart from that it must do more than its share in facilitating the spread of prosperity and equality to the lesser developed countries in our region of influence.

(e) whether the design of the proposed scheme will send appropriate investment signals for green collar jobs, research and development, and the manufacturing and service industries, taking into account permit allocation, leakage, compensation mechanisms and additionality issues; and

The currently proposed scheme sets low emissions targets at 2020, rewards inept industrial management and high polluters, and attempts to reinforce an industrial and economic structure deemed reasonable in the 1950’s after World War II. As such, it is hard to see why an astute investor would seek medium term returns when all of the ETS policy signals remind us of Saint Augustine’s prayer of “Give me chastity and continence, but not yet”. Parallel policy measures for ‘green cars’, ‘ceiling insulation’, and investment in renewable R&D, give some relief to this bleak prognosis but these diminish with the level of reliance given to in clean coal technologies (see my Point 6) by both current Government and the Coalition. The current slow down in the global economy offers a rare moment when pain is inevitable and probably tolerated in the short to medium term. Putting the domestic and world economy back together with the same cookie cutter that produced this mountain of environmental ineptitude, is perverse and illogical. Now is the time to redesign the structure and function of the modern economy. The ETS as currently promised must not take us back to a flawed and polluting entity which promises only constrained times for future generations of Australians.

(f) any related matter.

The excess of energy supply and its knock-on carbon effects present an almost biblical metaphor for the state of Australian society and the economy that fitfully serves it. Cheap energy provides cheap energy dense foods that make Australians obese, unfit and sad as they drive unsafe ugly streets in their search for meaning and fulfilment. My suggestion that Australia’s physical ‘energy’ affluence be reduced to 1980’s levels (see my point 9) as we move from a consumption-driven to an investment-led economy will help redress a number of these issues. Stimulus packages (admittedly in critical times) that tell us to spend and consume just reinforce the failed dogma of economic theory and function promoted over the last 50 years and more forcefully in the last 20 years. The much misquoted ‘Wealth of Nations’ Adam Smith sought justice and equality and a ‘reasonable life’ for most citizens. He did not envisage fat sad television watchers eating toxic fast food. Our CPRS policies have the chance to reformat our society and economy into a more liveable, healthy and responsible structure.

These policies must not reward the rich, inept and corrupt corporations who represent the last of the dinosaur age.

Let us embrace the opportunity for breadth, insight and wisdom

Yours Sincerely

Barney Foran
Independent Scientist

ATTACHMENT 1

Carbon Capture and Storage

Abstract

Carbon sequestration and storage (CSS) technology is effective in reducing net carbon dioxide emissions from electricity production for the scenario period 2006-2051. However it should only be used in combination with advanced fossil generation so that higher efficiencies therein, can accommodate the parasitic energy loading caused by the pollution scrubbing, transport and storage processes. The well developed mono-ethanolamine (MEA) scrubbing technology is simulated and applied to 80% of the fossil generation capacity, starting in 2016 and reaching full implementation by 2026. Applying scrubbing reduced net carbon dioxide emissions by four and ten billion tonnes for the base case and advanced fossil scenarios respectively, and had relatively minor impact on economic outcomes. However lower efficiency of generation in the base case requires additional generation capacity which increases base case emissions by an extra four billion tonnes, thus adding to the overall CO2 pollution load that has to be abated. The core CSS scenarios are sensitive to a doubling and tripling of capital cost and the electricity requirements for pollution abatement across the full capture and storage chain. However the scenarios are robust in relation to cost of the chemical solvent and its rate of degradation as it undergoes the regeneration process. A key issue flagged is the balance between domestic use and export volume of Australia's natural gas reserves. The best performing fossil scenario depends on natural gas and becomes fragile after 2051 if stocks deplete. In a whole economy sense, there seem few financial barriers to widespread rollout of CCS technologies integrated with advanced generators having electrical efficiencies of 60% or more. Geological storage for the six to ten billion tonnes of CO2 sequestered over the next 45 years is judged not to be a problem. In comparison, a rapid transition to an 80% renewable electricity infrastructure gives similar CO2 reductions, but with superior financial and national wealth outcomes. The CCS option of using end of pipe technologies to capture and store emissions contrasts starkly with the renewables transition which avoids emissions.

Introduction

Carbon sequestration and storage (or CCS) is a mechanical or technical approach to reducing carbon dioxide emissions from many industrial processes, particularly electricity generation. Of the many approaches available to do this, the one tested economy-wide in this chapter uses a chemical solvent to extract carbon dioxide from the exhaust gases of a power station. The 'captured' carbon dioxide is then compressed and transported along pipelines to a storage reservoir for 'geological sequestration' where it is injected deep underground into rock matrices or saline ground waters, usually at depths greater than 800 metres where the gas becomes liquid, or enters a supercritical phase. Provided that the storage site is remote from geological activity and has a good layer of geological capping material, expert opinion hold that permanent storage is 99% assured for period of 1,000 years or more. The proven system for extracting natural gas from a gas and oil well provides a practical 'mirror image' metaphor for the CCS process and its expected stability.

The two key findings from a 2007 federal House of Representative's review *Between a rock and a hard place: The science of geosequestration*[1], give a robust summary to introduce this chapter. They are as follows:

> *Much of the science which forms the basis for CCS is understood. It is being applied on a small scale at various sites around the world, including in Australia. The three stages of CCS (separation and capture, transportation, and storage) remain at different points of development and will require greater research and experimental application before CCS becomes a truly viable greenhouse gas mitigation strategy.*
>
> *There is a consensus that all three technologies* [.....for carbon dioxide capture] *(post-combustion, oxyfuel and pre-combustion) should be pursued, to be applied in different circumstances. In particular, there is agreement that governments should not attempt to pick technology winners.*

The year 2007 literature in combustion science and generator engineering highlights four strong themes. The first is its integration in life cycle terms. Whole systems analysis is the norm, be it the full fuel cycle and all components for an individual generator type, or often a country's entire electricity system by future generation options. The second is an almost universal acceptance that combined cycle gas turbines fitted with CCS are far superior in whole system electrical efficiency and greenhouse avoidance terms, compared to all other fossil based technologies. Additionally there is still much technological improvement for gas turbines that is foreseen, but awaiting development. The third is that if CCS is deployed at a speed and scale sufficient to markedly reduce emissions, then it requires a new electricity network with generators close to geological storage. If a new transmission network is required, the question then becomes should it be integrated with a pipeline network for waste combustion products, or linked to solar and wind resources fitted with renewable electricity generators. The fourth is that in the face of accelerating climate risk, net emissions per kilowatt hour becomes the ultimate efficiency benchmark for the electricity network, rather than cents per kilowatt hour or million dollars per megawatt of generator capital cost. As the increased costs posed by CCS will be passed onto relatively affluent consumers anyway, an effective emissions transition will be best served by the technical design that best avoids emissions, rather marginal cost considerations for the consumer.

Much of current technical literature focuses on the 'energy penalty'[2] of CCS and how to balance penalty minimisation with emissions avoidance. Many studies confirm the advantages of combined cycle gas turbines even under high natural gas prices but note that integrated gasification and combined cycle plants (IGCC) may perform well with cheap coal[3]. Analyses across the full production chain for a range of promising technology sets confirm that the energy cost of most CCS systems is generally split 90% to capture and compression, and 10% to transport and storage[4]. The relative immaturity of CCS at a practical scale for the entire German electricity system highlighted the phasing problems of infrastructure renewal in the face of aggressive targets for emissions reduction[5]. At the very least, this required that all new fossil fuel plant be built with CCS fitted even without storage sinks in place, and this is now legislated for all new fossil plant in neighbouring Holland. Given the technical and social uncertainties surrounding CCS, this study suggests that renewable energies, principally offshore wind and solar thermal with storage, offer assured emissions reductions and less deployment risk. Finally, significant electrical efficiencies and CCS emissions avoidance are promised by 'advanced mixed cycle' gas turbines[6] and integration of solid oxide fuel cells with gas turbines[7]. The latter option can capture 100% of power plant emissions and give a carbon dioxide intensity of electricity production of 40-60 grams per kilowatt hour, which verges on the life cycle emissions of nuclear power and photovoltaic electricity.

Australia has initiated at least nine practically scaled CCS pilot projects designed to develop local capability and industry as a launch point for possible full scale implementation one to two decades from now[8]. Initial studies suggest a theoretical geological storage capacity of 740 billion tonnes of carbon dioxide. Most storage potential exists in saline ground waters with for example, three billion tonnes of storage available in the deep saline waters of the Great Artesian Basin. Many centres of industrial emissions or 'emissions hubs' are within 500 km pipeline distance of good potential storage sites. However New South Wales does not have good storage sites and may require more radical approaches since storage in coal seams is not considered a mature technology[9]. Current assessments suggest a practical and economic potential of up to 120 million tonnes of storage yearly. This chapter reports a storage requirement of up to ten billion tonnes out to 2051, well within the theoretical maximum storage, but more than the economically viable flow rates on a yearly basis.

The technical process at the heart of this chapter is the use of amine solvents to capture carbon dioxide from the flue gas of a power station that can be regenerated for reuse, releasing the carbon dioxide for transport and storage. Although a large research effort worldwide is directed at membrane technology and better chemical systems, monoethanolamine or MEA has been used effectively in the chemical industry for more than 60 years and represents known 'of the shelf' technology[10]. Its major advantages are its strong attraction for carbon dioxide in an exhaust gas environment and its relative ease of regeneration and reuse. Notwithstanding its maturity, there are many aspects of the process that require improvement but often cheaper solvents that are easier to regenerate do not have the same speed of capture[11]. By mid-2008, the Delta Energy power station at Munmorah on the Central Coast region of New South Wales will be using a related ammonia solvent in a pilot test to capture carbon dioxide prior to full scale implementation for storage in unmineable coal seams[12].

Most Australian energy and emissions policy studies require CCS as a key component of successful mitigation outcomes. The 2006 ABARE study (*Technology: Its Role in Economic Development and Climate Change*) assumed that 28% of generation plant was fitted with CCS by 2050 and that globally it delivered a 25% reduction in emissions compared to the base case scenario. In the 'enhanced technology' scenario of ABARE's 2007 study (*Technology: Towards a Low Emissions Future*), 8% of greenhouse mitigation at 2050 was supplied by CCS derived from the assumption that all new fossil plant after 2020 was fitted with CCS. Generally the ABARE studies are circumspect about the economic potential of CCS and expect that other mitigation options will be cheaper, and therefore preferred by free market actors. The recent Climate Institute study *Leader, Follower or Free Rider?*, assumed 25 years from now that 80% of all fossil generators would be fitted with CCS. A similar assumption was used by the WWF's *Prosperous Low Carbon Future*, that fossil generators should not be allowed into service unless they were fitted with CCS. The most recent global WWF study *Climate Solutions*, assumed that by 2050 fossil generators might still be required but that all would be fitted with CCS and supply 26% of global electricity. Interestingly, the WWF study risk manages the potential of CCS and has enough mitigation buffering to allow CCS to fail and for global targets still to be reached.

Arraigned against the positive and 'can do' conventional wisdom on CCS, are the technical and environmental views that doubt the effectiveness of yet another silver bullet technology in bringing economy-wide emissions under control. An engineering perspective[13] notes a general technical inability in Australia (skills, scale, distance) to implement complex solutions at a scale sufficient to make a real difference. A specialist energy perspective[14] contrasts the failure to implement proven 'off the shelf' low carbon technologies such as gas turbines and wind, with the expectation that an expensive unproven and complex solution will prove the answer in the medium to long term. Environmental advocates[15] add the legal quandary of who will underwrite 40-year project lifetimes that are expected to give permanent, assured and incontrovertible storage for periods in excess of 100,000 years. Science media groups[16] bring many of these expert issues together under headings such as "Pipe Dreams" highlighting the doubt that the best technical outcomes will magically and fluently coalesce some time in a distant future.

While this chapter implements a conventional approach with industrial solvents, two additional capture and storage approaches are worth noting. The first so-called 'air capture' uses extensive industrial complexes of large absorbent columns where a sodium hydroxide (NaOH) spray captures carbon dioxide converting to calcium carbonate ($CaCO_3$) is regenerated by heating[17]. While still an immature approach and too financially and energy expensive, it could be deployed to capture non-point emissions from vehicles or used in a mass global deployment if atmospheric concentrations were verging on a climate change tipping point. Similar chemical processes are being examined for artificially accelerating the rock weathering process[18]. Somewhat analogous is a second 'bio-char' process producing stable carbon compounds through pyrolysis from plantation forests grown for carbon sequestration[19]. Adding these 'char' carbon compounds to soils to artificially engineer manmade 'terra preta'[20] soils increases the productivity and resilience of agricultural systems and can give carbon storage lifetimes in excess of 1,000 years[21]. This second storage mechanism is applicable to scenarios for wood-based bio-alcohol in subsequent transport fuel chapters in this study. Additionally, gas turbine generators fuelled by gasified biomass can be fitted with CCS to produce negative emissions electricity with carbon dioxide intensities of minus 200 gms per kilowatt hour[22] and produce a by-product of the combusted char described above.

This chapter uses the recent technical literature, much of it European, to describe the physical characteristics and probable function of a fossil fuelled electricity sector with 'assured and off the shelf technology' for carbon sequestration and storage applied, admittedly at a grand scale, to an evolving Australian economy. The key assumptions are relatively conservative and should be robust, especially when bounded by the sensitivity analysis. As expected within this analytical approach, any technological innovation which makes physical processes more efficient and thus cheaper, often re-stimulate the economy thus losing some or all of the expected emissions reductions. Rebound control through a future fund mechanism is used here to control buoyant growth scenarios and thus constrain the overall economic outcome to that of the base case.

Simulation Settings and Rationale

The application of carbon capture and storage transition is simulated for a traditional growth economy within both the base case and advanced fossil scenarios (Table 1). Results from the advanced fossil scenario and the contemporary literature suggest that whole-economy outcomes for carbon scrubbing will be superior with advanced generators rather than the current infrastructure. However the two scenarios are compared to quantify the differences. The scenario assumes a rapid rollout of carbon capture and storage being retrofitted to present generators and all new ones. The pollution treatment is in place by the mid 2020s and is probably too optimistic but assumes that mitigation of global change is on a 'war footing'. An implementation limit of 80% is set so that smaller generators and those distant from pipelines are excluded, as well as two thirds of the distributed fuel cells in the advanced fossil configuration.

Table 1. Description of key scenario settings implemented for the carbon sequestration and storage simulation.

Scenario Setting	Rationale and Detail
Goals for carbon sequestration and storage	Two scenarios where the MEA (mono-ethanolamine) scrubbing process capture 90% of power plant carbon dioxide and is applied to 80% of fossil generators in the base case and advanced fossil scenarios. A third scenario is developed where 30% wind power is deployed to power the scrubbing technology in the advanced fossil case and each technology therein reduced from 30% to 20%.

Electricity requirement for carbon scrubbing and solvent regeneration	Assumption is that 70 kWh of electricity per tonne of CO2 scrubbed is required for carbon scrubbing and solvent regeneration. It is assumed that thermal heat requirement for MEA regeneration is recycled from heat exchangers in the combustion and generation infrastructure.
Electricity requirement for transport and storage	15 kWh per tonne for CO2 compression, transport and injection. An average pipeline distance of 300 km is assumed for the 80% of generation capacity where CCS is installed.
Capital cost of carbon scrubbing technology	Carbon scrubbers effectively double the capital cost of a contemporary coal or gas fired plant.
Rate of solvent degeneration and cost	2 kg of MEA degrades for each tonne of CO2 extracted, and must be replaced. Cost of MEA is Euro 1,000 per tonne or AU$ 1,600.
Achievement of goals	Rapid implementation begins in 2016 and is complete by 2026. By 2051 approximately 100,000 MW of generation infrastructure is fitted with MEA-like scrubbing and storage capacity.

The generally available off-the-shelf scrubbing technology used in the oil and gas industry is used with a regenerative solvent Mono-EthanolAmine or MEA. There are a wide range of solvents and scrubbing technologies currently under development and current literature[23] is used to set some best practice technical parameters with the possible effect of innovation examined in the uncertainty section (Table 3). There is a generic pipeline infrastructure sector describing high pressure gas pipelines which triples in size over the scenario period and is assumed sufficient to transport CO2 extracted. An additional scenario was implemented where in parallel, a major investment in wind turbines was made to power the pollution abatement on the fossil generators. This caused a number of dynamic problems in the modelled economy and while the results are presented in Table 2, the scenario is not discussed further.

Scenario Results

Both the base case and advanced fossil scenarios with carbon capture show a dip in yearly GDP growth rates in the first two decades of implementing carbon capture and storage (Figure 1). Thereafter, the advanced fossil scenario shows higher growth rates due to higher generation efficiencies while carbon capture applied to the base case closely follows the untreated scenario. The large dip in growth rates because of domestic gas depletion occurs earlier in the advanced fossil case than the base case scenarios but its recovery is quicker and stronger. Average GDP growth rates are one tenth of one percentage point lower than the untreated base case in both cases. By 2051 in absolute GDP terms, the treated scenarios bracket the untreated base case with the advanced scenario $200 billion higher and the treated base case $100 billion per year lower. In accumulated terms, the treated base case is $1,600 billion lower than its untreated state, while the advanced fossil scenario is equivalent to the base case because of rebound control (Table 2).

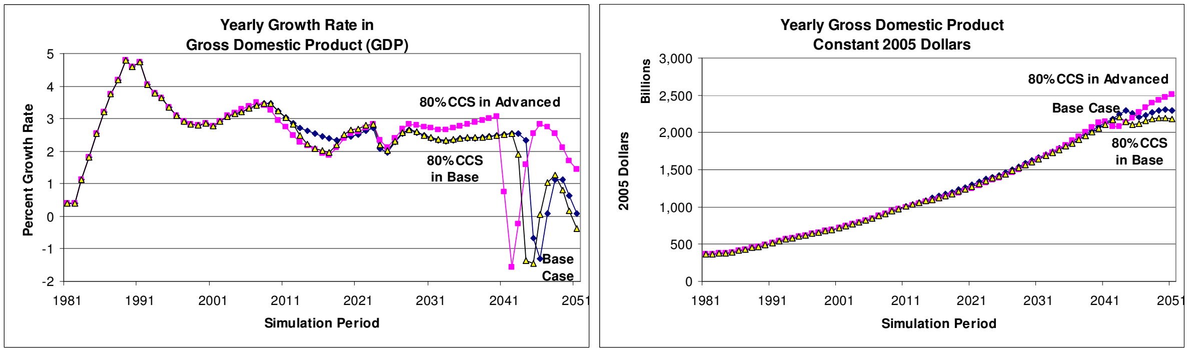

Figure 1. The GDP growth rate (left hand graph: %) and GDP absolute (right hand graph: 2005$) for the base case and carbon scrubbing within the advanced fossil and base case scenarios.

The trajectories for both per capita physical affluence and carbon dioxide emissions are lower for the advanced generator option compared to the treated base case (Figure 2). However for physical affluence at least, they converge in the final decade to around 160 GJ of embodied energy equivalent, or 60% higher than current levels. It is worth highlighting that the physical affluence measure excludes food and housing, and can be assumed to be mostly consumer items. In accumulated terms however the differences are larger with the treated base case 400 GJ and the scrubbed advanced generator option 1,400 GJ lower than the untreated base case. In consumer terms this is equivalent to foregoing the purchase of three or 12 new medium sized motor vehicles over the 45 year period. However the combined effect of lower physical affluence and scrubbing technology in reducing emissions to the atmosphere is considerable. In accumulated terms, this is four and 10 billion tonnes for the treated base case and treated advanced generator respectively, the latter outcome being equivalent to the renewable electricity transition.

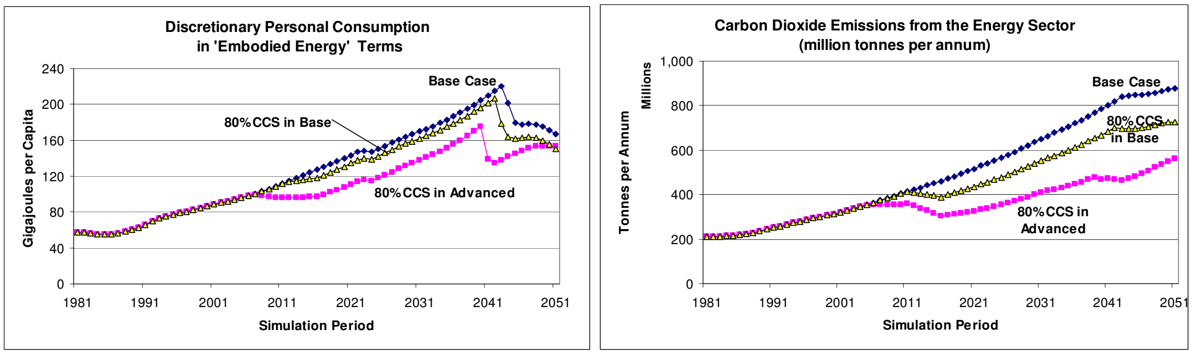

Figure 2. Simulations of the personal affluence indicator (left hand graph: GJ per capita) and net carbon dioxide emissions from the energy sector (right hand graph: million tonnes per annum) for the advanced fossil electricity and base case scenarios.

The dynamics of generation, capture and storage give an interesting insight into why only advanced generators should be considered if the capture technology is to be used. Both treatment scenarios capture and store about 6.6 billion tonnes. However the less efficient generators in the treated base case cause whole-economy emissions to increase by three billion tonnes as more generators are required to run the pollution abatement. When this efficiency penalty is added to normal working of the economy, the difference in net greenhouse emissions between the two treated scenarios is an accumulated six billion tonnes.

The emissions dynamics for the electricity generation sector are shown in Figure 3. The treated base case gets a step-down of 50 million tonnes as the technology is implemented, but emissions continue to increase thereafter as the technical capability of the generators plateau, and economic growth requires expanding energy supplies. By contrast the advanced generators get a step-down of about 100 million tonnes and this stabilises or even slightly declines for the remaining 30 years of the scenario period. The amount of carbon dioxide captured and stored (right hand graph immediately below) is similar for both scenarios, and it is overall generation of carbon dioxide at a whole economy level, mainly to run pollution abatement, that is the difference between the two scenarios.

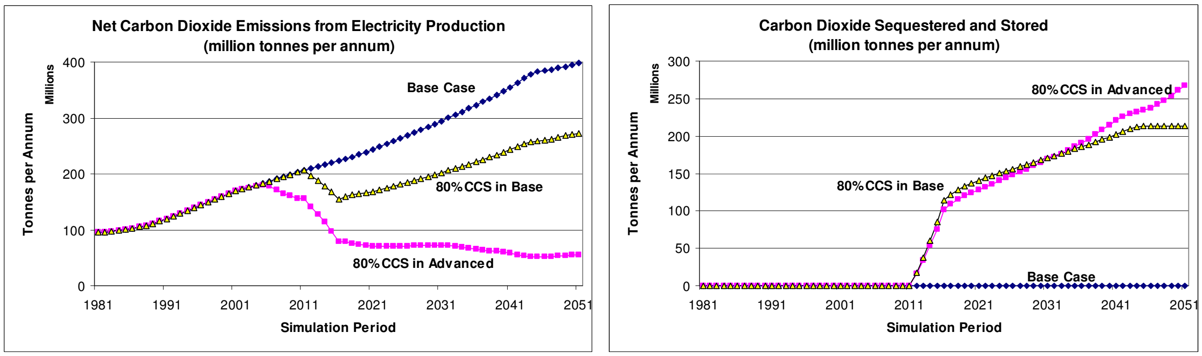

Figure 3. Million of tonnes of carbon dioxide emitted (left hand graph) and sequestered and stored (right hand graph) for the base case and carbon scrubbing in base and advanced fossil scenarios.

Accumulated oil requirements over the scenario period is similar between the treated and untreated scenarios as, apart from short term variations in GDP growth rate, there are no deliberate transport fuel policies implemented here (Table 2). The accumulated coal usage in the treated scenarios increases by 14,000 PJ due to the extra electricity required to run pollution abatement while accumulated gas requirements are 11,000 to 24,000 PJ higher for similar reasons. This increased gas requirement in particular questions the wisdom of entering into long term contracts for gas exports given the value of gas in powering high efficiency generators and thereby maintaining economic growth, and the additional requirement to scrub and store emissions from those same generators. The possibility of using gas to power the domestic vehicle fleet will be explored in a later section.

Table 2. A comparison of key indicators over the 45 year scenario period (2006-2051) for the base case and advanced fossil (30% each of advanced coal, combined cycle gas and fuel cells) scenarios.

Indicator	Base Case	80% CCS in Base Case	Advanced Fossil	80% CCS in Advanced Fossil	30% Wind 80% CCS in Advanced Fossil
Average GDP growth rate--%	2.2	2.1	2.5	2.4	2.9
Accumulated stock of GDP--billion 2005 dollars	73,813	72,213	73,454	73,440	72,563
Accumulated stock of net CO2 emissions--billion tonnes	28.72	24.68	23.12	18.59	18.48
CO2 scrubbed and stored: billion tonnes	0	6.6	0	6.8	2.5
Accumulated Future-fund: billion 2005 dollars	0	0	5,669	4,835	7,781
Personal consumption stock: GJ per capita	7,245	6,809	6,006	5851	4669
National capital stock at 2051 : embodied PJ	24,672	23,993	25,858	25,946	27,737
Accumulated oil use --PJ	149,000	145,000	145,000	145,000	139,000
Accumulated gas use --PJ	149,000	160,000	175,000	199,000	167,000
Accumulated coal use --PJ	156,000	170,000	75,000	87,000	59,000
Accumulated 'managed' water use: GL	1,611,000	1,624,000	1,490,000	1,507,000	1,399,000
Electricity production at 2051: GWh	682,044	849,422	713,000	947,703	760,306
Total electricity infrastructure: Installed MW at 2051	111,191	138,799	135,626	179,515	193,416
CO2 intensity of electricity production at 2051: grams per kilowatt hour	653	360	380	65	274

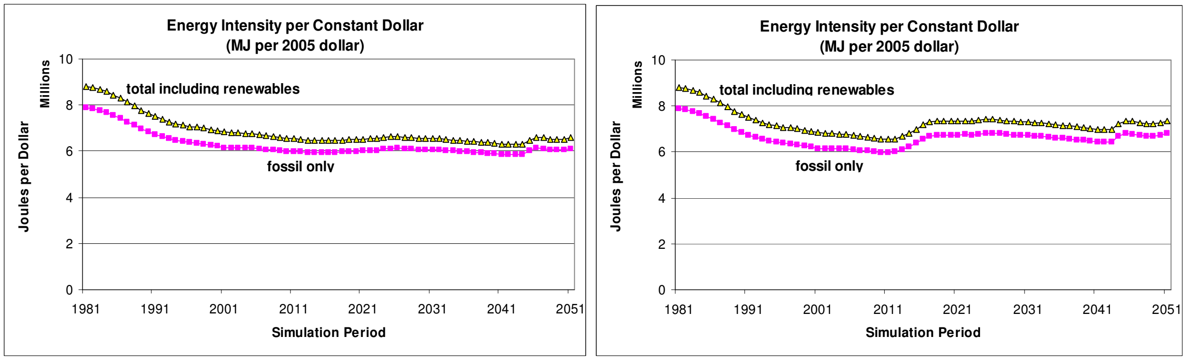

Figure 4. Simulations of the energy intensity of GDP (MJ per constant 2006 dollar) for the base case (left hand graph) and base case with carbon scrubbing scenarios (right hand graph). Note: the two bottom line graphs (red blocks) conform to international energy accounting standards while the top graph includes renewable electricity.

Implementing carbon scrubbing with base case technology increases the energy intensity of GDP because of the dynamic described above where additional energy is required for pollution abatement in parallel with more energy being required to fuel economic expansion (Figure 4). An additional 25-30% electricity production is required for the carbon scrubbed scenarios. Clearly the policy issue is not energy intensity but net carbon dioxide intensity of GDP which is reduced at 2051 by 13% in the scrubbed base case (from 380 gms/$ to 330 gms/$) and by 43% in the scrubbed advanced fossil case (from 380 gms/$ to 220 gms/$).

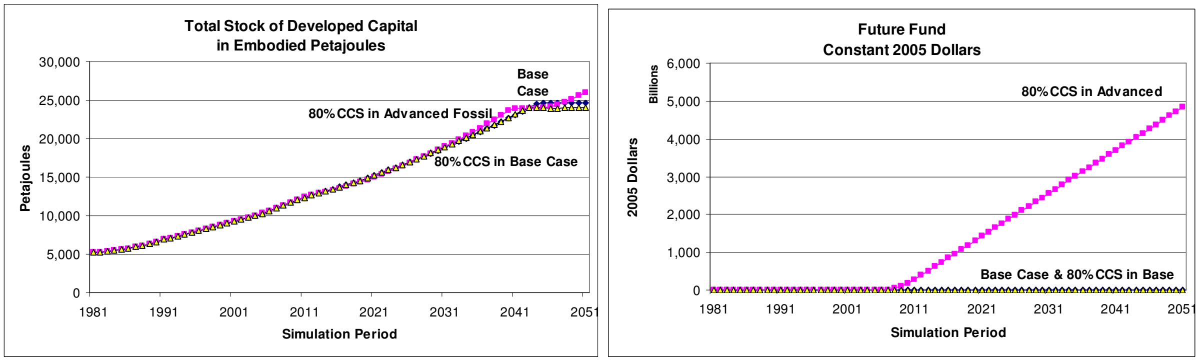

Figure 5. Simulations of the national stock of 'developed' infrastructure capital (left hand graph: embodied energy in petajoules) and the financial stock in the national 'future fund' used to control technology rebound (right hand graph: billion 2005 dollars).

Both carbon scrubbing scenarios generate a stock of developed capital (a national wealth stock in embodied energy terms) similar to the base case (Figure 5). However the buoyancy of the advanced generator scenario requires control of technology rebound and this produces a future fund stock of $5,000 billion by 2051 or about five times the current stock of superannuation investments. The carbon scrubbing process requires an increased electricity production of 100,000 GWh above the base case from 30,000 MW of additional infrastructure to run it (Figure 6). The more buoyant growth of the advanced fossil scenario stimulates more electricity production and additional infrastructure requirements in the final decade of the scenario. Constraining this growth spurt presents a dilemma since more rebound control would give more carbon dioxide reduction but also void the simulation assumptions that where possible, all scenarios should be GDP neutral.

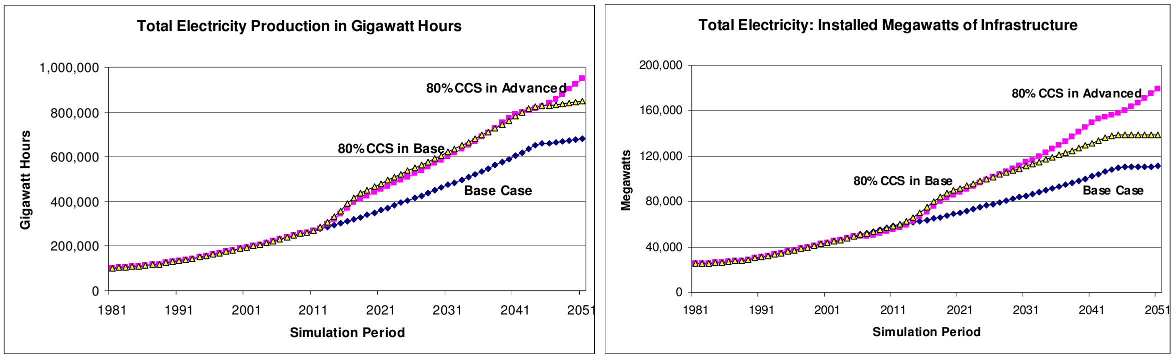

Figure 6. Total electricity production (left hand graph: GWh) and electricity infrastructure (right hand graph: MW) for the base case, and carbon scrubbing in base and advanced fossil scenarios.

By 2051, the combination of carbon dioxide scrubbing and efficient generators decreases the net carbon dioxide intensity of electricity production to 65 gms per kilowatt hour (minus 90%) for the advanced generator case and 360 gms (minus 45%) for the scrubbed base case, compared to the untreated base case of 650 gms (Figure 7). These results could be improved by changing scenario assumptions such as the 80% proportion of generators treated but on reflection this remains a defensible assumption. The trajectory for natural gas requirements show that advanced generators with capture require 2,000 PJ more per year than the treated and untreated base case and this advances the gas depletion point by four years. Domestic gas requirements here increase by an accumulated 50,000 PJ or one third compared to the untreated base case causing gas exports fall by 40%. As noted in the previous chapter, gas is a critical fuel for low carbon electricity production to help meet greenhouse targets and may also be required as a transport fuel when oil becomes constrained globally. Whether to use national gas domestically or provide other nations a fluent pathway to lower carbon futures requires a complex evaluation of the risk and benefits over two human generations. Even with large additional discoveries, natural gas will become constrained in the next three human generations or 75 years. The key issue is when and where to use this resource endowment to most advantage. These scenarios do not give an answer to this quandary that but serve to highlight the importance of the issue.

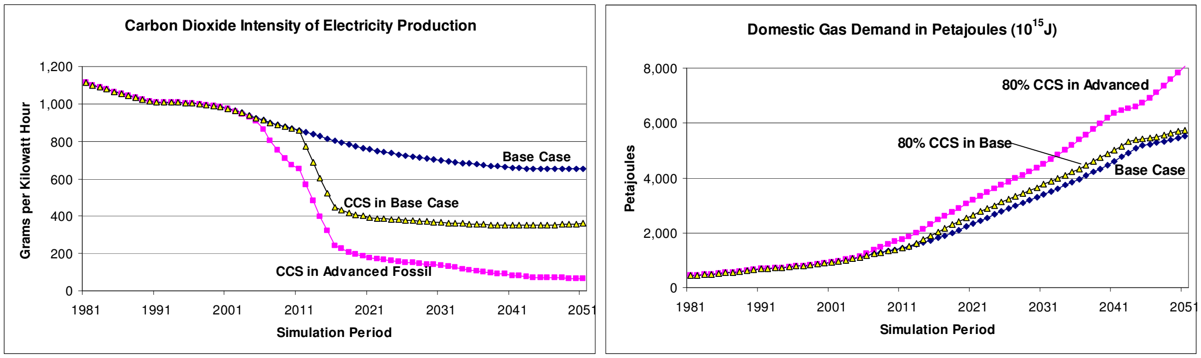

Figure 7. The carbon dioxide intensity of electricity production (grams per kilowatt hour) and domestic gas requirements (in petajoules) for the base case, and carbon scrubbing in base and advanced fossil scenarios.

The transport energy demand for both cases of carbon scrubbing is similar to the base case out to 2040, and apart from differences due to the onset and recovery from domestic gas depletion finishes 100 PJ on either side of the unscrubbed base case at 2051(Figure 8). The requirement for managed water for the advanced fossils case is lower than the treated and untreated base case due to less water required by thermal electricity generation, coal washing and agriculture. However all scenarios converge on the 40,000 GL range by the year 2051.

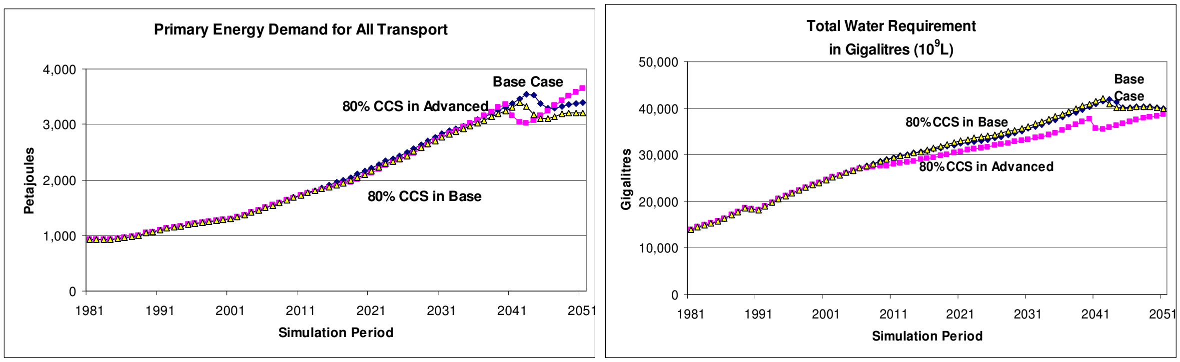

Figure 8. National requirements for transport energy (left hand graph: petajoules) and managed water (right hand graph: gigalitres) for the base case and advanced fossil scenarios.

Risk and Uncertainty of Scenario Results

Against a core assumption that implementing scrubbing technology on advanced generators doubles the capital cost of each generation technology, a doubling and a tripling of that assumption (effectively four or six times the unscrubbed capital cost), reduces the accumulated GDP by 5-10% and thus the accumulated carbon dioxide emissions by a further 1-2 billion tonnes (Table 3). The same assumptions for the base case give larger reductions of 17-22% because of the economy-wide effect of lower generation efficiency and similar emission reductions. At least for the advanced generator scenario this should make the case for scrubbing unequivocal as even the core capital cost assumption is a generous one and made in order to cover the expectation of project blowouts as technology rollout transitions from pilot scale to a full practical implementation. Assuming that the extra capital cost is supplied by the domestic economy and not for example by international debt or overseas investors, then other sectors must also decrease. Thus for the advanced generators with triple capital cost, both per capita physical affluence and developed capital fall by 14% compared to the core scenario. At 2051 for the advanced generator case, the physical affluence measure expressed in the embodied energy content of personal consumption (gigajoules per capita) is still 33-16% above the level today for the double and triple case respectively. It is reasonable to assume that technological and behavioural improvements over the next two human generations will ensure that the goods and services supplied per unit of embodied energy will markedly increase.

Table 3. A comparison of key indicators over the 45 year scenario period (2006-2051) for the base case and the advanced fossil scenarios.

Indicator	Induced Effect	Effect on main scenario outcomes
Capital cost of carbon sequestration and storage	Doubling and tripling	A doubling and tripling of capital cost of CCS used with the advanced fossil technologies causes a reduction of $4,000-8,000 billion (5-10%) in accumulated GDP. Accumulated CO2 emissions reduce by a further 1-2 billion tonnes because of lower rates of GDP growth. Increasing CCS capital costs in the base case reduces accumulated GDP by $13,000-16,000 billion (17-22%). Accumulated CO2 emissions are also reduced by a further 1-2 billion but lower production efficiencies generate more gross emissions that have to be scrubbed and stored.
Electricity requirement of sequestration, transport and storage	Doubling and tripling	For advanced fossil, accumulated GDP is reduced by $4,000 -17,000 billion (5-23%) and accumulated CO2 emissions remain the same as the core CCS scenario because lower GDP growth rates are balanced by higher energy requirements per tonne of CO2 sequestered and stored. CCS in the base case reduces accumulated GDP by $1000-9,000 billion (1-12%) and increases net CO2 emissions 3-7 billion tonnes compared to the core scenario.
Cost and degradation rate of solvent for carbon scrubbing	Doubling and tripling of cost of MEA solvent, and the degradation rate increased to 10 and 20 kg per tonne of CO2 scrubbed	All combinations of cost per tonne or degradation rates of MEA solvent have relatively minor outcomes with a highest effect of a $500-600 million reduction in accumulated GDP when 20kg of solvent is degraded for each tonne of CO2 sequestered. This is ten times the rate assumed in the core scenario.
Decrease in capture rate of CO2	20% and 40% decrease per unit of scrubbing infrastructure	Decreases in CO2 capture rates have negligible effects on financial outcomes and increase accumulated CO2 emissions by 7-14% (i.e. less than the 20-40% decrease in capture rates) due to less solvent supply and re-processing.
Co-occurrence of all of the above issues	Two worst case scenarios with medium and high assumptions	For advanced generators, combinations of all of the above factors decrease accumulated GDP by$10,000-16,000 billion and increase net CO2 emission by 0.5 billion tonnes. For the base case with CCS, accumulated GDP is reduced by $4,000-20,000 and accumulated CO2 emissions increase by 3-8 billion tonnes.

The development of carbon capture and storage over the next two decades will focus on reducing the full chain energy cost of storing each tonne of carbon dioxide. The media and policy makers generally express this in dollars per tonne of carbon dioxide permanently stored but as the scrubbed base case has shown the physical efficiency of the overall system should be the key focus. The core energy assumption over the full chain from capture to geological storage is that 85 kWh of electricity is required for all powered processes in addition to free recycled thermal energy from generation plant required for solvent regeneration (Refer Table 1). For the advanced generators, doubling or tripling the electricity requirement per tonne of carbon dioxide stored decreases the accumulated GDP by 5% and 23% respectively. The lower rates of GDP activity cancel out extra carbon dioxide emissions and so the emissions outcome is relatively neutral. The same changes to the base case reduce accumulated GDP by 1-12% but actually increase emissions above that of the untreated base case.

The development of regenerative solvents that capture carbon dioxide is currently the focus of increasing technological development. Against the core assumptions used here, both the cost of the solvent and its rate of degradation (MEA degrades on each pass through capture and regeneration and requires additions to retain the capture ability of the integrated process). At an economy-wide rather than a corporation level, quite large increases in the solvent cost and its rate of degradation give discernable but minor effects. Decreases in rates carbon dioxide capture in the scrubbing plant obviously decrease the emissions captured and stored but the overall emissions rise by only one third of the capture decrease because of less electricity required for transportation and storage. For the advanced generators, combining worst case assumptions treated singly above reduces accumulated GDP by 30% and increases accumulated carbon dioxide emissions by 500 million tonnes compared to the core scenario.

The sensitivities explored here are a series of worst case scenarios and so reductions in capital cost or improvements in solvent chemistry should give better financial outcomes. However in a free market economy better economic buoyancy will inevitably flood over into other sectors (even in other countries), increase economic activity and probably increase emissions. Thus lower cost or more efficiency in the absence of rebound control (implemented here by a future fund or a carbon tax) could give counter intuitive effects to the main goals of technological development. A somewhat costly and medium efficiency complement of pollution abatement equipment may be the most effective for economy-wide pollution abatement.

Discussion

The key results in this chapter are somewhat unsurprising, especially in light of the 2007 peer reviewed literature, most of it European, referenced in this chapter's introduction. Simply put, CCS should only be applied to generation systems with high electrical efficiencies to maximise both the avoidance and the capture of carbon dioxide emissions. The added nuance from this whole-economy analysis is that large technological advances in generation plant, in the absence of rebound control, may increase other emission producing activities outside of the electricity sector.

Insights from the literature and this analysis make it doubly clear that the relatively mature technology of combined cycle gas turbines offer the assured pathway to a lower emissions electricity sector in the medium term of 20-30 years. However the capacity of gas turbines with CCS to supply the greater emissions reductions thereafter to 2050 will be limited technically and may further result in stranded capital if a decision is then made to proceed with a renewables transition. A further technical step improvement is possible by new technology combinations such as fully integrating solid oxide fuel cells with advanced gas turbines. The analyses here have simulated both fuel cells and gas turbines in parallel, but not as an integrated set where significant emissions avoidance can be made.

While the technical barriers to a full implementation are immense, the peer reviewed literature warns of an almost complete absence of institutional and governance frameworks in most developed countries. Issues are complex and intersecting. These include the ownership of the 'pore space' in deep geological storage, the long term legal liability for the stored emissions over many human generations, the partition of carbon credits between the separate entities or companies that actually capture, compress, transport, inject and finally monitor the stored carbon dioxide[24].

The reliance of the 'advanced fossil with CCS' scenario on a natural gas fuel is a problem should domestic or global supplies become constrained. This analysis allows natural gas exports to grow in line with an expanding world market so that domestic stocks become critically low by the early 2040s. Ceasing gas exports would allow another 15-20 years of successful scenario operation perhaps to 2070, but the depletion issue and the alternative solution become even more acute by then as economy-wide transitions require 35 years or so to get in place. Natural gas depletion is not yet a domestic policy issue although it is flagged by the Western Australian Government[25] requesting the securing of a domestic buffer stock and by independent energy analysts such as Brian Fleay[26]. Not tested here is the option to use gas fuels to around 2030, and then embark on a rapid transition to renewable electricity generators.

Contemplating a radical switch from advanced fossil with CCS to renewable generators at the mid point of a scenario raises the question of whether or not to bother with advanced fossil systems in the first place. Clearly the advanced generators with CCS give the same emissions reduction overall of ten billion tonnes from the base case of 28.7 billion to the successful scenario outcomes of 18.6 billion tonnes accumulated. The transition to fossil with CCS will require complex integration of many generators and their pollution abatement, the construction of new transmission and pipeline networks and the enactment of legislation and institutions required to last for millennia. The renewables transition requires much of the same complexity but most of its components including storage technology, are already off the shelf items perhaps not yet produced at the scale required to underpin a resilient and growing economy. A similar conclusion was reached by the German analysts (referenced in the introduction) facing the aggressive emissions reduction targets set for set by their Federal Parliament.

The primary outcome of this chapter is that the future of fossil fuel fired electricity generation in Australia commensurate with sustained emission reductions, is physically dependent on currently minor ‘peaking’ or ‘distributed’ power sources because of their production cost in an economy without a carbon price ie gas turbines and solid oxide fuel cells. This result agrees with current technical literature mostly from Europe and disagrees substantially with the consensus view formed by Australian industry and government over the last one to two decades. Central to this consensus view is that the Australian economy owes its competitiveness to a cheap price for electricity. Economic causality tests[27] appear to prove that real GDP in Australia is driven by electricity use in the medium term of 35 years. If this outcome can be broadly supported across a number of analytical methodologies and their underpinning philosophies, then current energy policies are already defunct. The nature and direction of structural change in this physically dependent economy is now even more challenging.

Issues Linked to Other Scenarios

- Implementing carbon scrubbing with advanced generators gives a 10 billion tonne reduction in accumulated CO2 emissions but does not approach the 22 billion tonne reduction required if global reduction goals per country are set to 20% of the base case in this study.
- Given the expectation of rapid technological progress in the face of dire global change prognoses, it now seems rational policy to only permit advanced generators with carbon capture as new fossil plant, and to rapidly retrofit existing fossil infrastructure.
- The scenario of advanced generators with carbon capture becomes fragile around 2050 when natural gas stocks may deplete domestically and globally. From a scenario-centric viewpoint, the long term rationale for expanding natural gas exports is doubtful given the requirements to rapidly decrease net carbon emissions and effectively weather global oil depletion
- Applying carbon scrubbing to the complement of moderate efficiency generators described in the base case gives marginal in emissions reductions. Given this, the electricity industry requires national long term targets stipulated for 80 years (double its infrastructure lifetime) to help them leapfrog into advanced low carbon generators.
- Nuclear electricity may complement the ‘conventional electricity’ mindset for two reasons. Its relatively high cost may dampen down technology rebound caused by advanced generators, and secondly it may lessen scenario dependence on lower carbon natural gas.
- A lateral outcome from this chapter is the development for CCS requirements of char combustion products from combined cycle gas turbines fuelled from gasified biomass, possibly fitted with CCS to give negative emissions. This should be a key component of a final ’renewables’ scenario which includes bio-methanol. In process engineering terms it is unclear of the decrease in electrical efficiency that might be required to produce long lived char for soil amelioration.

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