Novel CO_2 Capture Task Force

Report

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EXECUTIVE SUMMARY

A portfolio of low-carbon technologies are required to be developed to reach Government targets for CO_2 emissions. A large proportion of Australia's electrical energy is generated using coal and there is an increasing use of natural gas. Geological sequestration of CO_2 from these fossil sources is being extensively studied in Australia. The present study was convened by the sponsors BCIA[1], ANLECR&D[2] and the Global CCS Institute[3] to investigate CO_2 capture and storage by means alternative to geological storage. The technologies for novel CO_2 capture considered by the Task Force fall into the areas of *bio-sequestration* and *mineral sequestration*, given by the following definitions:

> *Bio-sequestration* is the capture and storage of atmospheric CO_2 by biological processes. This may be by increased photosynthesis (through re-forestation, or decreased de-forestation); by enhanced soil carbon trapping in agriculture; or by the use of algal bio-sequestration to absorb CO_2 from industrial processes.
>
> *Mineral sequestration*, or mineral carbonation, involves reaction of CO_2 with metal oxides that are present in common, naturally occurring rocks. This process mimics natural weathering phenomena, and results in natural carbonate products that are stable on a geological time scale.

The Task Force study commenced in January 2011 and concluded in August 2011. The first activity involved convening independent experts from industry, universities and the CSIRO to a workshop where an action plan for the study was developed. As part of the workshop, a series of "hypotheses" to be answered were developed as a key component of the action plan. These "hypotheses", and their answers as determined by the Task Force during the study, were:

Hypothesis 1: "There is sufficient scientific and technical literature on novel carbon capture technologies for the task force to assess the feasibility and develop a ranking of the various processes."

Answer: A qualified "YES".

Hypothesis 2: "By 2020, Novel CCS projects will be bankable at commercial scale."

Answer: "NO"

Hypothesis 3: "By 2015, scientific consensus will be reached on permanence and sustainability of implementable Novel CCS"

Answer: Generally "NO"

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[1] Brown Coal Innovation Australia Limited, Melbourne

[2] Australian Low Emission Coal Research and Development, Canberra

[3] Global Carbon Capture and Storage Institute Limited, Canberra

Hypothesis 4: "By 2020 coal, together with novel methods for carbon capture and sequestration, will be the lowest cost option for base-load power in Australia at emissions of 150kg/MWh, with sufficient storage capacity to make a material contribution to GHG reduction targets".

Answer: "NO"

Hypothesis 5: "By 2015 novel carbon capture and storage will be accepted by the community and regulators through effective consultation and education, through informed social consent".

Answer: "NO"

Hypothesis 6: "By 2015, an internationally accepted methodology for quantifying CO_2 sequestration 'reserves', analogous to HC reserve system SPE 2007, will be developed."

Answer: "NO"

Hypothesis 7: "A map of the mineralization feedstocks in Australia, graded by desirability, can be produced".

Answer: "A qualified YES"

Further explanation of the answers to the above hypotheses is included as a key section of the report. Many aspects of the problem were considered by the Task Force in order to answer the hypotheses. These included a comprehensive review of the available public literature, discussions with commercial proponents of the technologies, review of the issues with scientific experts in the respective areas, discussions with venture capital suppliers and bankers, and a financial analysis by the Task Force using option valuation and other financial analysis methods. All these aspects are covered in detail in sections of the report.

Based on the literature review and discussions with both experts and the technology proponents, most of the technologies under consideration were considered by the Task Force to be "conceptual" or "embryonic" at the present time. "Conceptual" technologies are those that are based on an idea, rather than hard scientific data and analysis. "Embryonic" technologies are those that have bench-scale scientific experimental data to back up the claims of the proponents. In this context, most of the technologies are not yet at the "pilot" scale of development, let alone at the commercial stage of commencing to provide key competitive advantage. This is one reason that most of the hypotheses above are answered in the negative.

Algae growing technologies are well developed for the production of high value products such as nutraceuticals. Some of these utilise CO_2 in the atmosphere and large ponds to grow the algae in areas of high insolation. However, higher productivity algal processes aimed at utilising CO_2 at higher concentrations are in their infancy. There are many publications in the last few decades describing these processes, mainly using paddlewheel raceways in open ponds to agitate the algal slurries. To date, these processes have not been scaled up to the size that would be required for capture of coal-fired power station CO_2. The land areas required for this application are very large, and for a typical installation would be many thousands of hectares for every million tonnes of CO_2, based on reported productivities. A full-scale power station emits over ten million tonnes of CO_2 per year, so it is clear that the land area requirements are very significant for this application. Moreover, the Task Force has found that a wide range of productivities have been reported, and this adds to the uncertainty in the scale of a commercially sized system. Calculations undertaken by the Task Force indicate that large-scale micro-algae based on photosynthesis can only consume CO_2 for a fraction of the 24 hours in a day, owing to the availability of sunlight. This may result in collection of only 20 to 25% of CO_2, since storage of flue gas is not feasible at the flows involved. Therefore, apart from the other land and cost issues, algal growth can only be seen as a partial solution to the CCS problem. Niche applications of algal growth using power station CO_2 may however be appropriate, with commercial application aimed at the production of valuable algae products such as algal oil and agricultural feedstock.

There is ongoing public debate about whether algal “re-use” of CO_2 is really sequestration. The Task Force has taken the view that algal energy products such as methane and algal oil will displace equivalent fossil fuels and, all other things being equal, this means that the displaced fossil fuels remain entrapped inside the earth. Under these conditions the algal capture of CO_2 can be considered in the same way as (say) biomass combustion to produce electricity.

Mineral carbonation of magnesium and calcium containing rocks using power station CO_2 has been studied for many years. The chemical reaction between CO_2 and the rock is very slow and in some cases requires activation of the rock using heat. Studies have shown that high pressures and temperatures are required in order to cause the carbonation reaction to occur. In NSW, large quantities of suitable rock are available in reasonable proximity to where some of the power is generated. Approximately three tonnes of rock are required for every tonne of CO_2, so the scale of a mineral carbonation operation is significant. For example, over 30 million tonnes of rock need to be mined annually for a single NSW Hunter Valley power station to capture the emitted CO_2, and this gives rise to almost 40 million tonnes of fine carbonate tailings. The environmental impact of the technology will necessarily be large, and this may affect the social acceptability of the technology. Because of the large amounts of raw materials and/or gases that need to be involved, it is likely that the viability of mineral carbonation processes will depend significantly on their location. In general, it will mean that the facilities will need to be located near the source of the magnesium oxides.

There is the possibility for valuable by-products from the rock, including iron, chromium and nickel oxides, and this assists the potential economic viability of the process. Nevertheless, the capital and operating costs of this technology are shown in the literature to be generally high. Financial analyses undertaken by the Task Force indicate that high prices for CO_2 (of the order \$175/t CO_2 total cost) will be required for the conventional processes to be economic at reasonable rates of return. However, scientific and chemical engineering research into mineral carbonation is also still at the “embryonic” stage and at bench scale. Some new approaches aimed at improving efficiency and lowering costs are under development. It is thought by the Task Force that the necessary scale-up accompanied by efficiency improvement will present a significant challenge to mineral carbonation. However, it is clearly necessary for the viability and sustainability of the process in the future.

There are some other new mineral carbonation processes based on novel chemistry and flowsheets that may have higher efficiency and for which lower costs have been proposed. These processes should be evaluated further, since mineral carbonation is one of the few technologies with sufficient scale and raw material resources to genuinely and permanently sequester the required quantities of CO_2 for centuries.

Managed forestry is a mature technology that is presently used to sequester CO_2 from the atmosphere. Indeed, the general public can purchase CO_2 credits to offset their CO_2 emissions from transportation on a voluntary basis at a relatively low CO_2 price in Australia and large Australian companies are utilising commercial CO_2 sequestration by forestry. At normal commercial returns the Task Force has found that CO_2 prices close to the projected prices under a global carbon trading scheme make this business relatively attractive financially for an investor provided that the cost of land is reasonable and the productivity of the forest is acceptable. However, the availability of such land in Australia is low and agriculture and forestry are not yet included in the proposed national carbon trading scheme. The potential for total contribution to CO_2 sequestration from forestry for coal-fired power plants is therefore considered by the Task Force to be relatively low at present. Further, the uptake of CO_2 by forests is non-linear, with a peak in sequestration about 10-20 years after the forest is planted.

The sequestration of carbon in soils is a current topic of great interest politically. It is also a topic of scientific uncertainty. There is anecdotal evidence, both modern and ancient, that increases in soil carbon improve agricultural productivity. Projects such as the Carbon Farming Initiative that aims to increase soil carbon in Australia through farming practices will no doubt have positive impacts on this productivity.

Placement of carbon in soils to sequester carbon from the atmosphere is more controversial. Carbon in soils is not necessarily permanent, and Australian soils have lost carbon appreciably over the last two centuries. The literature shows that, depending on the nature of the carbon, it can transfer out of the soil back to the atmosphere relatively quickly thus making the sequestration illusory. On the other hand, dense carbon charcoals produced from biomass (biochars) may stay in the soil for centuries and may enhance the “endogenous” soil carbon content[4]. This is particularly relevant to the enhancement of soil carbon using derivatives of fossil fuels such as lignite, where permanence is required. Techniques such as this lignite derivative placement may well enhance agricultural productivity, but cannot yet be guaranteed to sequester large amounts of atmospheric CO_2 over long time scales. The Task Force believes that further high quality scientific studies are required in this area.

There are generally two aspects of the soil carbon area that are uncertain. Firstly, the science of the movement of soil carbon to and from the atmosphere is not well understood - it changes both spatially and temporally. That is, soil carbon dynamics vary from location to location and from time to time, especially seasonally and as a function of weather events such as drought. Secondly, one of the reasons this phenomenon is not well understood is related to the high costs and low efficiency of

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[4] “Endogenous” means the carbon in the soil generated by the soil itself through the action of plant roots and species living in the soil.

soil carbon measurement techniques. The Task Force believes that development of soil carbon flux measurement techniques using remote sensing should have high national priority in the context of acquiring deep understanding of soil carbon dynamics.

A number of recommendations have been made by the Task Force in relation to the novel technologies. These are provided in the next section of the report.

RECOMMENDATIONS

The recommendations of the Task Force are as follows:

1. The growth of algae by consumption of CO_2 from coal-fired power stations using photosynthesis can provide a relatively small contribution to their overall CO_2 emissions. The R&D on algae for CO_2 mitigation should be focussed on:
   - Increasing algal productivity, including new algal species research
   - Reduction of capital costs and raw material requirements
   - Mass transfer efficiency for CO_2 absorption in bio-reactors at low CO_2 concentrations.

2. Mineral carbonation technology in Australia has been found by the Task Force to be apparently following two streams: (i) development of the work undertaken previously in the USA on serpentine rock heat activation followed by reaction with CO_2, and (ii) technologies based on novel chemistry and flowsheets. Since the technology offers the scale and permanency required for the capture of CO_2 from coal-fired power stations at locations close to the rock resources, the Task Force recommends that RD&D be continued so that the nation can have multiple options in the area, including:
   - Further fundamental research at the bench scale to move the novel chemistry technology approaches beyond the concept stage.
   - Scale-up to beyond bench or laboratory scales to demonstrate that small-scale performance can be achieved at larger scale
   - Focused RD&D on the reduction of capital costs and increase in the efficiency of use of raw materials and energy. This should include rock activation, comminution, carbonation, particle separation technology, tailings dewatering, and tailings disposal.
   - Independent review of the costs of mineral carbonation for the different processes, taking into account expected efficiency improvements due to RD&D and innovative process developments.

3. It is recommended that the regulatory environment for forestry sequestration of CO_2 from the atmosphere in terms of credits for CO_2 capture be resolved to provide investment certainty. It is recommended that RD&D in the forestry area be focused on life cycle carbon accounting, including soil carbon effects. Risk management in terms of the impact of natural events should also be undertaken.

4. Sequestration through soil carbon enhancement has potential to make a contribution to CO_2 mitigation and to improvements in agriculture. There are, however, questions about carbon permanence in soils at the time scales required. It is recommended that RD&D be carried out in the following areas:
   - Effective and efficient methods of soil carbon measurement, including remote technologies to monitor CO_2 and other greenhouse gas fluxes into and out of soils
   - Bench and field trials at scale to monitor the soil carbon balance over time and space, including a range of soil carbon amendment types and simultaneous scientific measurement of the beneficial effects on agriculture

5. Biochar is a potential soil amendment that could provide permanence while improving agricultural outcomes. It is apparent that permanence of biochar is variable, but could be available for centuries under some conditions. It is recommended that RD&D be carried out in the following areas in relation to biochar:
    - As in the soil carbon recommendations above, field trials should be undertaken on different biochars to investigate the carbon flux to and from soils into which biochar has been added. This is particularly important in the case of fossil-derived biochars and humic materials.
    - The pyrolysis and chemical treatment processes to produce biochar should be scaled up and the resulting produced biochars should be used to scientifically establish permanence criteria as a function of char properties
    - The balance between exogenous and endogenously developed soil carbon for biochar additions should be scientifically investigated as a function of biochar type, soil type, space and time
    - Scale-up of existing pyrolysis processes should be investigated to determine whether the costs of large-scale pyrolysis can be reduced

6. Life Cycle Analysis (LCA) in terms of CO_2 permanent sequestration *vs.* CO_2 emission to the atmosphere in the process is a common theme in all of the technologies investigated. It is recommended that rigorous LCA analysis should be routinely employed in any analysis of CO_2 sequestration by the above technologies.

ACKNOWLEDGEMENTS

The Task Force is grateful to the people and organisations that made contributions to this study. These contributions were wide-ranging and involved many institutions and individuals. Their valuable expert input is acknowledged and appreciated.

The Task Force thanks the sponsoring bodies for suggesting and supporting the study and providing useful advice as the project progressed. In particular, staff at ANLEC R&D who administered the project deserve special mention and thanks for their assistance.

CSIRO provided a number of expert scientists and facilities for the Task Force. Numerous discussions were held and key information provided. In particular, the CSIRO scientists participated in the initial Task Force workshop and thereby provided high quality analysis at the start of the study. This assistance was invaluable to the progress of the project and is gratefully acknowledged.

The Melbourne Energy Institute at the University of Melbourne provided the secretariat and research assistance for the study. This input was again invaluable to the study outcomes. This assistance is also gratefully acknowledged.

The Australian Academy of Technological Sciences and Engineering (ATSE) provided access to their option value financial model for the study. This contribution is gratefully acknowledged.

Many individual scientists and professionals participated in discussions with the Task Force. These people ranged from technology proponents, to NGOs, academics, bankers and to providers of venture capital. The large number of people involved with the Task Force in the study is listed in Appendix A, while the contributors to the Task Force Strategy Workshop are listed in Appendix B. The study outcomes could not have been achieved without the input of these individuals, and their contribution is acknowledged with gratitude by the Task Force.

Experts from several of the technologies considered reviewed this report in draft form. The comments of the reviewers added to the report outcomes and their suggestions are gratefully acknowledged.

Important Note

Most of the information in this report is published in the public domain, and this is clearly footnoted in the report. However, some of the information was provided through personal communication with researchers, experts and developers of the technologies in question. Again, this is clearly noted and acknowledged in the report. Where such information is presented in the report, it is done so with the permission of the provider of that information. Responsibility for the veracity and accuracy of that information rests with the footnoted information provider.

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Appendices

1. INTRODUCTION

The Novel CO_2 Capture Task Force (NCTF) was convened by BCIA, ANLECR&D and the Global CCS Institute to investigate CO_2 capture and storage by means alternative to geological storage. The technologies for novel CO_2 capture considered by the Task Force fall into the areas of *bio-sequestration* and *mineral sequestration*, given by the following definitions:

> *Bio-sequestration* is the capture and storage of atmospheric CO_2 by biological processes. This may be by increased photosynthesis (through re-forestation, or decreased de-forestation); by enhanced soil carbon trapping in agriculture; or by the use of algal bio-sequestration to absorb CO_2 from industrial processes.
>
> *Mineral sequestration*, or mineral carbonation, involves reaction of CO_2 with metal oxides that are present in common, naturally occurring rocks. This process mimics natural weathering phenomena, and results in natural carbonate products that are stable on a geological time scale.

The full scope of the Task Force study is given in Appendix A.

Criteria for assessing technologies in the Australian context

A key requirement of a carbon sequestration technology is that it can make a significant contribution to meeting Australia's commitments to Greenhouse Gas (GHG)[5] emission reduction. Australia's emissions, excluding deforestation and agriculture, are estimated at 537 Mt per year of CO_2-e for the year ending December 2010[6]. Under a business-as-usual case it is projected that this will rise to 690 Mt CO_2-e per year by 2020 and to 803 Mt CO_2-e per year by 2030[7].

The growth in Australia's GHG emissions over the period to 2020 are projected to come primarily from extraction and processing of energy resources (including power generation), offset in part by the effect of existing emission reduction policies. Certain of these policies have defined time limits, for example the renewable energy policy presently provides for the proportion of electricity energy being supplied from renewable resources to increase to 20% by 2020. In the absence of policy changes requiring an increase in the target post 2020, this has the result that emissions from this sector will increase more over the period 2020 to 2030 than in the previous decade. The benefit by 2020 from existing policies to reduce GHG emission, but excluding impact of a future introduction of carbon tax or cap and trade scheme, is set out in Table 1.1.

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[5] Million tonnes per annum of carbon dioxide equivalent. Carbon dioxide equivalent (CO_2) aggregates the warming potential of individual greenhouse gases (CO_2, N_2O, CH_4. HFCs, PFCs and SF_6) into equivalent tonnes of CO_2 using Global Warming Potentials for each gas.

[6] "2010 National greenhouse gas inventory" - Accounting for the Kyoto target. Canberra, Australian Government Department of Climate Change and Energy Efficiency.

[7] "Australia's emission projections", Department of Climate Change and Energy Efficiency, Australian Government, 2010.

Table 1.1 GHG reductions at year 2020 from existing policies

Policy	GHG reduction benefit at Year 2020 (Mt CO_2-e)
Large and Small Scale Renewable energy targets	29.9
National strategy on energy efficiency	42.6
State Land Clearing Legislation	18.4
Others	18.1

The Australian Government has set an unconditional target for GHG emissions reduction of 5% below the year 2000 level (558 Mt CO_2-e) by 2020. It has also indicated a willingness to seek reductions of up to 15% below 2000 levels by 2020, conditional on an international agreement where major economies agree to restrain GHG emissions and advanced economies take on reductions comparable to Australia; and to 25% under conditions where international agreement is reached on global action capable of stabilising emissions to a maximum of 450 ppm by 2020.

From these projections the level of abatement required under each of these cases is given in Table 1.2. This Table shows the reduction requirement by the year 2030 assuming no further tightening of targets.

Table 1.2: GHG emission reduction requirements under alternative emission targets.

Condition	GHG Emissions by 2020 (Mt CO_2-e per year)	Emission reduction requirement 2020 (Mt CO_2-e per year)	Emission reduction requirement 2030 (Mt CO_2-e per year)
Continue current policy settings	690		
5% reduction on 2000 level	530	160	273
15% reduction on 2000 level	474	216	329
25% reduction on 2000 level	418	272	385

The value of novel technologies to contribute to meeting Australia's GHG emission reduction targets may be measured against the emission reduction requirements set out in the table above. This suggests that technologies with an ability to provide in excess of 1 Mt/a CO_2-e per facility, or some 5 to 10 Mt per year in total for Australia, should be targeted. This would represent 1 to 4% of Australia's emission reduction requirements by 2030 through the novel technologies in this study.

Overview of storage technologies

Numerous schemes have been proposed to capture and store carbon dioxide both at the point of release to the atmosphere and remote from the source by extracting previously released CO_2 from the atmosphere. These can be broadly categorised as geophysical, geochemical or biological processes. To date most attention has been paid to geophysical processes that depend on the capture of CO_2 from large point sources and sequestration of it to porosity in rocks at depth[8]. These processes are well suited to large scale industrial applications and derive from expertise in the hydrocarbon extraction and processing industries.

However, numerous geochemical and biological capture and/or storage processes exist. For the purposes of this review these are categorised as Novel Technologies and the review provides an assessment of the potential contribution that these technologies could make to Australia's GHG reduction targets over the period to 2020 and beyond.

Introductory overview of the technologies considered in this report

This review has been conducted in the context of increasing demand for diverse commercially deployable processes that help to reduce atmospheric CO_2 levels.

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[8] "National Carbon Mapping and Infrastructure Plan – Australia", Carbon Storage Taskforce Full Report, Department of Resources, Energy and Tourism, Australian Government, 2010.

Research and development of carbon sequestration in Australia has recently focussed primarily on geological sequestration – a family of processes that separate CO_2 from flue gas and store it under pressure in subterranean formations.

Other processes have been proposed that may be adapted and scaled-up to remove significant quantities of CO_2 from flue gas or directly from the atmosphere. This report considers the realistic potential for these so-called novel processes to contribute to Australia's emissions reduction targets.

Each of the technologies considered by the Task Force can be categorised as in Figure 1.1:

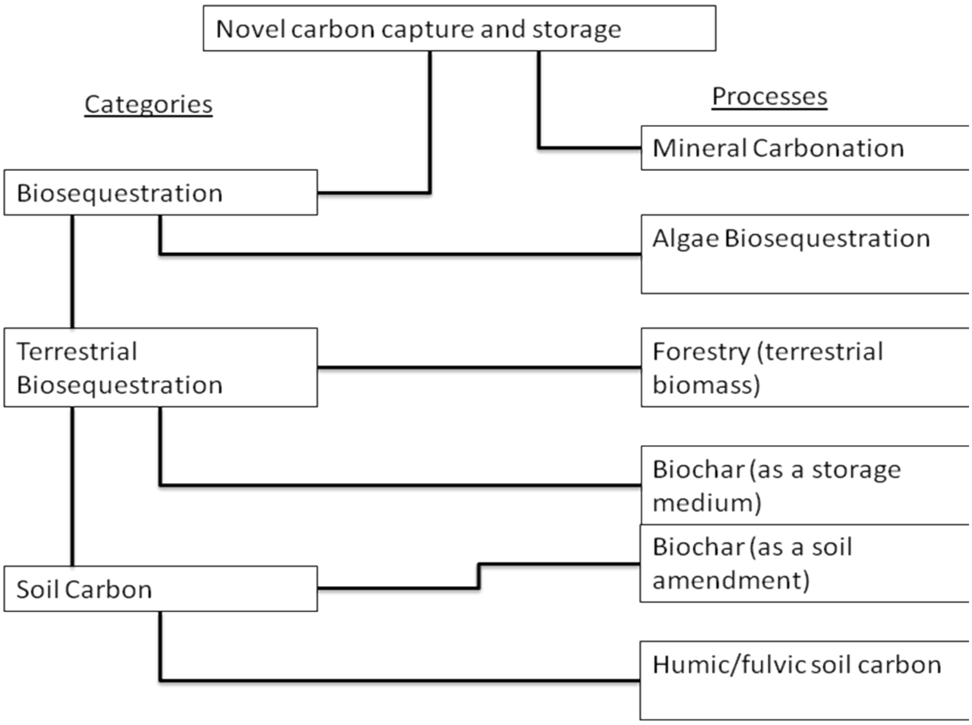

Figure 1.1: Range of technologies considered.

Mineral Carbonation

Mineral carbonation is the only means of sequestering carbon emissions considered by the Task Force that is not based on biological processes. Mineral Carbonation is instead based on the chemical reaction of metal cation-bearing compounds with CO_2 to create carbonates. The most common cations proposed for this process are Mg and Ca, most commonly found as silicate compounds in ultramafic rocks throughout the world.

Bio-sequestration

Bio-sequestration is a category of processes that at their core use photosynthesis to assimilate CO_2 into higher energy bio-chemicals, then various process routes to reform that carbon into long-term storage products. Bio-sequestration is herein further divided into sequestration by algae (algal bio-sequestration) and sequestration by land plants (terrestrial bio-sequestration).

Terrestrial bio-sequestration can be further divided into forestry (here including plantations and environmental plantings) and soil carbon, which includes processes designed to increase the carbon content of the soil.

Biochar is another process that is proposed to sequester carbon by two fundamentally different routes; as a storage medium itself (being formed from biomass-derived carbon processed into a stable form of charcoal) and as a soil amendment that increases the ability of soils to take up more atmospheric carbon by increased productivity. The former process is categorised as terrestrial bio-sequestration because it depends on a biomass feedstock, the latter process is categorised as soil carbon as its effect is mediated by a similar process to humic/fulvic soil amendments.

The technologies are categorised for convenience in Table 1.3 below.

Table 1.3: Novel Capture and Storage Technologies

Class	**Biological capture and Storage**			**Geochemical Capture and Storage**		
Category	**Terrestrial**	**Aquatic**	**Marine**	**In-situ**	**Ex-situ**	**Marine**
Technology	Forest based sequestration (re-forestation, or less de-forestation)	Pond Based algal culture	Ocean Fertilisation	Basalt based carbonation	Mineral carbonation using mined magnesium or calcium silicate rocks	Limestone weathering
	Endogenous Soil Carbon enhancement (‘Carbon Farming’)	Photo-bioreactor algal culture			Carbonation using brines containing magnesium or calcium ions.	
	Exogenous Soil carbon addition				Carbonation using waste materials (e.g. “red mud” from alumina production)	

Identified Issues and Challenges for the Technologies

For all the above bio-sequestration and mineral sequestration methods there are a number of key issues that need to be resolved. An expert group at a workshop run by the Task Force in late January 2011 explored these challenges. Briefly, the following key issues were identified at the workshop:

Algal Bio-sequestration

a) Land space and availability, and large land area required
b) Costs of algal bio-sequestration
c) Impact on water resources
d) Feasibility of using dilute flue gas in any algal culture system, and CO_2 capture efficiency
e) High cost of enclosed algal photo-bioreactors and bio-chemical engineering costs in general for algae processing
f) Life-cycle effect of offsetting carbon emissions from fossil fuels through biofuels
g) Permanence of algal bio-sequestration storage and use of by-products

Terrestrial Bio-sequestration

a) Availability of land
b) Community acceptance
c) Fire risk
d) Liability for carbon storage
e) Impact on water resources
f) Impact on food growing resources

Soil Carbon Bio-sequestration

a) Permanence of carbon storage in consideration of climate effects (e.g. fire, storm, flood) and changes in land use
b) Permanence of carbon storage in terms of the type of carbonaceous material added to soils
c) Reliable and cost effective measurement methodology for carbon in soils, given the spatial and temporal variability of carbon in soils
d) High costs of carbon farming and carbon transportation
e) Community and farmer acceptance of changes to farming practices
f) Impact on water resources
g) Impact on food growing resources

Mineral Sequestration

a) Inherently slow carbonation kinetics and the need for high pressure, high temperature processing
b) Large resource requirements for feedstock
c) Environmental effects of resource extraction
d) Large amount of waste product for disposal
e) High cost of facilities to process CO_2, including additives

General

Ability to obtain finance for development of the technologies (“bankability”)

Appendix B gives more detailed information on these identified issues, the workshop process and attendees.

Hypotheses to be answered by the Task Force

Following the discussion and listing of the issues and challenges in the two groups of workshop attendees, the participants re-convened as a single group to articulate the possible futures for the novel carbon capture and storage technologies. This took the form of a set of "hypotheses". For each postulated future, the whole group then listed the potential actions that the Task Force could take to either prove or disprove the "hypotheses". Following the workshop, seven hypotheses were developed, as listed below. Further details on these hypotheses, with supporting comments, are provided in Appendix B.

Hypothesis 1: "There is sufficient scientific and technical literature on novel carbon capture technologies for the Task Force to assess the feasibility and develop a ranking of the various processes."

Hypothesis 2: "By 2020, Novel CCS projects will be bankable at commercial scale."

Hypothesis 3: "By 2015, scientific consensus will be reached on permanence and sustainability of implementable Novel CCS".

Hypothesis 4: "By 2020 coal, together with novel methods for carbon capture and sequestration, will be the lowest cost option for base-load power in Australia at emissions of 150 kgCO_2/MWh, with sufficient storage capacity to make a material contribution to GHG reduction targets".

Hypothesis 5: "By 2015 novel carbon capture and storage will be accepted by the community and regulators through effective consultation and education, through informed social consent".

Hypothesis 6: *"*By 2015, an internationally accepted methodology for quantifying CO_2 sequestration 'reserves', analogous to HC reserve system SPE 2007, will be developed".

Hypothesis 7*:* *"*A map of the mineralization feedstocks in Australia, graded by desirability, can be produced".

The Task Force has undertaken work to assist in answering these hypotheses in the affirmative or not. The conclusions associated with this and the answers to the hypotheses, with reasons, are given in Section 6 of the report.

2. DESCRIPTION OF TECHNOLOGIES AND LITERATURE REVIEW

2.1 Biological Sequestration

Bio-sequestration can be broadly described as those technologies that exploit the natural photosynthetic process used by plants whereby light energy is used to assimilate carbon dioxide into higher-energy bio-chemicals.

2.1.1 Algal Bio-sequestration

Among plants, algal species offer particular advantages for carbon sequestration. These include faster growth rate, the ability to use brackish, saline, ocean or waste water rather than fresh water, and no reliance on arable land resources. The use of algae therefore offers a higher rate of carbon capture than terrestrial plants and may avoid competition with food crops for limited supplies of land and water.

For these reasons, research into using algae for oil production has been conducted for over 50 years. As a result, there is much published information on the large-scale culture of algae. A comprehensive study into these systems was the Aquatic Species Program (ASP) conducted by the U.S. Department of Energy (1978-1996)[9]. Publications of this work together with an IEA Bioenergy Report (2010)[10], CSIRO[11] and other specific publications have been used to provide the following summary. Specific published case studies of commercial operations such have also been provided as examples.

Artificial light systems

The Task Force considered the use of artificial light to drive algal bio-sequestration. It was concluded from an analysis carried out by the task force that the electricity produced by combustion of coal, if converted to light by high-efficiency LEDs, is sufficient to provide the necessary energy to sequester by photosynthesis only a small fraction of the CO_2 released by its combustion. Considering this result, the Task Force does not therefore further consider artificial illumination of algae in this report.

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[9] Sheehan, J., T. Dunahay, J. Benemann and P. Roessler (1998). “A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae (close-out report)”. Golden, Colorado, National Renewable Energy Laboratory.

[10] Darzins, A., P. Pienkos, and L. Edye, “Current status and potential for algal biofuels production, in Commercializing 1st and 2nd generation liquid biofuels from biomass”, International Bioenergy Task 39, Editor. 2010, International Energy Agency (IEA).

[11] Campbell, P.K., T. Beer and D. Batten, “Greenhouse Gas Sequestration by Algae: Energy and Greenhouse Gas Life Cycle Studies”. CSIRO. 2009.

Solar growth systems

There are two types of solar algal growth systems, each with CO_2 injection:

1. shallow ponds open to the atmosphere, with mechanical devices to promote mixing of nutrients, maximise exposure to the sun and keep living and dead algae in suspension, and
2. "photo-bioreactors", where the algal growth is enclosed in a transparent vessel exposed to the sun and the algal medium is pumped through the reactor.

In the first case the ponds are shallow (~0.4m deep) and generally in the shape of a "raceway" with paddles to move the water growth medium in a circular direction. In the second case, the photo-bioreactors comprise a variety of materials, sizes and shapes and they can be positioned either horizontally on the ground or at an angle to the vertical to minimise the land area required and maximise exposure to the sun. There are therefore many different photo-bioreactor designs in the literature. Cazzola (IEA Bioenergy Exco 64)[12] has outlined the strengths and weaknesses of each design:

Open ponds:

- Large scale possible
- Subject to contamination from predator algae strains
- Subject to evaporative water and CO_2 loss to the atmosphere
- Difficult to control temperature (day vs. night, seasonal variations)
- Small biomass concentration (1g/litre)
- Require a large amount of nutrients

Photo-bioreactors:

- Have no contamination and can cultivate a single algal species
- Allow accurate control of nutrients and temperature
- Allow a higher biomass concentration
- Have larger energy consumption
- Have higher capital costs, potentially doubling the final cost of algae product relative to open pond systems

Photo-bioreactors produce an ideal environment for algal culture where aseptic cultures can be grown under controlled conditions. These types of culture systems are used for the production of high-value products such as pharmaceuticals and enzymes (values >$100,000 per tonne). They are currently too expensive for the production of algal nutraceuticals such as astaxanthin[13] (>$10,000

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[12] Cazzola, P. "Algae for biofuel production: Process description, life cycle assessment and some information on cost." in IEA Bioenergy executive committee 64. 2009. Liege, Belgium: International Energy Agency.

[13] Olaizola, M., "Commercial production of astaxanthin from Haematococcus pluvialis using 25,000-liter outdoor photo-bioreactors." Journal of applied phycology, 2000. 12(3): p. 499.

per tonne) and almost all experienced expert advice suggests that photo-bioreactors will not be cost-effective for the production of low-value biofuels (>$1000 per tonne) in the foreseeable future. However, photo-bioreactors may conceivably be used to grow high-density aseptic algal populations as inocula as a precursor for larger, most cost-effective open ponds.

DoE Aquatic Species Program (ASP)

The DoE Aquatic Species Program (ASP)[9] aimed to prove algal fixation of CO_2 from upgraded coal-fired power plant flue gas and production of renewable fuel (biodiesel) from the extracted algal oil. The main focus of the DoE Aquatic Species Program was to select algal species and develop processes to maximise production of algal-oils. Significant information was also produced on the growth of algae under a wide range of temperature, pH and salinity. Algae were collected from a variety of sites in the USA and the large collection was eventually culled to about 300 species, mostly green algae and diatoms.

The program commenced with laboratory-scale equipment and then proceeded to larger scale in Hawaii. The final experiments were undertaken in the 1990s in New Mexico, where 0.1 ha (1,000 m^2) ponds were employed. These ponds were of an open 'raceway' design, where shallow (0.3-0.5m deep) water was circulated using a motorised paddle wheel to circulate the algae. The paddle wheel was 5m wide with a nominal axial liquid speed of 0.2 to 0.4 ms^{-1}. The shallow pond depth was necessary to ensure sunlight penetration throughout the suspension.

Costs and Scale Magnitude of Algal Capture of CO_2

The ASP study showed that, with careful control of pH and pond temperature, greater than 90% of the pure CO_2 injected could be utilised by the algae. Productivities were generally found to be in the range 10 to 40 g/m^2/day of dry algal biomass, with some single day productivities as high as 50 g/m^2/day, but with an average of ~ 20g/m^2/day. It was found that the solar insolation and growing season were key parameters, with productivities falling markedly in winter (to around 3 g/m^2/day) in the open ponds. The study recommended temperature control (heating) or pond enclosure to alleviate this problem, but noted that this would increase costs.

The focus of the ASP program was algal oil production. It was found that nutrient deprivation (nitrogen for green algae, silicon for diatoms) led to higher oil production in the algal cells, but that this was outweighed (negatively) by slower algal growth rates overall.

The ASP final report contains several economic analyses of the algal growth processes employed. Depending on the CO_2 price, oil price and the productivity achieved in the ponds, it was found that circumstances did exist where algal production of algal-oil could be economic. The study did, however, point out that low capital costs were required for this to occur and that enclosed bio-bioreactors, including those using artificial light or fibre-optics, were unlikely to be economically viable.

Many publications and presentations since the ASP study have presented data on what has been achieved in terms of algal growth and its economics. Benemann (2009)[14] noted that current total commercial cultivations of algal biomass are small (9,000 t per year) and the value of these products is high (~$10,000 per tonne). The challenge is to produce millions of tonnes of product at a cost up to two orders of magnitude less using these technologies if algae are to be used for CO_2 mitigation.

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[14] Benemann, J. "Algae biofuels: Challenges in scale-up, productivity and harvesting." in ExCo 64. 2009. Liege, Belgium: IEA Bioenergy.

The costs, growth rate of algae and the consumption efficiency of CO_2 by the algae are key parameters for the economic analysis of the technologies by this Task Force. Ben-Amotz (2008)[15] of Seambiotic reported on the growth of *Dunaliella sp.* in Israel in raceway type ponds. He noted that the theoretical CO_2 consumption is 2 kg/kg algae produced but that the actual CO_2 consumption achieved was 4.3 kgCO_2/kg algae. That is, some CO_2 was lost to the environment. In summer, the consumption rose to 10 kg/kg algae due to further CO_2 losses to the atmosphere from the open ponds. These results could have important implications for algal capture of CO_2, since this aim (rather than oil production) will require high total efficiency of capture of the input greenhouse gas.

Productivities achieved in trials by Ben-Amotz were around 20g/m^2/day. On the other hand, Clarke (2010)[16] proposed that a managed pond should achieve productivities of 30g/m^2/day and that an appropriate target for algae growth rate is 50g/m^2/day. The IEA concluded in a recent review that "while several reports and presentations have projected yields of 100 t/ha/year, or an average of 30 g/m^2/day over an 11 month growing season, with a cell containing 30% oil (triglyceride), these types of productivities still remain to be achieved experimentally, at a reasonable scale and over a full year of cultivation."[17]

Growth rate of algae has a direct impact on the size of algal ponds required. For example, an algal oil production of 100 ML/year, a growth rate of 20g/m^2/day and an algal lipid mass of 30% requires a pond surface area of ~4,000 ha whereas a growth rate of 50g/m^2/day gives a pond surface area of ~2,000 ha, IEA Bioenergy Task 39 (2010)[10]. At the theoretical rate of 2 g CO_2/g algae, the 20g/m^2/day rate gives an annual CO_2 consumption rate of ~500,000 t.

The area required for CO_2 capture in an algal system from a commercial power station will therefore be very large. For example, a 500 MW power generator operating at 85% capacity factor and 0.9 kg CO_2/kWh will release around 3.4 Mt CO_2 per annum. This will require between 28,000 ha (20 g/m2/day) and 14,000 ha (50 g/m2/day) of pond area to assimilate. For 1 Mt CO_2 per year, the pond area required will be between 4,000 and 9,000 ha on the basis of these IEA estimates; in addition substantial area will be required between ponds for infrastructure and access routes. Kadam (1997)[18] estimated a pond surface area of 14,000ha would be necessary for a 500MW power plant, made up of individual ponds no larger than 20ha each, or 700 ponds and assuming an algae growth rate of 45 g/m^2/day. In contrast to this Heimann has quoted productivity values of up to 100 g/m^2/day[19] at the laboratory scale.

At 4,000 ha per Mt/year CO_2, and with Australia's electrical power generation sector emitting around 200 Mt CO_2 per year, the total pond area required for algal capture of part of this CO_2 (depending on capture efficiency) can be calculated to be 8,000 km^2 of levelled and ponded surface

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[15] Ben-Amotz, A. "High value products and biofuel production by marine microalgae." 2008. Israel: The National Institute of Oceanography. Also: Ben-Amotz, A. "Bio-fuel and CO2 Capture by Algae", 11th ICAP (International Conference on Allied Phycology), Galway Ireland, June 2008.

[16] Clark, S. B. "Coupling earthen pond algaculture with algae photo-bioreactors for cost effective biofuel production." in Bioenergy Australia. 2010. Sydney.

[17] Spitzer, J. and J. Tustin, "IEA Bioenergy Annual Report 2010." 2010, International Energy Agency: Paris.

[18] Kadam, K.L., "Power plant flue gas as a source of CO_2 for microalgae cultivation: economic impact of different process options." Energy Conversion and Management, 1997. 38: p. S505.

[19] Heimann, K. "Using algae for Bio-CCR and Bio-CCS: An update on R&D funded through the AMCRC." in Bioenergy Australia. 2010. Sydney.

plus allowance for infrastructure and topographic features (e.g. unusable slopes). This, while small in proportion of the total land area of Australia, must be located in reasonable proximity to the power generators and is therefore likely to be very costly.

Maximum Rate of Algal Production

There appears considerable discrepancy between estimates of ultimate theoretical maxima in the literature. For example, Seambiotic claim theoretical maximum algal production rate of 25g/m^2/day; ASP claim 50g/m^2/day; and the IEA Bioenergy Task Force report a theoretical maximum of 100g/m^2/day.

In considering this data it is important to understand the basis assumed. In particular attention must be paid to the assumptions in respect of light and temperature. Growth will be inhibited at both high and low temperatures and at high light levels, depending on species. Therefore the maximum annual production at any location will reflect the local diurnal and seasonal variations in light and temperature and will differ substantially from the maximum daily production in summer. It has been suggested that the ideal climate is “within the tropics and dry”, with average temperatures above 15 ^{o}C year round unless novel algal species are deployed. This zone excludes coastal and southern NSW, all of Victoria and southern regions in South Australia and Western Australia. The Task Force made a limited assessment of the impact of some of these variables on potential production and CO_2 consumption in Australia. This is presented in Appendix C.

There is more agreement about practical productivities achievable, with most falling in the range 15-30 g/m^2/day. Many photo-bioreactors have tubes or bags stacked vertically, so the area in the productivity claims needs to be carefully defined and verified. Proponent yields can be expressed relative to land area (plant footprint), not the actual size or volume of the photo-bioreactor itself.

In addition to the algal growth dynamics outlined above, Benemann (2011)[20] has noted some key economic issues for capturing CO_2 from a coal fired power plant by algae. Key amongst these issues for open ponds were:

- Cost of transport from the CO_2 from the facility to the capture plant, including the need to store CO_2 at night when the algae are inactive and to design the pipeline and infrastructure for the highest CO_2 consumption rate in the summer.
- Loss of CO_2 during transfer to the algal pond and through outgassing for open ponds.
- Inefficiencies mean that only 40-60% of the CO_2 actually fixed by the algae is present in the final algal oil.
- Benemann concluded that the “maximum plausible” CO_2 final capture in open ponds is only 10% of that emitted by the power station.

Microalgal culture using flue gas

Flue gas from coal fired power stations comprises around 12-15% CO_2, together with other oxide gases such as SOx and NOx. The ASP study conducted several trials in both laboratory and scaled-up processes growing microalgae in water with simulated flue gas and found no inhibitory effects from

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[20] Benemann J. R., “Scale-up of microalgal cultivation: Recent developments and commercial requirements”, International Society for Applied Phycology, Halifax, NS, Canada, June 20, 2011.

flue gas on the productivity of microalgae. The program noted that some authors (for example Negoro *et al*. 1992)[21] proposed that SOx and NOx concentrations can inhibit algal growth, but concluded that any inhibitory effects may have been attributable to rapid drops in pH due to excessive rates of flue gas delivery. On the other hand Seambiotic (Ben-Amotz (2008)) have conducted several trials of microalgal production using coal-fired flue gas for their commercial process and concluded that SOx could be toxic to microalgae in concentrations over 60ppm in the flue gas. Seambiotic have gone on to successfully culture microalgae to high concentrations on de-sulphurised flue gas that has passed through the industry-standard FGD (Flue Gas Desulphurization) process. Most coal used in Australia for power generation is low-sulphur coal so FGD has not been implemented. It therefore remains to be seen if SOx emissions from Australian coal-fired power stations (typically in the range 300 to 500 ppm) are inhibitory to algal growth.

Seambiotic also found that *Nannochloropsis sp.* grows better on coal FGD flue gas than on pure CO_2. In their trials Seambiotic have achieved an average growth rate of $20g/m^2/day$, but claim a long-term theoretical maximum of $25g/m^2/day$.

A further key issue related to flue gas is its delivery to the algal culture facility. Kadam (1997) concluded that aeration of open ponds directly with flue gas is more expensive than MEA capture of CO_2 and delivery of concentrated gas. Most proposed commercial systems assume flue gas is directly injected to open ponds, although the implicit mass transfer issues have not been studied in detail. Flue gas is around 12% CO_2, so the driving force for mass transfer to water is only about one eighth in the case of flue gas *versus* pure CO_2. In work by the University of Newcastle on a photo-bioreactor[22], it is stated that the mass transfer is liquid phase diffusion controlled for flue gas, so appropriate gas dispersion design techniques to enhance the interfacial area (i.e. small bubbles) should enable dilute flue gases to adequately transfer the necessary CO_2 into the bio-reactors.

Nutrients, water and other inputs

Algae like all autotrophs require nutrients from which to synthesise the biochemicals used for growth and cell division including N, P, K, Fe and a number of other trace elements. Nitrogen is a key component of proteins and for most algal strains must be sourced as fixed nitrogen (as opposed to N_2 gas). Common forms of fixed nitrogen are ammonia, urea and nitrates.

Phosphate is a key component of Adenosine Phosphates ADP and ATP, which are the basic currency of cellular energy for all living systems. It is also essential for DNA and RNA synthesis and as a buffer in the cytosol.

For these reasons fixed nitrogen and phosphates are the key ingredients in common fertilizers and the same is true for algal culture. High rates of algal productivity must be supported by appropriate concentrations of fixed nitrogen and phosphates. In particular circumstances such as the use of organic wastewater these nutrients may be provided in the water stream, however in most cases some or all of the nitrogen and phosphate will need to be provided externally.

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[21] Negoro, M., N. Shioji, Y. Ikuta, T. Makita and M. Uchiumi (1992). "Growth characteristics of microalgae in high-concentration co<sub>2</sub> gas, effects of culture medium trace components, and impurities thereon." Applied Biochemistry and Biotechnology **34-35**(1): 681-692.

[22] Moberg, A., G. Ellem, G. Jameson and J. Herbertson (2010). "Process engineering in the design of a high performance photo-bioreactor." Bioenergy Australia, Sydney.

In the case of Seambiotic, the fertilisers provided to the algae are in the form KNO_3, NH_4NO_3, KH_2PO_4, and H_3PO_4. Seambiotic published project costs of around $0.05 per kg of algae when using flue gas, since NO_x in the flue gas is expected to fertilise the algae.

Depending on the strain of algae in use, the water requirements could vary from clean fresh potable water to wastewater high in organic contaminants to brackish or saline ground water to ocean water.

Waste water and deep ocean water have the benefit of containing significant amounts of nutrients, including fixed nitrogen, phosphates, high chemical oxygen demand, and so on. Waste water carries additional cost benefits, since co-location with a wastewater stream can reduce the existing cost of water treatment, however depending on the type of water it may require pre-treatment before use in algal culture.

Brackish or saline water can also be sourced from groundwater interception schemes. Water source is an important consideration for algal bio-sequestration facilities as the amount of gas produced by coal-fired power stations requires very large amounts of water for the CO_2 to be absorbed. In addition the large volume of gas may in some cases increase evaporation rates in the algal system.

Contamination of algal cultures is a significant problem encountered outside the laboratory. Algal cultures are rich in biomass and nutrients and are therefore prone to contamination by wild algae strains, bacteria, and predation by protozoa and brine shrimp. Contamination of this type is recognised as a major cost to commercial operations as it in most cases necessitates emptying and cleaning culture vessels offline from time to time. To combat contamination operators have employed several different strategies; the first is using enclosed photo-bioreactors in place of open ponds. As discussed previously, enclosed photo-bioreactors offer protection from contamination and higher algal production but also add considerable cost to the point that open ponds are considered the only commercially feasible option for low-value products. Other operators have employed a hybrid design whereby a biomass-rich inoculum is grown first in enclosed photo-bioreactors and is then inoculated into an open system. The high concentration and vitality of the inoculum resists contamination and by the time it does become contaminated the algal culture can have doubled a number of times yielding adequate productivities. Still other operators have employed antibiotics and anti-fungals or tried to engineer superior algal strains. These approaches have had less practical success. Another approach to this contamination problem is to use wild algal strains from a hostile environment and then situate the ponds in this environment, as described by Borowitzka.[23]

Manipulation of the biochemical pathways in algae by genetic modification or environmental conditions was a major component of the ASP research. Genetic modification has continued to be a key goal for many commercial operations today. However one of the ASP's own major conclusions was that enclosed photo-bioreactor systems are highly unlikely to be economically feasible, and open pond systems are prone to contamination. By far the most likely commercial algal system will be subject to contamination and genetically modified organisms are unlikely to be viable in such an environment. This together with community resistance to the use of genetically modified organisms means that proposals for systems employing genetically modified strains are unlikely to profitably produce low-value products such as biofuel or carbon sequestration.

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[23] Borowitzka, M. Sustainable "Algae Biofuels." in Bioenergy Australia. 2010. Sydney.

Process energy costs

High process energy costs are one of the biggest inhibitors of the commercialisation of algal technologies. Some of these such as system design, contamination and nutrient production/delivery are encountered in the upstream side and are addressed above. Most process energy costs are encountered in downstream processing, particularly in dewatering (separating algal biomass from surrounding water), extraction (extracting oil and other components from the algal biomass) and refining the ultimate products from those precursors (such as the transesterification of oils to produce biodiesel). Also of consideration is that this process energy consumption has a consequent CO_2 emission and reduces the overall efficiency of carbon sequestration.

Case Studies on Algae Sequestration

Seambiotic

Seambiotic was founded in 2003 in Israel, primarily through a related company called Nature Beta Technologies Ltd (NBT) in Eilat[24]. Since 1988 NBT has cultivated *Dunaliella*, a salt-loving algae species, in 10 ha of open-pond facilities. The algae is processed, dried and inserted into capsules. The food supplement or "nutraceutical" is high in ß-carotene, and it is sold in Japan at a retail price of about $4,000/kg. The cost to produce is $17/kg and about 70 t/year are produced.

Seambiotic was established to develop new environmental end-uses for microalgae. R&D pilot studies have been carried out at the Israeli Electric Corporation's power station located on the Mediterranean shore near the city of Ashkelon. Open-pond facilities were built, to utilise flue gas from the power-plant stack and to use sea water at no cost.

According to the company (Ben-Amotz, 2008), trials on several species have been successful, with some species productivity of 20 g/m^2/day. Using flue gas instead of purchasing CO_2 has pushed productivity up by 30%, possibly due to nutrients in the gas (e.g. NOx). Maintaining original inoculation species has proved a challenge, the whole culture sometimes changing due to a wild diatom species. The algae are harvested via low-cost self-flocculation technique.

Samples have been converted to biodiesel and showed 12% w/w daf yield of biodiesel from microalgal biomass. Seambiotic are of the opinion that production costs could be as low as $0.34/kg, based on a comparison with the NBT operating cost and scale of operation. At 12% yield, this is still over $2.80/kg of biodiesel feedstock.

Some Examples of Australian Algae Developments

Cognis

Cognis Australia operates a 400 ha algae plant at Whyalla, South Australia and a similar size plant at Hutt Lagoon, Western Australia growing *Danaliella salina* to produce beta-carotene, a nutraceutical product[25]. These commercial plants are thought to have the largest area of algal cultivation for carotenoids in the world.

Murdoch University

Murdoch University is also involved in a $3 million pilot scale algae to fuel and bio-products project at Karratha, Western Australia[26].

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[24] Bruton, T., Lyons, H., Lerat, Y., Stanley, M., & A, R. B., "A Review of the Potential of Marine Algae as a Source of Biofuel in Ireland." Sustainable Energy Ireland Dublin, 2009.

[25] http://www.cognis.com/countries/Australia/en/Company+Profile/

[26] http://www.murdoch.edu.au/News/Clean-algae-biofuel-project-leads-world//

Aurora Algae

Aurora Algae are based at Maitland (Karratha) in the Pilbara region of Western Australia[27]. They have an open pond demonstration facility of 6 acres (~ 2.4 ha) producing 15 tonnes of algae per month. This is equivalent to an algal productivity of about 20 g/m^2/day. They plan to scale up to five 50 acre ponds (~ ha) producing 600 t/month of algae consuming 40 t CO_2 per day. This is again equivalent to ~20 g algae/m^2/day and a 2 tCO_2/t algae sequestration rate.

MBD Energy

MBD Energy is the most relevant algal proponent for the Task Force study as they are the only Australian proponent currently using authentic coal-fired flue gas for algal culture.

MBD Energy has an algae R&D facility at James Cook University in Townsville[28] . The Task Force has inspected these facilities during a visit to JCU. The work there includes:

- Algae strain identification and selection
- Culture optimisation
- Production and scale-up
- Harvest, extraction and separation processes
- End use products

Over the 12 months beginning in late 2011, MBD have reported that they will construct and operate a $5M 1 Ha “proof-of-concept” facility at Tarong power station in Queensland. This project will utilise a “growth membrane bags system” photo bioreactor method to grow the algae. MBD then plan to develop a “stage 2” project at a cost of $30M requiring land of 80 Ha producing about 100 tonnes of algae per day. Initial production of biomass will be sold as stockfeed.

With scale-up of the project MBD Energy will pursue the extraction and sale of oil for biodiesel production. It is claimed that this “stage 2” project will abate approximately 70,000 tonnes per annum of Tarong power station’s CO_2 emissions. The targeted algal productivity of this facility can be calculated as 125 g/m^2/day.

MBD are also assessing new projects at Eraring power station in NSW and Loy Yang power station in Victoria. Initially these projects are in the range 1-10 Ha in terms of algae growth area. MBD have an aspiration to directly capture up to 50% of the total emissions from power stations. MBD state that the associated by-product production would be 1.7 M barrels of algal-oil and 370,000 tonnes of stockfeed per million tonnes of CO_2 captured.

MBD Energy is a founding member of a Bio-CCS roundtable group that is also considering soil carbon, land management, forests and other technologies.

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[27] http://www.aurorainc.com/technology/facilities/karratha-facility/

[28] Lawson, A. (2010). “Bio CCS – “Natures” long term approach to CCS.” National CCS Week, Melbourne, Australia, November 2010. Also: http://www.mbdenergy.com/

2.1.2 Bio-sequestration *via* Carbon Forestry.

Australian forests currently occupy some 150M ha and hold around 12 000 Mt of carbon equating to an average storage of 80 t Carbon/ha (equivalent to 290 t CO_2/ha)[29]. Expanding Australia's forests could therefore provide significant CO_2 storage capacity. In addition ancillary benefits such as increased amenity, improved habitat for native species and mitigation of salinity and erosion may be realised. Carbon forestry presently provides a technically viable means of sequestering carbon at scale.

The Task Force has sought to quantify the potential contribution of carbon forestry to reducing Australia's emissions. Numerous reports have been published on the subject including a large number addressing Australia in particular[30,31]. The latest report considered by the Task Force was published by Polglase *et al*. (2011)[32] indicating a maximum average rate of approximately 2Mt of carbon sequestration per year to 2020, and a potential maximum of up to 100Mt of carbon sequestration per year from 2020 to 2050 if action is timely***.***

The major limiting factors to carbon forestry are land availability and the commercial environment. Polglase *et al.* include an economic assessment that suggests at a high cost of establishment ($3000 per hectare), commercial discount rate (10%) and a low carbon price ($5 per tonne) there is no economic incentive to expand carbon forests. In contrast if commercial conditions conducive to carbon forestry are realised, such as a social discount rate of 1.5%, low establishment cost of $1000 per hectare, realistic carbon price and an adequate regulatory environment then significant land area may be planted cost-effectively and the rates quoted above can be realised. Further financial analysis of this Polglase *et al*. study has been undertaken by the Task Force and is described in section 5 of this report.

Campbell[33] has noted that there are policy and other constraints associated with the tree planting method of sequestering CO_2, even though this method is the most mature, cheapest and most feasible of all the methods studied by the task force. Spatial location and the configuration of the carbon plantings in the landscape is a crucial consideration in order to minimize the necessary trade-offs associated with water and food production, fire risks and invasive species. However, planting on marginal lands and/or low rainfall areas will necessarily reduce sequestration potential. Campbell has also noted second major constraint on private lands is the issue of "guaranteed permanence". Relatively few landholders are willing to enter into multi-decadal contracts over their land beyond small sections of their farms that have low opportunity costs. Outright land purchase for carbon

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[29] ABARES (2011) "Australia's forests at a glance 2011" Commonwealth of Australia Canberra (http://adl.brs.gov.au/data/warehouse/pe_abares99001800/Forests_at_a_glance_2011.pdf).

[30] Van Kooten, G.C., "Economics of forest ecosystem carbon sinks: A review." International review of environmental and resource economics, 2007. 1(3): p. 237.

[31] Richards, K.R., "A review of forest carbon sequestration cost studies: a dozen years of research." Climatic change, 2004. 63(1): p. 1.

[32] Polglase, P., A. Reeson, C. Hawkins, K. Paul, A. Siggins, J. Turner, D. Crawford, T. Jovanovic, T. Hobbs, K. Opie and J. A. Carwardine, A. (2011). "Opportunities for carbon forestry in Australia: Economic assessment and constraints to implementation." CSIRO.

[33] Campbell A., Director, Research Institute for the Environment and Livelihoods, Charles Darwin University, Review Comments to the Task Force, October 2011.

plantings and subsequent focused management is in many ways the cleaner option in terms of permanence, but this has social implications in terms of displacing farming families, with subsequent impacts on rural communities, schools and so on. The planted lands then need to be managed long term for fire protection, feral animals and weeds.

Campbell has indicated that models which integrate carbon sequestration and bioenergy into farming systems, like those being developed by the Future Farm Industries CRC[34], are worth pursuing. This CRC notes that the mallee eucalypt is a dual-purpose crop; it is processed into biofuels but it can simultaneously produce carbon credits as it grows. One third of its growth occurs in its roots and coppicing can be undertaken to harvest the above-ground biomass. It has extreme drought and fire tolerance, and the below-ground sequestered carbon is relatively secure. For example, mallee trees providing feedstock to a biofuels plant would require 8,000 to 12,000 ha of mallees for sequestering a lifetime total of 500,000 tonnes of CO_2, and the biofuels plant itself would provide an additional net emissions reduction of 50,000 tonnes CO_2 per year from the biofuel produced, comprising crude bio-oil, gas and char (gross CO_2 avoided less the CO_2 emitted in the processing).

Australian Proponents of Carbon Forestry

CO2 Australia Group

The CO2 Australia Group[35] is the Australian market leader in the establishment of forest carbon sinks intended for registration under formal emission reduction schemes. It is operating commercially at scale. During 2004, it became the first reforestation company to be accredited under the NSW Government Greenhouse Gas Abatement Scheme (GGAS), the second largest carbon market in the world. The CO2 Australia Group supplies carbon credits to Origin Energy, Country Energy, Eraring Energy, Macquarie Bank, Qantas Airways, Woodside Energy, the City of Sydney and EDS Australia. The company has a staff of 31 located across 6 offices across three Australian states. Large-scale tree plantings have been successfully established and managed in NSW, Victoria and Western Australia, totally some 22,000 ha of mallee eucalypts and 3,500 ha of native bush. CO2 Australia Group plantings are being established in medium to low rainfall zone areas on farms that are often considered marginal. CO2 Australia's model has shown that the plantings can be undertaken mechanically and the mallee eucalypts do not require fencing from stock. It is probably the most efficient option for integrating carbon plantings into farming systems, as opposed to displacing agriculture with carbon plantings. It is noted that these new mallee plantings lead to a range of soil improvement outcomes, such as reduction in soil salinity, soil erosion and the degradation of soil structure. The plantings also improve biodiversity and habitat values for wildlife relative to farming land.

> *Qantas Airways example*: Qantas and Jetstar's voluntary carbon offset programs were launched by Qantas in 2007 in collaboration with CO2 Australia Group. Three eucalyptus plantations were established near Dubbo and Wagga in NSW. The plantings are monitored every month, inspecting for weeds, pathogens, insect damage, browsing and erosion. More than 200,000 trees have now been planted for Qantas. In October 2011, the cost of CO_2 emission abatement for Qantas passengers was \$9.25 per tonne of CO_2 at the time of

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[34] http://www.futurefarmonline.com.au/

[35] www.co2australia.com.au

> purchase of a Qantas ticket. This is the lowest cost option that the task force found during the study.
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> *Woodside Energy example*: More than 6 million mallee eucalypts have been planted over 2008-9 to offset CO_2 emissions from the Pluto Woodside LNG project[36]. These have been planted over more than 4,500 ha of land in NSW and Western Australia. Further plantings will be undertaken over several years by CO2 Australia Group and over a period of 50 years it is estimated that over 9 million tonnes of CO_2 emissions will be sequestered. The plantings represents Australia's biggest commercial offset program based on dedicated forest carbon sink plantings.

CO2 Australia Group has stated that it will manage these trees for at least 100 years from the time of planting. The company states that the risk of major fire is very low due to strict fire risk-management procedures. The CO2 Australia Group states that only a fraction of carbon that is stored in above ground tree parts is likely to be lost in the event of fire, and even then this is only temporary. Moreover, the mallee species planted store a large amount of carbon below ground in their extensive root systems. It is noted that this underground root system, which includes a structure known as a lignotuber, allows the mallee to survive even the fiercest fires and will rapidly re-sprout fresh foliage. CO2 Australia have not had a fire to date, and employ unique insurance products that allow for the replacement of any lost carbon credits.

Greenfleet

Greenfleet is a not-for-profit organisation offering carbon offsets to private customers under a voluntary scheme to account for carbon dioxide emissions from transportation. Greenfleet has, since 1997, planted over 6.8 million trees at a rate of 750 to 1200 stems per ha. Each hectare is expected to sequester 268 t CO_2 over 20 years[37], amounting to a total of 1.9 Mt CO_2 stored at the end of the 20 years and assuming the mean planting rate of 975 stems per ha.

As a terrestrial biomass plantation system proponents such as Greenfleet are subject to the rate and scale limitations discussed earlier, but current planting rates of over 370,000 trees per year (equating to around 0.1 Mt CO_2e per year) are clearly sustainable for the next two decades.

2.1.3 Bio-sequestration *via* biochar as a storage medium

Living vegetation can store CO_2 in its biomass, but if that biomass dies and decays the carbon is re-released into the atmosphere. This is a major source of carbon emissions including logging, agricultural and municipal waste. In the case of organic waste streams that terminate in landfills this carbon is also often converted to methane, which is a far more potent greenhouse gas.

Instead of decay and decomposition some of this biomass can be converted to biochar; a more stable form of carbon resistant to decay. Biomass is typically converted to biochar by pyrolysis – combustion under anaerobic conditions. Commercial pyrolysis units have existed for decades for the production of charcoal, but only recently have dedicated biochar pyrolysis units been developed.

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[36] "Pluto Pulse", Woodside Newsletter, January 2010. www.woodside.com.au/pluto

[37] Greenfleet. "Greenfleet technical information." 2011; Available from: http://www.greenfleet.com.au/Global/Researchers/Technical_information/index.aspx.

These units all produce biochar and off-gas from biomass feedstock in an exothermic pathway. The off-gas from this process can be captured and used for local electrical production, while the rest of the original carbon is converted to biochar.

Biochar is produced by heating biomass in a low-oxygen environment (pyrolysis). This produces synthesis gas (syngas) and biochar; syngas can be used to generate electricity for use on site or sold on the grid, and biochar can be placed into soils to increase the exogenous soil carbon component. The use of biochar in soil has been considered in a recent comprehensive CSIRO report (Sohi *et. al.* (2009)[38], where it is noted that there is global *potential* for annual sequestration of atmospheric CO_2 at the billion tonne per year scale. Ramankutty *et al.* (2008)[39] report that there is an estimated 15×10^9 ha of cropland globally. Garnaut (2008)[40] has calculated that the application every 10 years of biochar to this land would result in a CO_2 equivalent gain of 0.65 GtC/year. However, biochar production is constrained by the availability of biomass feedstock and the commercial exploitation of biochar as a soil amendment is still in its infancy.

In the Sohi *et al.* report, the following key points are noted:

- Biomass cultivation removes CO_2 from the atmosphere during photosynthesis and biochar made from this source, if long-lived when embodied in soil, should reduce CO_2 in the atmosphere. There could also be a synergistic effect associated with soil biochar in increasing the growth of plants and hence increasing soil carbon through plant roots, plant debris and increased soil microbial and invertebrate activity.

- Biochar is not a uniform homogenous product. Key chemical and physical properties of biochar are greatly affected by the choice of feedstock and the process conditions. For example, biochar from woody biomass retains pores and tube-structures that can retain water and adsorb nutrients whereas biochar produced from green waste or manure can contain nutrients that accelerate breakdown of the humic and labile carbon soil pools, in some cases causing the release of NOx and methane. Biochars produced at higher temperatures are more porous and more adsorptive. A rapid screening technique to compare biochars does not currently exist.

- The yields of biochar from pyrolysis processes are variable, and in the range up to 35% for slow heating rates. The gases produced during the manufacture of biochar can be used to replace fossil fuels and thus reduce CO_2 emissions from this source.

- Studies of charcoal from natural fire and ancient anthropogenic activity indicate millennial-scale stability in soils. However, the permanence of biochar in soils is dependent on its properties.

- In terms of safety in use, biochar has small concentrations of toxic combustion products (e.g. polycyclic aromatic hydrocarbons), but these are not present at environmental risk levels if the pyrolysis process is efficient.

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[38] Sohi S, Lopez-Capel E, Krull E, Bol R., “Biochar, climate change and soil: A review to guide future research.” 2009, CSIRO Land and Water Science, E Krull (Ed).

[39] Ramankutty, N., “Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000.” Global biogeochemical cycles, 2008. 22(1): p. GB1003.

[40] Garnaut R., “The Garnaut Climate Change Review”, Cambridge University Press, Port Melbourne, 680pp, 2008.

- The interaction between biochar with soil microbial communities and plants are not yet understood in terms of soil carbon dynamics. It is understood, however, that some biochar is highly stable in soil and that soil organic matter accumulation and enhancement of soil microbial activity occur with the use of biochar.
- Biochar has been shown to assist in the water holding capacity of soils, although the mechanisms involved are poorly understood.
- Economic viability of biochar will depend not only on its production costs from biomass, but also on the price of carbon in the future and the efficiency of carbon sequestration from both the biochar itself and the increased efficiency of plant growth.
- The mitigation of not only CO_2 but other greenhouse gases such as N_2O and CH_4 will be important. However, a full greenhouse gas life cycle analysis has only been undertaken for some project-specific cases.

It should also be noted that biochar is a carbon storage product in itself and does not necessarily have to be dispersed in soils. Biochar can be disposed of in a large range of sites under varying conditions.

Sohi *et al*. (2009) also note that, to be workable, a biochar project aimed at soil carbon enhancement must:

1. Assess the monetary value and amount of direct and indirect CO_2 emission savings arising from the use of biochar against alternative uses,
2. Assess the security, stability and consistency of price for pyrolysis feedstocks,
3. Provide certainty on the stability of biochar carbon in the soil,
4. Provide certainty, verification and evidence of carbon savings, and:
5. Consider the indirect costs and benefits to land users for the use of biochar in soil.

In short, a full life-cycle analysis is required.

Australian Biochar Proponents

BiG Char

Black is Green Pty. Ltd.[41] (BiG Char) is a private Australian company with offices in Maleny, South East Queensland and Mackay, Central Queensland. BiG char has developed novel pyrolysis technology that addresses one of the key major issues for biochar production, seasonal feedstock production. In practice, the biological residues used as feedstock for biochar production follow a seasonal pattern of production. In addition, events such as droughts, floods, fire, and storms can result in an incidental buildup of feedstock in a particular location. Building on-site pyrolysis facilities in response to these incidents is not feasible and a pyrolysis operator must maximise the continuous operation of their facility. At the same time it is not economic to transport large volumes of biomass feedstock long distances to a centralised pyrolysis facility. To address this problem BiG char has developed mobile pyrolysis technology that can be readily transported to a site of available feedstock, and once this has been fully processed, can be transported to the next best source of feedstock.

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[41] Joyce, J. and Joyce, S. "Update on progress with BIGchar biomass to biochar/bioenergy systems." in Bioenergy Australia. 2010. Sydney.

The company has developed a proprietary biomass to biochar process that can be carried on the back of a truck or on a trailer. The process is aimed at farms in Australia as well as villages in developing countries. The Big Char 2200 fast rotary hearth process has a nominal rate of 1 t/h biomass, producing 250 kg/h biochar and a gross heat release of 2-3 MW. This would give a co-generation capacity of 400 kW. They also have a larger unit, BiG Char 3500, used to dry 500 tonnes per day of sugar cane fibre in Western China. A variety of biomass feedstocks have been successfully trialled. BiG char has recently entered into an off-take agreement to supply biochar to an international company as a soil amendment in a proprietary process. This agreement ensures the financial viability of the BiG char business model into the future and will enable further growth and development.

PacPyro (Pacific Pyrolysis)

Pacific Pyrolysis is currently commercialising its proprietary BEST energies slow pyrolysis technology[42]. The Pacific Pyrolysis process produces a specific biochar under the brand name Agrichar which has been used in numerous technical trials to assess its contribution to soil productivity and carbon sequestration, along with syngas ideally suited to on-site electricity generation.

PacPyro is currently operating a 300kg/h demonstration unit and the same technology can currently be scaled up to 4 tonnes per hour. Pyrolysis companies such as PacPyro have a ready-to-market carbon neutral fuel generation process the scale of which depends on the availability of biomass feedstock.

The Crucible Group

Burns and Herbertson from The Crucible Group (2010)[43] have reported the development of both a bench- and commercial-scale demonstration facility to pyrolise biomass for biochar at a rate of 1 t/hour. The Task Force has visited the Crucible Group and inspected their pilot facility as well as seen the biochar product produced from materials as diverse as wood chips, wheat stubble and lignite. Their patented pyrolysis process is claimed to be low capital cost, high efficiency and be able to de-water the biomass feed without a significant energy penalty. The process also produces clean energy or synthesis gas that is high in hydrogen. The Crucible Group is in the process of demonstrating/commercialising their pyrolysis reactor at the 1 t/h, 1 MW scale in both agriculture and power generation applications. In the agricultural application, it is planned to convert stranded biomass (wheat straw) into biochar and biogas at a farm in Western Australia. In the case of power generation, Delta Electricity at Vales Point power station plans to convert wood into biochar and biogas for use as fuels. Both demonstration facilities will be commissioned in 2011. The Crucible Group also has plans to commercialise the technology using degraded biomass resources in Canada.

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[42] Downie A, Pacific Pyrolysis personal communication, 21 July 2011

[43] Burns, K. and Herbertson J. "Update on commercialization of the Crucible Carbon pyrolysis process." in Bioenergy Australia. 2010, Manly, and Herbertson J., Personal communication, 2011 (with permission)

2.1.4 Bio-sequestration *via* biochar as a soil amendment

While some biochars themselves under certain conditions may be considered long-term storage of carbon, biochar has also been claimed to have a positive effect on soil productivity if used as a soil amendment.

Proponents of biochar as a soil amendment point to characteristics such as its Cation Exchange Capacity (CEC), ability to adsorb nutrients, contaminants, pesticides and other soil components and its ability to reduce water loss through evaporation. These characteristics may confer a beneficial effect for the addition of biochar to soils in a similar way to the addition of humic/fulvic carbon mixtures. Claims have been made that these beneficial effects lead to increased productivity from the soil, giving increases in photosynthetic rates per unit of land and thereby the rate of carbon capture. This increased carbon capture into plant biomass is subsequently conferred to the soil in the death and decay of that biomass, which results in an increase in endogenous soil carbon.

This second property of biochar follows the same process as bio-sequestration by the addition of humic/fulvic fertilisers and is therefore, for the purposes of this Task Force report subject to the same uncertainties and limitations. A discussion of increased soil bio-sequestration by exogenous addition of soil amendments follows.

2.1.5 Bio-sequestration via humic/fulvic soil amendments

The soil carbon cycle

Terrestrial bio-sequestration can be envisioned as comprising two components; 1) plant biomass, (defined as "terrestrial" biomass) which exists as living plants above ground, and 2) soil carbon. Soils naturally contain significant amounts of organic carbon. Total Australian soil organic carbon stocks in 1990 were estimated at 19 Gt with an annual turnover of approximately 700 Mt/a through exchange between the soil and the atmosphere (Cowie *et al*., 2006)[44]. How this carbon exists in the soil and the processes that impact it are critical to an understanding of terrestrial bio-sequestration.

Soil organic carbon can be categorised according to its persistence or permanence, and falls into one of three categories (Cowie *et. al.* 2006):

1) Labile carbon (the "labile pool"), which typically exists in soils for 1 to 5 years. This pool comprises carbon in a form that is readily decomposable, such as simple sugars, microbial biomass, soluble carbon, etc.
2) Humic acid (the "humified pool"), which typically exists in soils for decades. This is defined as humus, a complex mixture of organic matter that has decomposed.
3) Charcoal (relatively inert carbonaceous organic matter), which is potentially highly resistant to decomposition. This component can take decades to thousands of years to decay. It includes biochar, which can be produced by pyrolysis of biomass and added to the soil artificially.

Carbon input to the soil is presently derived almost entirely from terrestrial plant biomass that dies and decays into the soil. Plant biomass fixes atmospheric CO_2 by photosynthesis into a variety of

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[44] Cowie, A. (Ed), "The role of soil carbon in the GHG balance of bioenergy systems," in Greenhouse gas balances of biomass and bioenergy systems, IEA Biotechnology Task 38, (2006).

compounds and this biomass is transferred to the soil by the development and death of the plant. Carbon loss from the soil is caused almost entirely by the activity of the soil bio-system. Soil biota, predominantly microbes, feed on the plant biomass deposited in the soil and via respiration release CO_2 to the atmosphere. The nature of the plant biomass defines how quickly it can be degraded: simple sugars such as starch can be digested very quickly whereas more recalcitrant compounds such as lignin are much more resistant to digestion.

The most important aspect of this pool of carbon to understand is that it is not static. No specific carbon that enters the soil stays there indefinitely – the soil carbon pool is a dynamic flux of carbon input and carbon output. This can be expressed by a simple first-order differential equation (Sanderman *et al*. 2010)[45]:

$$\text{Accumulation} = \text{Input} - \text{Output} \qquad (2.1)$$

$$dC/dt = \sum_{i=1}^{n} I_i - k_i \quad C_i \qquad (2.2)$$

Where: C is the carbon content of the soil

t is time

I is the rate of input of carbon into the soil

k is a rate constant for carbon removal from the soil

i is the form of soil carbon (e.g. labile, humic, charcoal)

It is useful to briefly discuss Eq. (2.2) because it helps explain some of the key issues surrounding soil carbon sequestration. If there is no input to the soil (i.e. $I = 0$), then soil carbon will decay at a rate proportional to the soil carbon concentration. If the carbonaceous material in the soil is from the “labile pool”, then the value of the rate constant k_i will be relatively large, and the soil carbon will return to the atmosphere quickly. On the other hand, if the carbonaceous material is long-lived biochar, then the rate constant k_i will be relatively small and the rate of carbon loss from the added biochar will be low, even though any additional soil carbon promoted by the biochar may have a higher value of k and may leave the soil sooner. “Humified” soil carbon will have k_i values between “labile” and “biochar” values. Also, k will vary with the type of soil and its temporal and spatial distribution and ambient conditions such as temperature and rainfall. It is also likely that k_i is not simply constant for each soil additive but also varies as a function of time.

Definition and knowledge of k_i is clearly of great importance in any discussion or conclusions regarding carbon sequestration in soils. Similarly, the value of the input rate of carbon to the soils, I, is important. For maintenance of elevated concentrations of soil carbon where k_i is relatively high (for the “labile pool” and the “humified pool”), then the input rate, I_i, must be maintained continuously over the years. This means that single application of some “labile” or “humified” types of carbonaceous materials to soil may not lead to a sustained increase in soil carbon, since the exogenous added carbon may rapidly decay with time. In undisturbed nature, a balance is struck

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[45] Sanderman, J., Farquharson and Baldock (2010). “Soil Carbon Sequestration Potential: A review for Australian agriculture.” C. S. Agriculture.

between input, I, and output, $-kC$; the accumulation rate, dC/dT, then becomes zero and the soil reaches an equilibrium carbon content.

In Australia, agriculture over the years has generally modified (reduced) the value of carbon input, I, by not returning an appropriate amount of carbonaceous material to the soil, leading to a lower equilibrium soil carbon content. The Carbon Farming Initiative seeks to increase the input rate, I, through appropriate farming practices. However, even with increasing deployment of land management practices such as no-till farming, soil carbon levels are still dropping across Australia.

Net primary productivity (NPP)

The second key concept for an understanding of soil carbon is net primary productivity, or NPP (Sandeman *et al*. 2010). NPP is the net production of organic carbon by plants in an ecosystem (Roxburgh *et al.* 2004)[46]. It has been widely used as an indicator of ecosystem function. Technically it is the amount of gaseous carbon fixed by plants (Gross Primary Production (GPP)) less the amount of gaseous carbon released by plant via respiration, (R):

$$NPP = GPP - R \qquad (2.3)$$

NPP has been intensively studied and well developed models exist for assessing current NPP as well as estimating maximum theoretical NPP. These methods range from 'top down' approaches involving remote sensing of the plant canopy to 'bottom up' approaches involving physiological plant growth models. (Keating 2003[47], Roxbugh *et al.* 2004). As part of the National Land and Water Resources Audit, models have been developed to assemble long-term steady-state balances of water, carbon, nitrogen and phosphorus (e.g. 'BiosEquil' model, Raupach *et al.* 2001[48]). The models employ empirical coefficients for leaf- and canopy-scale photosynthetic models. Although limited at local scales, the models have provided a reasonable indication of continental-scale NPP potential carbon capture by agro-ecosystems.

Only a fraction of the total CO_2 taken in by plants ends up as biomass carbon, since a large proportion (25% to 75%) of assimilated carbon is subsequently respired by plants (Lambers *et al.* 2005)[49]. Roxburgh *et al*. (2004) reviewed 12 model estimates of NPP for the Australian continent. A conservative 'BiosEquil' model estimate of 0.94 Pg C yr-1 was at the lower end of the continental NPP estimates for soil carbon sequestration compared to some of the other models. (See Sandeman *et al.* 2010, Figure 2) . The maximum achievable NPP is a direct indicator of the potential for a region of land to sequester CO_2. As such it can be referenced against claims of sequestration potential for assessment.

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[46] Roxburgh, S.H., D.J. Barrett, S.L Berry, J.O. Carter, I.D. Davies, R.M. Gifford, M.U.F Kirschbaum, B.P. McBeth, I.R. Noble, W.G. Parton, M.R. Raupach, M.L. Roderick, "A critical overview of model estimates of net primary productivity for the Australian continent." Functional plant biology, 2004. 31(11): p. 1043.

[47] Keating, B.A., "An overview of APSIM, a model designed for farming systems simulation." European journal of agronomy, 2003. 18(3-4): p. 267.

[48] Raupach, M.R., Kirby, J. M., Barrett, D. J. and Briggs, P. R., "Balances of Water, Carbon, Nitrogen and Phosphorus in Australian Landscape." Sustainable Minerals Institute Vol. 40/01 2001-12 CSIRO Land and Water

[49] Lambers, H., S. Robinson, and M. Ribas-Carbo, "Regulation of Respiration in Vivo." in Plant Respiration, H. Lambers and M. Ribas-Carbo, Editors. 2005, Springer Netherlands. p. 1-15.

Methods for increasing bio-sequestration

There are a number of very good reasons for proposing bio-sequestration as a method for abating CO_2 emissions. Soil carbon should be increased not only to combat climate change but to increase productivity of soils, biodiversity and general environmental health of the land.

As explained above, undisturbed biological systems naturally reach a point of equilibrium in respect of long-term averaged amounts of carbon held within the system. Artificial methods used to increase the rate of carbon input or decrease the rate of carbon output from the system can shift the equilibrium to a new level. These methods must therefore be maintained in place indefinitely if the new level of carbon storage is to remain constant.

Artificial methods for increasing soil carbon over areas sufficient to significantly contribute to meeting Australia's GHG reduction targets are likely to be expensive, so a rational approach for increasing soil carbon will use minimal intervention and work in concert with the natural system. Such a rational approach should follow these general steps in order of priority (Baldock and Battaglia, 2011)[50]:

1. Search for inefficiencies. Very little land in Australia remains unaffected by natural or artificial pressures, and these have created NPP inefficiencies. No land resources achieve 100% of potential NPP and many achieve much less.

2. Identify constraints. Constraints to maximising NPP may be singular and simple, such as a lack of fixed nitrogen, lack of water, excessive removal of biomass residues, and so on.

3. Eliminate the constraints to NPP. The constraining circumstances then need to be carefully assessed – if an ecosystem can be restored simply to a previously productive state then this will most likely be a sensible course of action.

4. Undertake Life Cycle Analyses. In many cases increasing NPP by removing constraints will require changes to the land management practices. These changes can result in adverse effects such as increased NOx or methane emissions. For this reason any extensive change in land management practices must first be assessed by a thorough life cycle analysis in terms of greenhouse gases.

5. Add exogenous carbon to the soil. The most effective and persistent method for increasing soil carbon is to remove any constraints to a naturally high NPP. If these methods are not suitable or have already been implemented, addition of exogenous carbon may be considered. The energy and carbon balance and CO_2 life cycle analysis of exogenous carbon addition must be evaluated first, including the production and transportation of the exogenous carbon source itself. The impact of the exogenous carbon source on the parameters in Eq. (2) above describing soil carbon rates of change and equilibrium must also be evaluated through R&D and soil carbon measurement activities.

Before point number 5. above can be employed, a more comprehensive understanding of the long-term effects of particular exogenous soil carbon sources in particular soils must be developed. For a better understanding of the current state of research the Task Force solicited advice from Patti and

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[50] Baldock, J., Battaglia M, CSIRO, Personal Communication, 2011.

Cavagnaro[51]. Their advice to the Task Force was consistent with personal communication by the Task Force with other Australian soil scientists including Krull[52], Singh[53] and Cowie[54]. Controlled laboratory tests of exogenous soil carbon amendments have suggested a beneficial effect on soil productivity, but these tests have not progressed to a comprehensive program of long-term field trials to confirm the effect over time under natural conditions.

Scale of Soil Carbon Storage

The ultimate scalability of terrestrial bio-sequestration depends greatly on the specific process involved. In the case of soil carbon, particularly for the "labile" and "humified" pools that can be increased by land management practices, the ultimate scale is certainly limited. Some authors suggest an upper limit of 20% increase in endogenous (self-generated) soil carbon content (e.g. Cowie (2006)).

In the case of biochar it is not clear what the ultimate capacity of soils to store carbon is. However, given that globally over 2,000 Gt of carbon is stored in soils versus over 500 Gt in terrestrial biomass, soil carbon is, in theory, an attractive potential target for long-term carbon storage via biochar. Terrestrial biomass can be regularly harvested and processed in a variety of ways to either store, e.g. via biochar, or reuse the carbon, and new biomass can be cultivated in its place. Through this cycle, terrestrial biomass and biochar may represent a large potential carbon sequestration capacity.

It should, however, be noted that although in theory plant biomass photosynthesis can fix large amounts of atmospheric CO_2, in practice this rate is limited by access to suitable land, the germination and growth rate of seedlings and the infrastructure to distribute them in appropriate locations. A large-scale terrestrial biomass sequestration operation begun today in 2011 will not reach ultimate carbon sequestration rates until after 2020 (Polglase, 2011)[55]. Similarly, the production and incorporation of biochar into the soil may incur significant costs. These factors limit the practicably achievable rates of terrestrial biomass plantings (biodiversity and plantations) and also biochar production.

Measurement of Soil Carbon

Determining soil carbon stored in soil over large land areas is notoriously difficult, as soil carbon concentrations vary widely both spatially and temporally. That is, soil carbon concentration can vary according to the type of soil and location, sometimes for land in close proximity. Soil carbon can also vary according to the seasons, land use change, nutrient delivery, rainfall and a variety of other factors.

Various approaches and models have been developed for quantifying the effect on soil carbon of changes in land management practices. However, these models are not universally accepted and require further development and validation through measurement. In the future, a variety of measurement methods will need to be employed to determine actual soil carbon levels and these

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[51] Patti and Carvagnaro, Monash University, Personal Communication, 2011.

[52] Krull E, CSIRO, Personal Communication, 2011.

[53] Singh B, NSW DPI, Personal Communication, 2011.

[54] Cowie A, National Centre for Rural Greenhouse Gas Research, New England University, Personal Communication, 2011.

[55] Polglase P., CSIRO, Personal Communication, 2011.

will need to be linked to predictive mathematical models. Land management practices have not yet been accredited under the Kyoto Protocol and scientific understanding and validation of the soil carbon balance will be required if this is to occur.

Labour intensive measurement methods involving manual core sampling of soils and carbon analysis in remote laboratories are time consuming and expensive. With this in mind, new methods for direct measurement of soil carbon levels are being developed. A number of promising technologies, including spectroscopic (infra-red) measurement, neutron scattering and gamma radiometric tools are being researched. These methods aim to reduce the cost of measurement such that accurate determination of soil carbon across large areas can be commercially and technically viable. For example, Rayner[56] advised the Task Force of the latest developments in carbon flux measurement by inversion analysis using regional CO_2 concentration data from new robust, low-cost air sampling units installed on mobile phone towers. Lauvaux (2009)[57] reported the results of one such trial in France while another larger trial in the US has recently concluded. The inversion analysis together with local CO_2 concentration data offers accurate measurement of carbon flux down to regions of the scale $25km^2$.

Risks associated with soil carbon storage

Bio-sequestration essentially stores carbon in a dynamic pool. As shown previously in Eq. (2) above, levels of carbon held in the pool reach equilibrium between inputs and outputs, and under these conditions considerable risk exists related to changes in the input/output circumstances. Any change to the conditions of the land can affect the amount of carbon stored in it. This includes managed conditions such as tillage, fertilisation, irrigation etc., and also includes uncontrolled conditions such as fire, flood and drought. Fire, in particular, is a major disruption to the carbon cycle. Fire can temporarily destroy CO_2-fixing plant biomass as well as release large amounts of carbon from biomass and soil. Fire can also release carbon from exposed biochar.

Australian Proponents of soil carbon enhancement

Ignite Energy Resources/LawrieCo

Ignite Energy Resources (IER) is an exploration company with rights to over 200 billion tonnes of brown coal in Gippsland, Victoria and is publicly committed to developing this resource in a carbon-neutral method[58]. To do this IER have partnered with LawrieCo, a fertilizer company based in South Australia that has brought to market a carbon-based fertilizer and associated land management practices referred to as BFS (Biological Farming System). The essential core of the Biological Farming System is a nutrient-rich substrate incorporating high humic/fulvic content brown coal, inoculated with a specially developed mixture of soil microbes. Using this fertilizer in concert with LawrieCo's recommended land management practices is claimed to increase the photosynthetic productivity of the land, thereby capturing and sequestering an additional volume of atmospheric CO_2 orders of magnitude greater than the carbon content of the fertilizer itself. LawrieCo have a well-advanced

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[56] Rayner P., CLIMMOD Engineering and University of Melbourne, Personal Communication, 2011.

[57] Lauvaux, T., "Bridging the gap between atmospheric concentrations and local ecosystem measurements." Geophysical research letters, 2009. 1: p. 17.

[58] White, J., Ignite Energy Resources, Personal Communication, 2011 (with permission)

on-farm program that has deployed this fertilizer on hundreds of operating farms throughout Australia. Customer testimonies are universally positive over the effects on farm productivity and improved soil quality. The carbon sequestration benefit of BFS is subject to cost-effective soil carbon measurement discussed elsewhere. It is noted however that soil carbon is a primary soil quality parameter for BFS farmers and they monitor soil carbon via their routine certified soil testing programs associated with fertilizer system design. Despite continual invitations by IER and LawrieCo to CSIRO and State Agricultural Departments to verify measured soil carbon increases on numerous BFS farms, few controlled field trials of carbon-based fertilizers have been completed to verify these results.

2.2 Mineral Carbonation Sequestration

Introduction

Mineral carbonation involves the reaction of CO_2 with a compound that forms thermally stable and poorly soluble carbonates at ambient conditions. Such compounds include the elements calcium, magnesium and iron. To date attention has primarily been paid to magnesium silicates (*serpentine* and *olivine*) and sometimes calcium silicates (*wollastonite*), which are widely distributed around the world. Iron appears not to have been investigated previously due to its value as a resource for steelmaking. However, Australia may be somewhat unique in this regard in having large deposits of low-grade magnetite that may be suitable for sequestration purposes.

Mineral carbonation occurs naturally and will ultimately sequester manmade GHG emissions through natural weathering of crustal rocks. However, the timeframe for this process is very large and the objectives of human intervention into the cycle are primarily to speed up the process.

Three key sources of published information have been instrumental in our understanding of mineral sequestration technologies. The IPCC published a Special Report on Carbon dioxide Capture and Storage (2006)[59], and the Abo Akademi University in Finland have published a number of technical and literature reviews (Zevenhoven *et al*. (2008, 2011)).[60],[61].

Zevenhoven *et al*. (2011) have presented a comprehensive, up to date literature review on the subject. They note that the basic idea of mineral carbonation is to mimic a naturally occurring process called “weathering”, where calcium (Ca) or magnesium (Mg) from silicate minerals is bound over geologic time with CO_2, forming environmentally benign and stable calcium and magnesium carbonates ($CaCO_3$, $MgCO_3$). The raw materials for this process are widely available globally in the form of magnesium silicates (*serpentine* and *olivine*) and sometimes calcium silicates (*wollastonite*). These minerals are found on the east coast of Australia, for example in the New England area rim.

There are recognised and well-documented advantages of mineral carbonisation:

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[59] “IPCC Special Report on Carbon Dioxide Capture and Storage”, 2006, pp320-337.

[60] Sipila J., Teir S., Zevenhoven R., “Carbon dioxide sequestration by mineral carbonation: Literature Review Update”, Faculty of Technology, Abo Akademi University, Finland, 2008.

[61] Zevenhoven, R., J. Fagerlund, and J.K. Songok, “CO_2 mineral sequestration: developments toward large-scale application.” Greenhouse Gases: Science and Technology, 2011. 1(1): p. 48-57.

- very large resources of the required minerals
- no post-storage monitoring needed, and some products may be useful for building products
- exothermic process chemistry

However, major issues that need to be addressed include:

- very slow reaction chemistry
- large material transport and storage requirements
- process costs and economics, including the process conditions and the cost of additives aimed at increasing the reaction kinetics

Background

The major sources of calcium and magnesium minerals of interest for carbonation occur in igneous deposits originating from oceanic plates. Minerals of interest, reaction energy and the quantity required to sequester a unit weight of CO_2, assuming complete reaction of the mineral, is shown in Table 2.1.

Table 2.1. Minerals of interest for mineral carbonisation[62]

Mineral	Formula	Products of complete reaction with CO_2	Mineral requirement (kg/kg CO_2)
Mg Olivine	Mg_2SiO_4	$SiO_2 + 2MgCO_3$	1.6
Mg Serpentine	$Mg_3Si_2O_5(OH)_4$	$2SiO_2 + 3MgCO_3 + 2H_2O$	2.1
Wollastonite	$CaSiO_3$	$CaCO_3 + SiO_3$	2.6
Basalt	varies	$MgCO_3$, $CaCO_3$, $FeCO_3$	4.9
Magnetite	Fe_3O_4	$Fe_2O_3 + FeCO_3$	5.3

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[62] Penner L., O’Connor W., Dahlin D., Gerdemann S., Rush G., “Mineral Carbonation: Energy Costs of Pretreatment Options and Insights Gained from Flow Loop Reaction Studies”, 3th Annual Conference on Carbon Capture and Sequestration, Va, USA, 2004.

The global reaction chemistry of the key minerals with CO_2 is illustrated by equations (4) to (6) below:

Serpentine

$Mg_3Si_2O_5(OH)_4$ (s) +3CO_2 (g) -> 3$MgCO_3$ (s) + 2SiO_2 (s) +2H2O (l) ~-1.4 MJ/kg CO_2 (4)

Olivine

$Mg_2Si_2O_4$ (s) +2CO_2 (g) -> 2$MgCO_3$ (s) +SiO_2 (s) ~ -1.4 MJ/kg CO (5)

Wollastonite

CaSiO3 (s) + CO_2 (g) -> CaCO3 (s) + SiO_2 (s) ~ -2.3 MJ/kg CO_2 (6)

Zevenhoven *et al*. (2011) also note that industrial by-products from steelmaking slags could also be utilised as a raw material for the carbonation process, since these contain both MgO and CaO. The available tonnage of these materials is not as high as the natural mineral deposits, but could amount to the fixing of a few 100 Mt/a of CO_2 worldwide.

The mineral mass necessary to bind unit mass of CO_2 as carbonate are in the range 1.8-3 t mineral/t CO_2 for relatively pure minerals. This means that for a 500MW unit emitting 3.4 Mt/a of CO_2, around 6 - 10 Mt of mined minerals per year would be required. This is a scale comparable with large mines in Australia for other minerals and coal for each 0.5 GW of generating capacity.

Experiments on Carbonation

The base reaction rate (natural weathering) of metal oxide-bearing ore is extremely slow. By simply crushing ore to particle sizes of 1mm and suspending in aqueous solution 100% dissolution can be achieved within around 2000 years (Hangx 2009)[63].

Various approaches have been adopted to try to improve the reaction kinetics, leading to the development of multi-stage process proposals now. Sipila *et al*. (2008) provide a table showing the state of the art in this regard, where it is shown that the three main routes are:

1. Direct Carbonation
2. Indirect Carbonation, and:
3. Other Routes

These routes and further sub-routes comprise at least twelve different proposed methods for increasing the carbonation reaction rate.

Direct Carbonation refers to processes where the reaction occurs within the mineral matrix and Indirect Carbonation to where the metal ion (Ca^{2+} or Mg^{2+}) is released from the matrix as a preliminary stage prior to carbonation.

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[63] Hangx, S.J.T., C.J. Spiers, "Coastal spreading of olivine to control atmospheric CO_2 concentrations: A critical analysis of viability." International journal of greenhouse gas control, 2009. 3(6): p. 757.

Studies at the Los Alamos National Laboratory in the USA (1997, 2002)[64],[65] found that gas-solid contacting at elevated temperature and pressure (500°C, 340 bar) gave 25% conversion after two hours with 0.1mm sized serpentine particles. Further work in Finland (Zevenhoven[66]) showed considerably lower reaction kinetics for the gas-solid contacting case than a direct aqueous process developed by the Albany Research Center (ARC) in the USA using $NaHCO_3$ and NaCl at 150 bar and 155°C for serpentine (O'Connor *et al.* 2004, 2005)[67],[68] This later research program achieved the benchmark reaction rates for mineral carbonation using an aqueous phase ex-situ direct activated cation approach which achieved up to 80% conversion of metal oxides to carbonates within 1.5 hours at costs of US$54-$78 per tCO_2 (in 1995).

Depending on the type of feedstock used for the direct carbonation process, different process conditions can be applied. Table 2.2 below gives the optimal carbonation conditions, (Gerdemann *et al*. 2007)[69]. It is important in this table to note the high pressures that are apparently required to achieve reasonable reaction times and conversion efficiencies. By comparison, the pressure to which CO_2 must be compressed to achieve supercritical conditions at atmospheric temperature for pipeline transportation to geological storage is around 75 bar. These aggressive process conditions suggest relatively high technical and economic risk.

Table 2.2: Process Conditions for Optimum Direct Carbonation of Minerals (Zevenhoven *et al*. 2008,2010)

Mineral	Temperature (°C)	Pressure of CO_2 (bar)	Additive Solution	Carbonation after one hour (%)
olivine	185	150	0.64M $NaHCO_3$ 1M NaCl	49.5%
wollastonite	100	40	water	81.8%

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[64] Lackner, K.S., "Progress on binding CO_2 in mineral substrates." Energy Conversion and Management, 1997. 38: p. S259.

[65] Lackner, K.S., "Carbonate chemistry for sequestering fossil carbon." Annual review of energy and the environment, 2002. 27(1): p. 193.

[66] Zevenhoven, R., "Mineral carbonation for long-term CO_2 storage: an exergy analysis." International journal of applied thermodynamics, 2010. 7(1): p. 23.

[67] O'Connor, W. K., D. C. Dahlin, G. E. Rush, S. J. Gerdemann and L. R. Penner (2004). "Energy and economic considerations for ex-situ and aqueous mineral carbonation." Report for U.S. Department of Energy

[68] O'Connor W., Dahlin D., Rush G., Gerdemann S., Penner L., Nilsen R., "Aqueous mineral carbonation: Mineral availability, pretreatment, reaction parametrics, and process studies", DOE/ARC-TR-04-002, 2005.

[69] Gerdemann, S.J., W.K. O'Connor, D.C. Dahlin, L.R. Penner and H. Rush, "Ex situ aqueous mineral carbonation." Environmental science & technology, 2007. 41(7): p. 2587.

serpentine	155	115	0.64M $NaHCO_3$ 1M NaCl	73.5%

It should be noted that the (expensive) additives in Table 2.2 cannot be recycled and reused when employed in the direct carbonation methods.

Sipila *et al.* (2008) state that the direct aqueous mineral-carbonation route appears to be the most promising CO_2 mineralisation alternative to date. However, although high carbonation degrees and acceptable rates have been achieved in the process, it is still too expensive to be applied on a larger scale. In 2008 the cost ranged from 40-80 Euro per tonne CO_2 (~$50-$100 AUD/tCO_2 at current exchange rates.

Mg^{2+} and Ca^{2+} cations do not exist as the ideal oxides or hydroxides in large deposits. In practice these cations are more commonly found as less-reactive silicates (olivine, serpentine) in ultramafic rocks at concentrations less than 50% (IPCC 2005).

If the process of mineral carbonation is divided into several steps it is characterised as **indirect carbonation.** In this case the reactive component is first extracted from the mineral as oxide or hydroxide and then, in another step, reacted with CO_2 to form the desired carbonates. The first step can be carried out at atmospheric pressure and this is then followed by the carbonation step at elevated temperature and pressure (>500^{o}C and >20 bar). Alternatively weak acids or bases can be used to form compounds such as MgCl in conjunction with Si chelators such as EDTA and citric acid to prevent the reverse reaction (called the 'Activated cation' process by the Clinton foundation 2011)[70].

It has been found in indirect carbonation that the kinetics of the reaction with MgO is slower than the kinetics of the reaction with $Mg(OH)_2$. However, a three step process (MgO to $Mg(OH)_2$ to $MgCO_3$) still has slow kinetics, even at 525^{o}C and 45 bar (Sipila *et al*. (2008)). These authors contend that research on high pressure gas-solid contacting in fluidised beds has the potential to improve this method of carbonation relative to the liquid-based techniques.

A pH swing process has been proposed in Japan (Yogo *et al*. (2005)[71]). In this process the gas is contacted by ammonia (NH_3) with calcium chloride ($CaCl_2$) to form ammonium carbonate $(NH_4)_2CO_3$ and $CaCl_2$. This solution is sent to a precipitator, where calcium carbonate is precipitated out of solution at low pH, leaving ammonium chloride. The pH is then raised in another vessel using 2CaO.SiO2 to re-form the NH_3 and $CaCl_2$ for recycling. In the Japanese experiments, the loss of NH_3 was considerable.

Acetic acid has also been used to convert the minerals into Ca^{2+} ions prior to precipitation of the calcium carbonate (Kakizawa *et al*. (2001)[72]).

The two primary goals of current research are:

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[70] Baird J., Clinton Foundation, Personal Communication, Melbourne, 2011.

[71] Yogo K., Eikou T., Tateaki Y., "Method for fixing carbon dioxide", Japan Patent JP2005097072, 14.4.2005.

[72] Kakizawa, M., A. Yamasaki, and Y. Yanagisawa, "A new CO_2 disposal process via artificial weathering of calcium silicate accelerated by acetic acid." Energy, 2001. 26(4): p. 341-354.

1. To increase the rate of the carbonation reaction at less severe process conditions (temperature and pressure) in order to reduce the size and cost of the process vessels, and:
2. To reduce the operating costs of the process. Of these process costs the two most urgent factors are the power plant parasitic load and improving the recycle rate of the chemical additives to avoid costly additive consumption.

The challenge for mineral sequestration is to find an optimal process that uses a (financial- and carbon-) cost-effective level of technology to achieve an acceptable reaction rate.

Transport and disposal

Two of the compelling features of mineral sequestration are the large reserves of reactant in common ultramafic rock and the permanence of the carbonated waste. These features are also a major challenge for carbonation processes. CO_2 must be physically combined with reactant, so in a high-throughput process either the CO_2 stream must be transported to the site of reaction, or the mineral must be transported to the site of CO_2 emissions. Alternatively, if a chemical such as ammonia could be used to contact the flue gases to remove CO_2, then this component could be circulated between the gas source and the mineral (see case studies below).

Australian coal and gas power stations produced slightly over 200 Mt of CO_2 in 2009[73] , which with an consumption rate value of 3 t mineral/t $CO_{2,}$ translates to around 600Mt of mineral reactant, plus overburden and 900Mt of product in order to sequester all the CO_2 from these sources. This is an extremely large operation in terms of logistics – for example, Australia's iron ore production in 2008 was around 350 Mt/year.

Sourcing, transporting and pre-treating this volume of minerals is a major economic and engineering challenge. Some of the product may be saleable, but the volumes produced are expected to very quickly overwhelm the market for these products so disposal is also very likely to be essential. This could possibly be achieved in the space left by the mining operations, although the mass and volume of waste carbonate is higher then the mined material.

Community acceptance

In addition to the materials handling challenges mineral sequestration must also have community support. Natural forms of chrysotile (mineral from which asbestos may be extracted) can be found in serpentine rocks. Technology proponents advised that these occurrences are generally localised and may be avoided by selective mining, or handled using practices standard in mining operations that process similar materials. On the other hand the mineral sequestration processes typically destroy 100% of asbestos contained within reactants even if full rock dissolution is not achieved (IPCC Special Report on CSS 2005). This may present an opportunity for mineral sequestration to be used to remediate asbestos wastes including abandoned mines.

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[73] "Australian national greenhouse accounts – National Inventory Report 2009" Dept of Climate Change and Energy Efficiency Canberra.

Case Studies on Mineral Carbonation Sequestration

Calera

The Calera process is a propriety process developed and marketed by the Calera company of USA[74]. A demonstration plant has been constructed at the gas fired Moss Landing power plant while a plant previously proposed for Yallourn in Victoria has now been cancelled due to the unavailability of brines of suitable quality and quantity. The Moss Landing plant has been demonstrated to capture flue gas CO_2 from a 10MW power generator at 90% efficiency.

US Patent 7887694 provides information of a range of embodiments of the technology[75]. Broadly the technology envisages the introduction of brines containing alkaline earth metal (calcium and/or magnesium) ions to a reactor where it is contacted with CO_2 containing gas. The CO_2 dissolves in the water to produce carbonate and bicarbonate ions, resulting in a decrease in the pH of the solution. The solution pH is then raised through the introduction of alkalinity to the point where the alkali metals are precipitated as carbonates. Additional cycles of introduction of CO_2, followed by additional alkalinity, may be applied to cause further carbonate precipitation. The carbonates produced are suitable for cement manufacture.

The technology requires the availability of a very large quantity of brines containing alkaline earth metal ions (Ca, Mg). These may be industrial waste water, mineralised spring water or sea water. This concept bypasses the rate-limiting step in mineral sequestration which is the dissolution of the alkaline earth ions from the parent minerals.

The source of alkalinity to initiate precipitation may be calcium or magnesium oxide, sodium or potassium hydroxides, alkaline flyash or by electrolytic decomposition of sodium chloride by application of a Calera propriety electrolytic cell. Proprietary precipitation enhancing agents may also be employed.

One issue with the technology is the quantity and quality of brine that must be processed to provide sufficient alkaline earth metals to sequester industrial quantities of CO_2. For example, seawater contains approximately 1270 ppm magnesium and 400 ppm calcium ions. Complete depletion of these ions would consume 2.7kg of CO_2 per tonne of water. A plant capable of sequestering 5 Mt/a of CO_2 will then require a minimum of 1851 Mt/a (5 Mt/day) of seawater. Brines of higher Mg and Ca content would be more suitable for the process, but their local availability in the quantities required is in question.

Integrated Carbon Sequestration Pty. Ltd. (ICS)

The ICS Process is a mineral carbonation process invented by Hunwick that is being developed by a

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[74] Zaelke D., Young O., Andersen S.O., "Scientific Synthesis of Calera Carbon Sequestration and Carbonaceous By-Product Applications", Consensus Findings of the Scientific Synthesis Team, Donald Brent School of Environmental Science and Management, University of California, Santa Barbara, January 2011. Also: http://www.calera.com

[75] Constanz, "Methods for sequestering CO_2", US Patent 7887694, 2011.

company he formed, Integrated Carbon Sequestration Pty Ltd. It is patented in Australia[76] , and patents have been received or are pending in other countries and regions around the world. It secures the permanent storage of carbon dioxide by reacting the gas with ultramafic rocks notably serpentinite and olivine, and other metal silicate rocks. It differs from other processes in that it avoids the need to handle pressurised, pure carbon dioxide: silicate rock is converted directly to carbonate (plus silica) by reacting it with the solution used to scrub the gas from the flue gases of the host power station (or other point source). Also, all rock-handling including emplacement of the carbonated product may be restricted to the mine area, with an interconnect to the power station and mine in the form of liquid pipelines. By avoiding having to strip pure carbon dioxide from a capture solution, compress the gas to supercritical pressures and heat-treat the rock, capital and operating costs are reduced and the parasitic energy demands are said to be reduced.

The ICS process has advanced beyond the proof-of-concept stage, with CSIRO having undertaken extensive experimental tests in a 300 ml autoclave studying the effects of temperature and pressure, backed up by detailed process simulation studies of various process configurations using the ASPEN package.[77]

CSIRO has also advised the task force that work of a more basic nature is being undertaken, funded by CSIRO[78]. These studies are attempting to get a better understanding of the mechanisms involved and the development of insight into ways to improve the process.

GreenMag Group

GreenMag Group have an alliance with the Priority Research Centre for Energy at the University of Newcastle, NSW. GreenMag Group are pursuing research and development in collaboration with the University to develop a global reference facility at laboratory, pilot and demonstration scales to sequester CO_2 using magnesium silicate deposits that exist in the New England area of NSW. A presentation on this approach was given by Marcus St. John Dawe at the National CCS Week conference in Melbourne in 2010.[79] The following information was provided publicly at this presentation:

- The process is commercially secret, and two provisional patents on the technology have been lodged.
- The economics is site-specific and the upper Hunter Valley in NSW is the best opportunity in Australia, since serpentine materials are available in the region. However, the process is relevant for all deposits of serpentine globally, which are widespread.

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[76] Hunwick, R., “System, apparatus and method for carbon dioxide sequestration”, Australian Patent AU2008/000232. 2008.

[77] Hunwick, R. (ICS) and Duffy G. (CSIRO Energy Technology), Non-confidential Personal Communication, August 2011, with permission.

[78] Duffy G. (CSIRO Energy Technology), Non-confidential Personal Communication, August 2011, with permisssion.

[79] St. John Dawe, M., “Mineral Carbonation (MC) – A potential large scale solution for carbon storage and utilisation.”, in National CCS Week Conference, 2011. Melbourne. (From notes taken by the Task Force Chair during the presentation at that conference and St. John Dawe M, personal communication 2012 (with permission).

- Most of the carbonated product would be placed back into the mined rock area after processing, with some used to make new building products.
- \$3.04M had been awarded from the NSW Clean Coal Council, and matching funds from the Federal Government have also been approved pending the final contribution from an industry partner of \$3.04M, which is now being sought. This will fund a pilot scale facility at the University at a new adjacent campus at the former BHP Billiton research laboratories.
- A pre-feasibility study has shown that the price of carbon dioxide required to make the mineral carbonation process viable is \$70/t CO_2 including a 25% energy penalty. The aim is to reduce this to \$40/t CO_2, including a 15% energy penalty. This latter target depends on new technology development.
- It is hoped by GreenMag Group that a demonstration scale project (100,000 t/year CO_2) can be developed by 2016 for a cost of \$85M. This could lead to a full scale 2 Mt/year CO_2 commercial plant for a cost of \$1 to \$2 billion by 2020.

The task force has discussed the project further with GreenMag Group and the principal academic researchers at the University of Newcastle as well as inspect the laboratory-scale laboratory facilities at the university, which are excellent. The discussions and further information obtained by the Task Force are commercial-in-confidence. However, an open public report on a design and financial analysis of a proposed unimproved mineral carbonation process has been carried out independently by Rayson *et al.* at the University of Newcastle (2008).[80] The Task Force has utilised this public information to undertake a financial analysis (see Section 5 of this report).

Orica

Orica is a large Australian company and is interested in mineral carbonation from the point of view of supporting a cleaner coal industry and reducing greenhouse gas emissions. Supply of explosives for the rock mining operation is a further motivation. The company is technologically advanced and has significant resources to apply to the problem, including ongoing alliances with the University of Sydney, Columbia University, University of Arizona and CSIRO. Orica has reviewed the information from the USA Albany Research Centre (ARC - mentioned in the literature review above) and believes that the efficiency of this process can be improved at several different levels. Orica has published in the field, including patent applications,[81,82] and has several innovative ideas that could be explored scientifically and in terms of chemical engineering. These include linking various carbon-intensive resource industries such as iron and steel and cement with a mineral carbonation process.

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[80] Rayson, M., M. Magill, R. Sault, G. Ryan and M. Swanson (2008). "Mineral Sequestration of CO_2 - Group 2, Phase 3", Discipline of Chemical Engineering, The University of Newcastle, NSW 2308. Report may be obtained by contacting the Discipline Secretary at the University of Newcastle.

[81] Brent G., "Integrated Chemical Process", Australian Patent Application AU2010100761 B4. Brent G., "Improved Integrated Chemical Process", Australian Patent Application, AU 2010100762 B4. Chizmeshya V.G., Brent G. F., "High temperature treatment of hydrous materials", Australian Patent Application AU 2010101031 A4.

[82] Allen D. J., Brent G.F., "Sequestering CO_2 by Mineral Carbonation: Stability against Acid Rain Exposure", Environ. Sci. Technol., 2010, 44 (7), pp. 2735.

Alcoa

It has been reported that Alcoa at Kwinana in Western Australia has developed a process to utilise the waste product “red mud” from alumina production to sequester pure CO_2 from its own operations[83]. At Kwinana, Alcoa is sequestering 70,000 t CO_2 per year using all the residue “red mud” from the refinery. This amounts to 30t “red mud”/tCO_2, which is about ten times the rate of serpentine rock usage envisaged by the proponents of the other mineral carbonation processes, above. At this rate of usage, about 300,000 tCO_2 per year could be sequestered by Alcoa’s “red mud” waste streams in Australia.

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[83] “Accelerating the Uptake of CCS: Industrial Use of Captured Carbon Dioxide”, Global CCS Institute, March 2011.

3. POTENTIAL SCALE AND CONTRIBUTION TO CO_2 SEQUESTRATION

Storage technologies may be characterised in terms of cost *vs.* cumulative sequestration rate by an 'S" curve as illustrated in Figure 3.1. At low sequestration rates the CO_2 sources that best match a particular technology characteristics will provide storage at low cost. In geological storage terms this could equate to high permeability and porosity sites in close proximity to large sources of concentrated CO_2. However, as the required sequestration rate increases then progressively less attractive options must be accessed. Under these conditions costs will rise, for example for sites with low permeability some distance from CO_2 sources and sources that require separation and compression of the CO_2 prior to sequestration. Ultimately some physical or resource limit will constrain further rate increases; this could occur, for example, when utilisation of all available geological storage sites occurs. In addition to the rate limit there may be some physical constraint on total cumulative sequestration, for example when all geological storage reservoirs are filled.

In practice such limits and trajectories are flexible as evolution of technologies removes practical limits and/or reduces the cost to access such limits to an acceptable level. This study, of necessity, considers only technologies as currently conceived. It should not be taken as defining the ultimate potential for any technology.

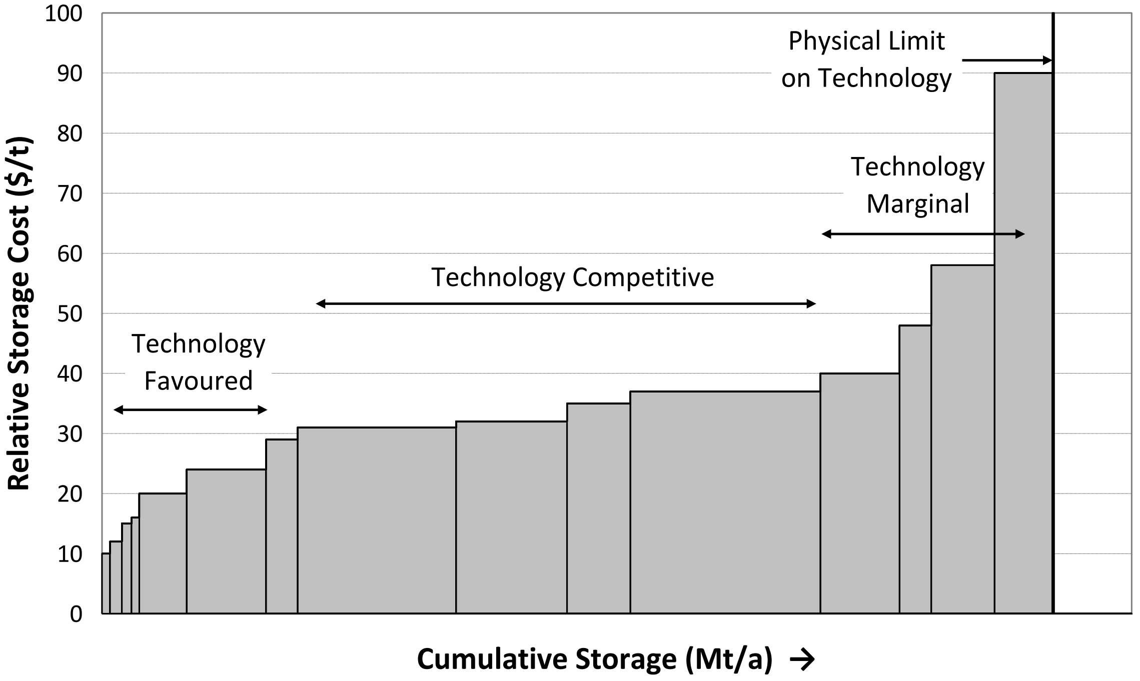

Figure 3.1: Relative storage cost vs. cumulative storage

Australia is unique at various levels in terms of climate, natural resources, built environment and social systems. These factors are likely to provide a constraint on certain technologies due to availability of essential inputs to the process. Alternatively they may also favour certain technologies that exploit opportunities unique to Australia.

This section provides a high level qualitative assessment of the potential of the novel storage technologies to contribute to Australia's GHG reduction targets. A summary of results is presented in Table 3.1 where the following categories of storage are defined:

- *Niche:* Technology may provide viable business opportunity in themselves but sequestration capacity across Australia not expected to exceed 1Mt/a of CO_2 .
- *Small:* Australia-wide storage within the range 1 to 10 Mt/a CO_2 is possible.
- *Medium:* Australia-wide storage within the range 10 to 100 Mt/a CO_2 is possible; storage sink expected to saturate in < 100 years.
- *Large:* Australia-wide storage exceeding 100 Mt/a CO_2 is possible for periods > 100 years; individual projects may process emissions from an industrial facility, for example a large power station or CO_2 hub.

  Recent reviews have considered sequestration potential for certain alternatives in Australia[84,85]. Conclusions from these studies are also discussed below.

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[84] Garnaut R. (2011) "Transforming rural land use" Garnaut Climate Change Review – Update 2011. (http://www.garnautreview.org.au/update-2011/update-papers/up4-transforming-rural-land-use.pdf)

[85] Eady S., Grundy M., Battaglia M and Keating B. (eds) (2009) "An analysis of greenhouse gas mitigation and carbon sequestration opportunities from rural land use" National Research Flagships - Sustainable Agriculture. CSIRO, St Lucia. Qld.

Table 3.1: Indicative Sequestration Potential for Novel Storage Technologies

Bio-sequestration - Algae		
Technology	***Contribution Potential***	***Comments/Limiting Factors***
Direct Flue Gas Feed	Niche/Small	Incompatibility between 24/7 hour industrial cycle and diurnal/seasonal biomass cycle Large land areas (> 100 km^2) required in close proximity to large industrial facilities
CO_2 removed direct from air	Small/Medium	Low areal productivity requiring extensive areas of flat land with access to large volumes of water
Bio-sequestration – Enhancement of Terrestrial Biomass		
Reafforestation	Small/Medium/Large	Limitations on available land Competition from alternative land uses
Bio-sequestration – Exogenous coil carbon		
Biochar	Small/Medium	Limited availability of biochar process feedstock Unknown persistence of biochar from friable feedstock
Mineral carbonation		
Ex-situ	Large	Large reserves of raw minerals Process compatible with industrial/ hub scale operations

3.1 Algae

The primary requirements for the culture of algae are energy in light to drive photosynthesis, CO_2 to combine into biomass, and appropriate temperature, supply of minerals and other nutrients and water to provide a culture medium.

For sequestration of CO_2 the source of light is ultimately the sun while CO_2 may be provided directly from industrial sources or extracted from the air by diffusion across the air/algal culture media interface. Temperature and nutrient availability may in principle be controlled as required. Water may be a specific constraint in certain Australian locations.

The solar aperture (area exposed to sunlight) of an algal facility will, in the absence of other limits, determine the amount of CO_2 that may be captured. To capture CO_2 in quantities relevant to large coal fired power plants requires an aperture of some hundreds of square kilometres and for cost reasons this dictates a need for systems based on open pond culture. With open pond culture water, temperature and CO_2 supply can also produce a significant practical constraint.

High productivity algal ponds require enrichment of the culture media by CO_2. In the context of industrial sequestration this requires either the separation of CO_2 from the process or the moving of flue gas to the algal facility. In the former case the algal facility may be separated from the industrial facility by distance if the CO_2 is compressed and piped. In the latter case it is not practicable to duct flue gases for long distances due to the large volumes involved and therefore the algal facility must be located within close proximity to the industrial facility.

Large point sources of CO_2 emission in Australia are related to power generation and industrial facilities and are located primarily along the east coast, with smaller nodes near Perth in WA and at natural gas facilities in the Pilbarra and Kimberley regions of WA[86]. Most of these locations have either topography that is not conducive to the construction of large arrays of shallow ponds or competing land use with high land costs. Significant areas of low topography exist within the interior of the continent and it is technically feasible to pipe CO_2 to these locations. However, high evaporation rates at these locations would constrain the deployment of algal pond systems. Further low overnight and winter temperatures will severely constrain production in many southern and inland sites.

The use of concentrating solar collectors could potentially reduce the surface area of algal media required, but not the solar aperture. Further, algae species are subject to photo-inhibition at light intensities well below that of normal full sunlight, means of transmitting the concentrated sunlight to the algal reactors and of dispersing it through the media would be required to overcome this effect.

Algal ponds cannot assimilate CO_2 from flue gas during periods where there is no sunlight. As power generators and other industrial plants operate on a 24/7 basis the maximum fraction of emitted CO_2 that can be sequestered is limited to that emitted during daylight hours. This will reduce collection to around 25% of that emitted.

Garnaut (2011) suggests a possible reduction in Australian emissions of up to 44 Mt/a CO_2 per annum by replacement of all fossil fuel diesel with biodiesel, to be produced from more than 550,000 ha of pond area across Australia. Eady *et al*. (2009) considered availability of suitable land

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[86] Carbon Storage Taskforce (2009), National Carbon Mapping and Infrastructure Plan – Australia: Full Report, Department of Resources, Energy and Tourism, Canberra

in proximity of point emission sources. It was estimated that Queensland would have 34,000 ha of land available to produce up to 750 Ml of bio-diesel per annum. On this basis around 0.5 Mt/a of carbon (equivalent to 1.8 Mt/a CO_2) would be captured in the bio-diesel with an additional amount of a similar order contained in the residual algal matter.

The difference between the two studies appears to relate primarily to the different area assumed (Australia-wide *vs.* Queensland only) however the basis for calculation on land area by Garnaut (2011) is not given. Since most NSW and Victorian power stations and heavy industries are constructed in urban or farming communities it seems likely that the algal farm area assumed in Garnaut (2011) is optimistic. It is noted that Campbell *et al.* (2009)[87] point to the difficulty in matching suitable land to CO_2 sources and identify Queensland, the Burrup peninsula and Whyalla as potential sites. However, none of these sites was considered suitable for a facility larger than 400 ha, highlighting the siting issues. Eady *et al.* (2009) do suggest that certain inland power stations may be paired with algal farms if sufficient land area and waste water streams from coal seam gas extraction can be demonstrated.

However, neither Garnaut (2011) nor Eady *et al.* (2009) specifically address the issues of integration of industrial plants and algal farms, in particular the low capacity factor for collection of CO_2 and the technical, environmental and economic factors of processing flue gas through widely dispersed ground level systems as discussed in Appendix C. Further, Eady *et al.* (2009) adopt the productivity data used by Campbell *et al*. (2009). That paper cautions the assumed productivity values are optimistic and that the technology does not necessarily scale well.

Algal biomass constitutes sequestration only in so far as fossil fuel consumption is displaced through bio-diesel use, displacement of electricity or the production of char from the algae. It can be argued that production of biodiesel merely defers the ultimate extraction of fossil oil and therefore, in the context of addressing the CO_2 emissions from coal fired power stations, only the production and storage of char from algae would be considered. It is therefore considered that algae constitutes a *niche* to *small* potential for sequestration of CO_2.

3.2 Biochar

Potential existing biochar source materials in Australia include residues from forestry, plantations and agriculture plus various organic waste streams and biomass from dedicated production operations[88,89]. In general, these resources are widely dispersed and can have a range of alternative uses including feed for livestock, management of pasture and crop soil conditions such as structure, fertility and water retention, composting for garden product manufacture, renewable energy generation and others. The quantity available for production of biochar is therefore expected to be only some part of the total biomass available.

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[87] Campbell P.K., Beer T. and Batten D. (2009) "Greenhouse gas sequestration by algae – energy and greenhouse gas life cycle studies" Proceedings of the 6th Australian Life Cycle Assessment Conference, Melbourne.

[88] Geoscience Australia and ABARE (2010) "Australian Energy Resource Assessment", Commonwealth of Australia. Canberra

[89] O'Connell D., Batten D., O'Connor M., May B., Raison J., Keating B., Beer T., Braid A., Haritos V., Begley C., Poole M., Poulton P., Graham S., Dunlop M., Grant T., Campbell P. and Lamb D. (2007) "Biofuels in Australia — issues and prospects" Rural Industries Research and Development Corporation. Publication No. 07/071. Commonwealth of Australia. Canberra.

A summary of these available resources is presented in Table 3.2. These values indicate the quantity that can reasonably be collected and neglects competing uses. In general values included in Table 3.2 are drawn from Geoscience Australia (2010) and O'Connell *et al*. (2007).

Table 3.2 Biochar feedstock material in Australia.

Feedstock		Potential availability in Australia	Comment
Existing materials			
	Grain and sugar crop residue	30 Mt/a	High variability due demand for primary crop and seasonal impacts, competing uses
	Saw logs and pulpwood	14 Mt/a	Existing markets
	Forestry operations residue	9 Mt/a	
	Urban wood waste	1.6 Mt/a	
	Urban wastes (excluding wood)	7.5 Mt/a	High moisture and contaminants
	Annual and perennial grasses	10 – 20 Mt/a	Existing markets
Potential new feedstocks			
	Future mallee – eucalypt crop	2 – 100 Mt/a	New source, potentially all available
	Future hardwood plantation growth	7 – 24 Mt/a	New source, potentially all available

From Table 3.2, the biomass feedstocks that have greatest potential to contribute to carbon sequestration through biochar production appear to be crop residues, wood and forestry residues and future mallee and eucalypt plantings. Urban wastes, saw logs and pulpwood and annual and perennial grasses either have existing markets or contain pollutants that may require containment. Other potential biomass feedstock including macadamia nut shells, cotton trash, rice husks, vine clippings and refuse from animal husbandry[90]. In general these are relatively small in quantity and while certain of these materials are collected at specific locations as an outcome of the farming operations, and may therefore constitute a viable commercial proposition to convert to char, they are not further considered as material here in the context of Australia's GHG reduction targets.

A brief review of potential for biochar production from crop residues is provided in Appendix D. It is calculated there that broadacre crops have a potential to capture some 5 Mt/a of carbon in biochar while sugar cane farming has the potential to capture around 2 – 4 Mt/a of carbon as biochar. This in

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[90] Moghtaderi B., Sheng C. and Wall T. (2006) "An overview of Australian biomass resources and utilisation technologies" Bioresources 1(1): pp93,115.

part is consistent with Eady *et al.* (2009) who estimate a national potential for storage in biochar of organic carbon from sugar cane of 2.5 Mt/a (equivalent to 9 Mt/a CO_2) but who do not consider broadacre farm residue potential.

Appendix D also considers the potential to produce biochar from strip mallee planting across Australia's wheat belt. The mallee plantings were proposed initially to control build-up of soil moisture but were subsequently recognised as potential sources of bioenergy, biochar or specialist chemicals[91]. It is calculated that some 2.9 M ha of mallee (5% of total cropping and improved pasture grazing land in Australia) could be planted which the production of about 4 Mt/a biochar and an additional 1 Mt/a of carbon stored in below ground root mass.

Waste woods and forestry wastes presently amount to around 10 Mt/a. This material is expected to permit storage or around 2.5 Mt/a of organic carbon as biochar (equivalent to 9 Mt/a CO_2).
This suggests that total biochar production from existing farm residue sources and expansion of mallee plantations across southern Australia could capture of the order of 15 Mt/a of carbon (equivalent to some 55 Mt/a CO_2).

However, a major uncertainty for biochar is the residence time of carbon in the soil. The amount of carbon that can be considered sequestered is that amount remaining after a defined period of time. The draft Carbon Farming legislation is presently proposing a nominal time period of 100 years[92]. Preliminary results of research now underway in Australia[93] suggest that a high proportion of high temperature (550 °C) chars produced from wood may persist in soils for periods well in excess of 100 years. However, chars produced from less structured material such as poultry litter decomposes more rapidly. This conclusion is consistent with results of a review of the published literature where chars produced from wood materials are generally found to mineralise to CO_2 more slowly than chars from straw and similar feedstocks (Appendix E). It appears clear that the total 15 Mt/a of char that could be produced from farm residues and mallee plantations could not all be assumed to qualify as sequestered carbon. However the proportion that would qualify could not be determined on the basis of data available to the Task Force.

It is noted that substantial benefits to soil, including an increase in endogenous soil carbon, have been suggested to result from the addition of biochar to farm soils[94]. If these benefits can be quantified for Australian soils, environment and farming practices then additional carbon sequestration amounts may be ascribed to biochar. The potential of this has not been addressed here due to the uncertainty surrounding endogenously generated soil carbon.

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[91] Enecon (2001) "Integrated tree processing of mallee eucalypts" RIRDC Publication No 01/160. Rural Industries Research and Development Corporation. Canberra.

[92] Dept of Climate Change and Energy Efficiency "Carbon farming initiative - Draft Guidelines for Submitting Methodologies. Commonwealth of Australia (http://www.climatechange.gov.au/government/submissions/~/media/publications/carbon-farming-initative/draft-methodology-guidelines-pdf.pdf - accessed 12/7/2011))

[93] Singh B.P., Cowie A.L., Smernik R.J. (2011) A novel 13C natural abundance approach for measuring biochar's stability and priming effect on 'native' soil carbon. In: 11th Australasian Environmental Isotope and 4th Australasian Hydrogeology Research Conference, Cairns, July 12-14.

[94] Sohi S., Elisa Lopez-Capel E., Krull E. and Bol R. (2009) "Biochar, climate change and soil: A review to guide future research" CSIRO Land and Water Science Report 05/09.

3.2 Mineral carbonation

Primary physical requirements for carbon mineralisation include sufficient supply of suitable reactive rock, space to deposit the reacted product, access to CO_2 in a suitable state and appropriate infrastructure including land and water.

Serpentine and similar magnesium silicates have been identified as able to react with and sequester CO_2. Stoichiometry requires that around 2.5 tonnes of rock be consumed per tonne of CO_2 sequestered, depending on the proportion of serpentine in the rock. Davis (2008)[95] has estimate the quantity of serpentine that is potentially available through open cut mining to a depth of 500 m in the Great Serpentine Belt between Bingra and Barraba in northern NSW at around 7×10^{10} tonnes. This is sufficient to sequester over 20 Gt CO_2 in total or 200 Mt/a for 100 years. In addition to this serpentine outcrops are found in a number of other regions of NSW and Queensland (Brent and Petrie (2008))[96].

CO_2 emissions from coal fired power plants in NSW are presently of the order of 70 Mt/a. To sequester this via mineralisation would require the mining, processing and subsequent emplacement of around 180 Mt/a of rock. While these material flows are large, they are within the scope of mining operations carried out at various locations around the world. The coal mining industry in NSW currently produces around 180 Mt/a of raw coal and routinely moves multiples of that in terms of overburden[97].

It is therefore concluded that mineral resource and scale of mining will not constrain carbon mineralisation in NSW. Mineralisation is considered to have large *potential* for CO_2 sequestration.

3.4 Forestry

Forest presently occupies some 150 M ha (19% of Australian land area), with 70% of this area held under leasehold or private tenure and around 2 M ha in forest plantations. The total carbon stored in Australian forests is estimated to exceed 12 000 Mt[98] (12 Gt). Clearly, subject to suitable land area being available, there is significant potential to sequester carbon through increasing forest area. Garnaut (2011) estimates a GHG sequestration opportunity from forestry at 394 Mt/a of CO_2 while Eady *et al.* (2009) estimate a sequestration potential of 853 Mt/a of CO_2. On these numbers the total carbon stored in Australia's forests would be doubled in 110 and 50 years respectively.

While these predictions of sequestration opportunity appear large relative to the existing carbon pool in Australian forests it is clear that a key limitation on achieving this level of sequestration is availability of land, which is strongly dependent on economic circumstances and not further assessed here.

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[95] Davis M. (2008) "The CO_2 sequestration potential of the ultramafic rocks of the Great Serpentinite Belt, New South Wales" Honours Thesis, Dept. of Earth Sciences, University of Newcastle.

[96] Brent G.F. and Petrie J.G. (2008) "CO_2 Sequestration by mineral carbonation in the Australian" Engineers Australia pp 1273-1283

[97] The Australian Coal Industry - Coal Production. The Australian Coal Association (http://www.australiancoal.com.au/the-australian-coal-industry_coal-production.aspx).

[98] ABARES (2011) "Australia's forests at a glance 2011" Commonwealth of Australia Canberra.

4. TECHNOLOGY GAP ANALYSIS

In Australia, several technologies have been proposed for novel CO_2 sequestration. In many cases the details of these proposals are confidential. In this section of the report, the Task Force has therefore undertaken an assessment in generic terms for these proposed technologies in terms of the status of the technologies. A Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis of the technologies is also carried out at the end of this section.

4.1 Technology development cycle assessment of proponent technologies

R&D and technology development in terms of the commercialisation cycle has been considered in detail by Roussel *et al.* (1991) from consulting firm Arthur D. Little.[99] These authors proposed technology development stages from "Embryonic", through "Pacing", to "Key" and finally "Base" in terms of the establishment of competitive advantage for the developer. Since some of the technologies being proposed now in Australia are little more than concepts, the Task Force has also proposed the additional term "Conceptual" for the development stage earlier than "Embryonic".

Simplified explanations of each of these technology development stages are:

Conceptual technology: The technology is still at the idea stage, supported by some order-of-magnitude calculations and flowcharting.

Embryonic technology: The development is early in the technology life cycle but there is some scientific study – probably at the stage of the gathering of scientific data or in university studies. The technology shows some promise, but there is more scientific work to be done to validate the idea.

Pacing technology: The technology already has the potential to radically change the whole basis of competitiveness and become "Key". There is strong potential for valuable IP rights. The technology is probably at advanced pilot scale or demonstration scale.

Key technology: The technology is developed, but not shared, and provides competitive advantage to the owner of the technology now in terms of commercial revenue.

Base technology: Technology that is proven, commercialised and widely shared already.

Table 4.1 gives the Task Force generic assessment of the technology development cycle status of the technologies examined**.**

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[99] Roussel, P.A., K.N. Saad, and T.J. Erickson, Third generation R&D - Managing the link to corporate strategy, Arthur D. Little. 1991, Boston: Harvard Business School Press.

Table 4.1: Technology development Cycle Status for Sequestration of CO_2

Bio-sequestration - Algae

Technology Component	***Status Assessment***	***Comments***
Algae biology studies and algae selection	***Embryonic***	• Experiments on optimum algae types have been undertaken at university at bench and field scales. • Different types of photo bioreactors have been developed and trialled.
Algae growth rates in bioreactors	***Embryonic***	• Bench and pilot (field) scale studies on growth rates of algae in open pond and photo bioreactors are being undertaken.
Scale-up pilot demonstration facilities	***Embryonic***	• Demonstration scale studies are being planned (80 ha scale, 100t/day algae).
Large-scale demonstration	***Conceptual***	• No large-scale (>1000 Ha) demonstration undertaken yet. • Expected scale = 1 Mt/year CO_2
Extraction of algal-oil from algae product	***Base***	• Demonstrated in the literature - many oil extraction technologies are available

Bio-sequestration - Biochar and Soil Carbon

Technology Component	***Status Assessment***	***Comments***
Production of biochar from biomass and simultaneous production of clean high CO/H_2 gas for power generation or chemicals synthesis.	***Embryonic*** ***Pacing***	• Small scale (100 - 1000 kg/h) demonstrated for a variety of high moisture biomass feeds. • 1 MW (1 t/h) systems being constructed and commercialised in agriculture and at a power station.
Biochar and oils production from lignites or biomass using supercritical fluids	***Embryonic***	• Pilot facility in operation over 2 years. • Demonstration plant (20,000 t/year as-mined lignite) being planned.
Use of lignite and humic/fulvic extracts (blended with trace minerals and biology as a fertilizer system) as an exogenous addition to soil to increase endogenous soil carbon	***Pacing***	• Anecdotal evidence, but few scientific results obtained on soil carbon permanence or leverage effect associated with endogenous carbon increase. • Some evidence from farming productivity increases due to soil carbon enhancement • Scientific studies being undertaken on humic materials in soils and CSIRO soils testing to verify soil carbon increases and analyse the biological farming system benefits. • Biological Farming System (BFS) involves 400 farmers on around 300,000 ha

Technology Component	***Status Assessment***	***Comments***
Growing of timber forests or mallee eucalypts to sequester CO_2	***Base***	• *Case 1:* 450 forests in multiple Australian states; 6.8 million trees planted since 1997. • *Case 2:* Large-scale tree plantings have been successfully established and managed in NSW, Victoria and Western Australia, totally some 22,000 ha of mallee eucalypts and 3,500 ha of native bush.

Mineral Carbonation

Technology Component	***Status Assessment***	***Comments***
Integrated process aimed at ammonia solvent recycle process for the carbonation of serpentine minerals	***Embryonic***	• Experiments undertaken to demonstrate the process chemistry. • Experimental test work studying the effects of temperature and pressure undertaken. • Flowcharts developed, supported by mass and energy balance calculations and process modelling (ASPEN[100]). • Patent applications granted.
Process based on activation of magnesium containing serpentine rocks	***Embryonic***	• University studies and laboratory tests undertaken in USA and Australia. Activation verified experimentally. • Mass and energy balance process modelling undertaken including CO_2 and energy efficiencies (ASPEN). • Process flowsheeting and full-scale plant design concepts undertaken. • Cost calculations reported. • Carbonate product stability studied and published. • Patent applications granted.
Precipitation of carbonates from alkaline brines containing calcium and magnesium ions	***Embryonic***	• Chemistry proven at pilot scale • Pilot electrolytic process developed for producing NaOH and HCl. • Flue gas captured using NaOH in USA (10 MW facility).

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[100] ASPEN – a comprehensive proprietary process modelling software: http://www.aspentech.com/core/aspen-plus.aspx

4.2 SWOT Analysis

Algal Bio-sequestration

Strengths

- Perceived high community support.
- No fresh water requirement if marine species are used.
- Utilizes solar energy.
- Potentially wide range of value-added products.
- Potentially highly scalable.
- Well-developed compared with other novel processes, with a large international research base.
- Capture processes could be less costly than alternative technologies (no need for CO_2 capture and concentration).
- The science of algal biology is well known and there are a very large number of algal species.
- Algae best with concentrated CO_2 source (located at bio-digesters, fermentation facilities, etc.).

Weaknesses

- No demonstration yet of algae growth on coal fired flue gas in Australia.
- Lack of real carbon sequestration data at commercial scale.
- Potentially high process energy and nutrient requirements (and costs).
- Potentially a very large land area required.
- High resource input requirements (including nutrients and water).
- Technology has not been assessed for environmental, economic and social sustainability.
- Some algal storage options require permanence validation.
- Potential for total CO_2 capture small due to low "CO_2 capacity factor".
- CO_2 capture efficiencies and gas separation technologies not yet developed or costed.
- Economics highly dependent on productivity and bio-oil price

Opportunities

- May produce a wide range of hydrocarbon, petrochemical and animal feed product alternatives and options.
- May provide feedstock for coal-algae-water fuel mixtures.
- May produce important value-added chemical products.
- Can treat wastewater in concert with carbon sequestration through integration.
- Low energy bioreactor design may reduce cost and installed size.
- May use saline/brackish groundwater.
- Potential for ambient pressure CO_2 capture technology to develop out of this technology.
- GM technologies may provide specialist algae with desirable properties.
- Australia may have some unique species of algae suitable for bio-sequestration and bio-production.

Threats

- Public concern over potential genetically modified (GM) strains.
- Public concern over large land use.
- Water usage could be high, coupled with public concerns about water availability.
- Increasing land cost coupled with large size requirements.
- Carbon tax or trading regimes or subsidies may be inadequate.
- Lack of infrastructure development and skilled labour.
- Time to develop at the necessary scale may preclude the technology.
- Changes in the markets for by-products or high by-product cost could affect business viability.
- Algae dewatering could be cost prohibitive.
- Growing trees could be just as cost and LCA effective.
- Lean flue gas CO_2 concentrations may prove too inefficient for PCC.
- Other new renewable technologies for energy generation may be more competitive in terms of costs.

Soil Carbon Bio-sequestration

Strengths

- Could be beneficial for agricultural industry in improved soil quality and carbon content and hence farming efficiency.
- Substantial community support probable.
- Biomass growing and coppice harvesting has been practiced at large scale before overseas (e.g. Brazil).
- Potentially large-scale carbon sequestration

Weaknesses

- Very wide distributed infrastructure could lead to high costs.
- There is currently no cost-effective method for reliable long-term soil carbon measurement, considering the temporal and spatial variability of different sites.
- Carbon permanence in soils over time is in question.
- Process costs associated with biomass growing and pyrolysis could be high (land/water/nutrients/transportation).
- The technology has not been assessed for environmental, economic and social sustainability.
- Land competition for biochar with food resources (land/water/nutrients) at scale could increase food prices.
- Estimates for soil carbon storage potential are widely variable.
- Groundwater supplies could be depleted through growing biomass.

Opportunities

- Revitalising agricultural and forest soils will have numerous consequent benefits, including economic and ecological.
- Improved land management may offer further potential to make use of the carbon cycle for products rather than sequestering carbon permanently.
- May improve agricultural land salinity through lowering of the water table.
- Farming could adopt a portfolio approach with some growing of biomass amongst food crops.
- Sustainable chemical and fuel by-products associated with biomass pyrolysis could be valuable.
- High intensity biomass harvesting methods could be developed, leading to a new industry.

Threats

- Would not be a viable option for quantifiable carbon sequestration without a cost-effective method for soil carbon measurement.
- High fuel costs transporting biomass may impact on industry economics and on LCA for carbon.
- Long-term storage appears highly dependent on changes in weather, climate, soil type and land use.
- The capacity for processing biomass and the supply chain for biochar production at necessary scale may rule soil carbon ineffective.
- A carbon LCA balance analysis has not been attempted at full scale deployment and this may rule out soil carbon storage in terms of inefficiencies.
- Tree growing may be more cost and LCA effective for CO2 sequestration.
- Other new renewable technologies for energy generation may be more

Mineral Sequestration

Strengths

- Carbonation products provide very stable long-term storage sinks.
- The theoretical abundance of ore (serpentinite) is large.
- Australia has mining expertise.
- Many of the necessary operations have already been developed for the mining and minerals processing industry.

Weaknesses

- Some ore reserves may be difficult to mine.
- Some processes have high costs.
- There are very large feedstock tonnage requirements.
- There is a very large amount of waste product that requires a suitable storage location or very large by-product market.
- The natural reaction rates are slow and process intensification may be required.
- Some feedstocks (e.g. Mg brines) are in short supply.
- The technology has not been assessed for environmental, economic and social sustainability.
- Some resource feedstocks have unfavourable trace elements (e.g. asbestos)
- Some processes require capture and concentration of CO_2 from flue gas

Opportunities

- Some valuable by-products may be developed (high quality calcium carbonate, building materials etc.)
- Improvements and process integration and innovation may lead to lower costs.
- This non-biological process may offer more capacity for scale-up and process intensification
- The may be niche markets for treating industrial waste (steel slag, red mud etc.)
- There may be niche markets for products (limestone for FGD process)

Threats

- Undesirable emissions may lose community support (e.g. asbestos).
- There may be no social “licence-to-operate” for mining of large tonnages of raw materials.
- Real reaction rates may not increase to the level required for viable large-scale operation, even with intensification with catalysts/additives and application of pressure/temperature.
- Cost of additive recovery may be excessive.
- Pre- and post- processing costs may be excessive.
- Time to develop the technology at the necessary scale may be too long.
- Small local Australian markets for large tonnages of by-products could limit the applicability of the technology.
- Other new renewable technologies for energy generation may be more competitive in terms of costs.
- Carbonate waste may prove to be difficult (e.g. dewatering, disposal)

5. FINANCIAL ANALYSIS

In this section the concept of “bankability” is explored and a financial analysis of the novel technologies is undertaken for those technologies where the data was in the public domain.

5.1 The Concept of “bankability”

Prospective new technology development in the “green environmental” or “sustainability” field needs to be funded in order to progress to commercialisation. There are several stages of this funding as the idea progresses from the laboratory to full scale. Theses stages are characterised as:

1. The desktop development of a concept or idea.
2. Embryonic studies to investigate and validate the science of the idea and demonstrating the concept at laboratory scale, usually funded by government,
3. The first technology studies taking the development out of the laboratory to pilot or demonstration scale, often funded by venture capital suppliers,
4. “First-of-a-Kind” (FOAK) full scale plant operating commercially, often funded by commercial banks in partnership with equity participants, OEMs and potentially governments.

The task force discussed the philosophy of this financing trajectory with several venture capital fund managers and banking institutions. One viewpoint from these discussions was the concept of the “**Twin Valleys of Death**” in financing a new technology project.[101] This concept is shown diagrammatically in Figure 5.1, where the financing requirement is plotted as a function of time.

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[101] Turacek J., Investment Manager, Cleantech Ventures, Personal Communication, Melbourne, 2011.

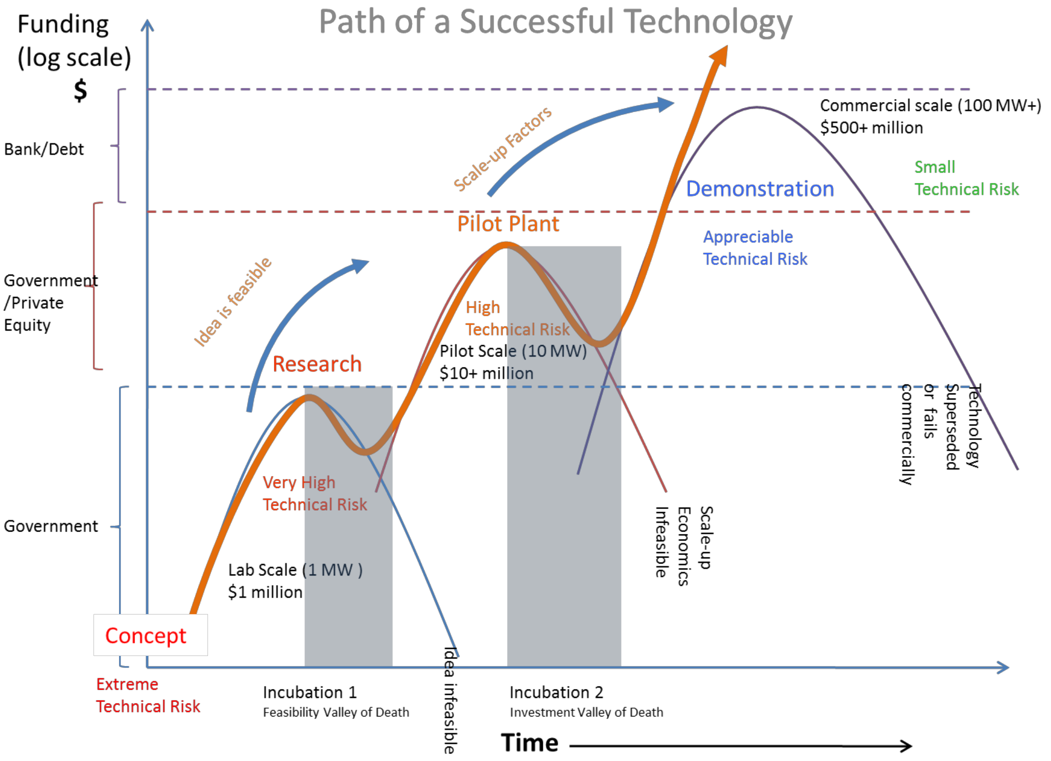

Figure 5.1: Financing requirement of new technologies as a function of time showing the "twin valleys of death" in blue. The orange trajectory shows a commercially successful technology, while the trajectories for unsuccessful technologies are shown to turn over in terms of funding as they fail to traverse the two "valleys of death". (Diagram drawn by the task force from discussions with financing organisations).

The "Twin Valleys of Death" trajectory shown in Figure 5.1 is brought about by two different funding philosophies. The first "Valley of Death", following the initial scientific studies, is the hurdle associated with the technology proponent convincing the venture capital suppliers of technical viability and market potential of the technology. The second "Valley of Death", after the technology has been demonstrated, is the hurdle associated with convincing commercial funding organisations of the marketability and commercial viability of the technology. Overcoming the second "Valley of Death" is what leads to "Bankability".

The risk appetite of the funding institutions is different for each of the "Valleys of Death". In the first "valley", a venture capital firm is funding the development with private equity, not debt. The venture capital firm is interested in (say) quadrupling its equity in a short time period (say 5 years) through investment in the technology IP, representing a return of approximately 30% per year. This is commensurate with the technology risk associated with going from the laboratory to the pilot plant. To achieve this return, the venture capital firm will have a strategy to monetise the increased value of equity in the IP and hardware of the technology if the pilot demonstration is successful. For this reason, a venture capital firm will be very selective in funding only those projects where an acceptable risk-adjusted chance of success can be demonstrated.

The second "Valley of Death" relates to debt funding by commercial banks for commercialisation of the technology. In this case there is a requirement of low risk by the banks, since the rate of return on debt is lower than the return on equity expected by the venture capital firms. By the time the larger bank funding is requested, most technology and product market risk associated with the project must be identified and addressed by the previous technology demonstration in order to yield an appropriate risk-reward balance for the providers of commercial bank credit.

To achieve “Bankability” by a certain date, a novel CO_2 capture technology project will need to traverse the “Twin Valleys of Death” shown in Figure 5.1. This means that business and R&D plans aimed at financial risk reduction must be in place prior to the first “valley”, and most technology and market risk must be quantifiable and minimised before debt funding by the banks for “first-of-a-kind” commercialisation can be provided. As shown in Section 4 above, most of the novel technologies are still prior to the first “valley of death” and embryonic in nature.

5.2 Financial model development

The task force financial model calculation is based on a free cash flow analysis[102]. Free Cash Flow (FCF) for a given year is defined as follows:

EBITDA = Revenues – Costs (5.1)

EBIT = EBITDA – depreciation (5.2)

Free Cash Flow = EBIT (1-tax rate) + depreciation – capital investment[i] (5.3)

The NPV is calculated by the summation of all annual free cash flows discounted at the cost of capital of the company, taken at the end of the year in question. The after-tax cost of capital for the investor is given by:

WACC = [D (cost of debt) (1-tax rate) +E (cost of equity)]/(D+E) (5.4)

where D and E denote proportion of debt and equity funding respectively.

Interest payments and payments to equity investors are accounted for by discounting the FCFs at the above WACC, which includes the after-tax cost of debt and the cost of equity.

Revenues for a novel carbon capture technology include both the price received for the CO_2 processed by the facility and the value of any by-products produced and sold. Costs for the technology include any CO_2 liberated to the atmosphere due to capture inefficiencies and energy used in the plant (at the prevailing carbon dioxide price) plus the variable and operating costs of the facility. Capital investment is handled in the calculation by allowing negative free cash flows in terms of overnight capital costs prior to commencement of operation of the facility in eq. (5.3) when EBIT and depreciation are zero.

There are a number of ways that the novel carbon dioxide capture technologies may be analysed financially:

1. Determine the internal rate of return of an investment, given a carbon dioxide price and values for by-products and required capital investment.
2. Determine the carbon dioxide price necessary to achieve a zero NPV, given a cost of capital, values for by-products and the required capital investment. This parameter is termed here the “Price of CO_2 Required”.
3. Determine the “option value” of the technology, given a cost of capital, carbon dioxide price trajectory, values for by-products and the required capital expenditure by calculating an NPV probability distribution for the investment.

The **Internal Rate of Return (IRR)** of the investment is the value of the free cash flow discount rate that gives a zero NPV. This parameter can be calculated iteratively by adjusting the discount rate.

The “**Price of CO_2 Required”** is the CO_2 price over the life of the investment that must be received to just achieve the cost of capital of the company. Again, this parameter can be

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[102] Higgins R C, “Analysis for Financial Management”, 6th Edition, Irwin McGraw-Hill, Boston, 2001, pp 326.

calculated iteratively to achieve zero NPV for a fixed set of input parameters, including the weighted average cost of capital. This calculation is more stable numerically than the IRR calculation.

An **"Option Value"** can be determined from the distribution of NPV calculated from a probabilistic analysis of the input variables. The NPV distribution in this calculation has a range of values, possibly including negative values. The option value is the proportion of the NPV distribution greater than zero in the investment year, the rationale being that an investor would not invest when the time comes to commercialise if the NPV is less than zero. This approach is a type of "value-at-risk" analysis, where the value at risk (or probability of earning less than the cost of capital) is that proportion of the NPV distribution less than zero, while the "option value" is that part of the future NPV distribution greater than zero, discounted to today's value at the cost of capital. The higher the "option value", the higher the likelihood that the future investment will achieve a return that exceeds the cost of capital. This approach has recently been used by the Australian Academy of Technological Sciences and Engineering (ATSE) to analyse low carbon new technologies for electrical power generation.[103]

Many of the parameters in the technologies under consideration are very uncertain. It is for this reason that the task force has elected to undertake a probabilistic financial analysis. Moreover, it has been found that for the technologies under consideration the internal rate of return is often negative, depending on the input parameters assumed. An iterative calculation of a negative IRR is difficult and unstable, since the cash flows are no longer discounted into the future, but increased over time. For this reason, IRR has not been used in the analysis presented here. However, results are presented for "Price of CO_2 Required" and "Net Present Option Value (NPOV)" in those cases where there is sufficient published data for the calculation to be made.

5.2 National Energy Technology Laboratories (NETL/DOE) Cost Estimation Methodology

The investment costs for a new project are required in order to undertake a financial analysis. Project cost estimates may be derived either by extrapolation from past experience with similar plant, or by a cost build-up from the individual facility components. With novel technologies there is usually little previous experience and therefore cost build-ups are necessary. In such cases, process flow sheets and their supporting engineering deliverables are used to identify the major components of the project and to develop cost estimates for them. However, there are numerous costs additional to those of the basic equipment that will be incurred in delivering a large-scale project. It is important that consistent allowance be made for these across technologies in order that a true comparison may be made.

Davies[104] has noted that experience shows that cost information taken from the literature or from project proponent estimates for new technologies is likely to materially <u>underestimate</u>

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[103] "Low-carbon Energy: Evaluation of New Energy Technology Choices for Electric Power generation in Australia, Australian Academy of Technological Sciences and Engineering, Nov. 2010. http://www.atse.org.au/resource-centre/ATSE-Reports/Energy/

[104] Davies M., Rio Tinto Plc UK, Review comments to the task force, October, 2011.

the costs and therefore overstate how attractive the technologies are. Davies cites the current high cost estimates for carbon capture technologies associated with geological carbon capture and storage as an example. Experience in the mining and mineral processing industry has also shown that significant capital cost escalation relative to initial estimates is the norm rather than the exception. For this reason, the task force has adopted the cost estimation process given by the USA Department of Energy (DoE) for new energy technologies to provide contingencies on the literature cost values obtained. It is recognised by the task force that, especially for large-scale mineral processing developments, that these costs may still err on the low side. Also, in this study, the task force has not taken any cost estimates for its analysis that are unpublished and not freely available in the literature.

A number of organisations have developed standard cost estimating methodologies. The approach recommended by the US DOE National Energy Technology Lab (NETL)[105], and briefly described below, has been used by the Task Force in verifying and updating costs for the alternative technologies under consideration.

The NETL approach is based on the cost build up method. The costs estimated for the process equipment components, with contingency applied as appropriate to the level of development of that component technology, are summed to give a Bare Erected Cost (BEC). Additional costs, fees and contingencies that are a normal part of delivery of a large engineering project are then added to arrive at a Total Overnight Cost (TOC). TOC is the total cost, excluding escalation and interest during construction, expressed in base date dollars.

The components that contribute to project costs are illustrated in Table 5.1. Allowances for additional fees, costs and contingencies are based on industry experience and are discussed in further detail below and in Appendix F.

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[105] National Energy Technology Laboratory. (2010) “Cost estimation methodology for NETL assessments of power plant performance” US Department of Energy DOE/NETL -2011/1455. (http://www.netl.doe.gov/energy-analyses/pubs/QGESSNETLCostEstMethod.pdf)

Table 5.1: Capital cost levels and cost components

<table>
<tr><td>Process Equipment
Supporting facilities
Direct and indirect labour</td><td>Bare Erected Cost (BEC)</td><td rowspan="2">Total Plant Cost (TPC)</td><td rowspan="3">Total Overnight Cost (TOC)</td><td rowspan="4">Total As Spent Cost (TASC)</td></tr>
<tr><td colspan="2">EPC Contractor services
Process contingency
Project contingency</td></tr>
<tr><td colspan="3">Start-up costs
Inventory capital
Financing costs
Owner development costs</td></tr>
<tr><td colspan="4">Escalation during capital expenditure period
Interest on debt during capital expenditure period</td></tr>
</table>

EPC Contractor services: estimated by NETL at 8 to 10 % of BEC and taken by the task force to be 10% of BEC.

Process Contingency: This is applied to each plant section based on the current development status of that component technology. It is intended to compensate for uncertainties in line with the development status of that technology. NETL provide the guidelines given in Table 5.2.

Table 5.2: Process Contingency Allowances

Component technology status	Component Contingency
New concept with limited data	+ 40% of associated capital
Concept with bench scale data	30 - 70% of associated capital
Small pilot plant data	25 - 35% of associated capital
Full size modules previously operated	5 - 20% of associated capital
Process used commercially	0 -10% of associated capital

Table 5.2 is adopted by NETL from American Association of Cost Engineers International Recommended Practice No. 16R-90: Conducting technical and economic evaluations as applied for the process and utility industries.

Since most of the technologies here are in the “concept” or “bench-scale data” phase, the process contingencies have generally been taken as 30 or 40% in this study, except for standard construction items that were taken as 15%. Details of the exact contingencies applied may be found in the Appendix F.

Project Contingency: estimated at 15 – 30% of (BEC + EPC fees + process contingency) and taken by the task force at 15%.

Start-up costs: estimated on inputs necessary to bring plant into operation including:

- 6 months operating labour for training,
- 1 month maintenance materials,
- 1 month non fuel consumables and waste disposal at full load,
- 25% of 1 month fuel costs,
- 2% of TPC.

Inventory Capital: estimated on inventory normally carried by a commercially operating plant including:

- Spare parts at 0.5% TPC,
- 60 days non-fuel consumables ,
- 60 days fuel (if not gas).

Land Costs: are incorporated into the capital costs in the task force analysis.

Financing Cost: estimated at 2.7% of TPC and includes cost of securing finance including fees and closing costs,

Other Owners Costs: estimated at 15% of TPC. This allowance includes:

- Preliminary feasibility and FEED studies,
- Legal and permitting fees,
- Associated works required outside plant boundary, e.g. access road/rail modifications,
- Owners engineer costs,
- Owners contingency for start-up delay, variation in equipment costs, unexpected labour costs.

The total overnight costs (TOC) in this analysis were therefore given by:

TPC = BEC + Process Contingency + EPC Contractor Services + Project Contingency

TOC = TPC + Start-up costs + Inventory Capital + Financing Costs + Owners' Costs

Analysis Methodology

The task force analysis assumes the investment decision will be made in 2020. The bare erection costs (BEC) were determined for each of the technologies from the published literature and the costs adjusted for 2011 dollars using the CPI.[106] The BEC data were then adjusted for contingencies according to the above NETL method. Appropriate economic factors (tax rates, depreciation rates, construction schedules, etc.) were employed, as given in Appendix F, to determine the free cash flows each year over the life of the facility. A real weighted average cost of capital (WACC) of 10% was assumed for the calculations. Investment was assumed to occur in 2020, with starting gas, electricity and CO_2 prices adjusted in real terms to that year. Since the technologies are still relatively embryonic, no technology learning was assumed by 2020 in terms of lower costs in 2020 compared with 2011, i.e. no change in cost of technology in real terms between 2011 and 2020.

Credits for Carbon Dioxide and Other Input Prices

Each of the technologies were assumed be able to claim a CO_2 credit under a carbon-pricing regime for the net emissions from the process that are either permanently stored or converted to energy values that replace fossil fuels. Any CO_2 emissions due to inefficiencies in capture or energy consumed by the process were calculated as a cost at this CO_2 price. Where CO_2 is from an associated industrial facility an efficiency of 90% was assumed in terms of CO_2 used as a fraction of the input CO_2 accepted.

In the case of the calculation of *"Price of CO_2 Required",* the constant CO_2 price required to earn the 10% weighted average cost of capital (i.e. zero NPV) was determined. Algal-oil and all other by-product prices were assumed in 2020 as the same as 2011 in real terms, while the constant natural gas and electricity prices were assumed to be the price in 2020 from the AEMO scenario analysis[107] and recent carbon price Treasury modelling[108], respectively.

Confidential and unpublished information not included

The task force has only used input data for the financial calculations from freely available information of sufficient detail in the literature. Information of a confidential or unpublished nature that was received by the task force has not been included in the analysis.

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[106] Australian Tax Office: http://www.ato.gov.au/content/1566.htm

[107] Australian Energy Market Operator (AEMO): http://www.aemo.com.au/planning/scenarios.html

[108] Australian Government Treasury: http://www.treasury.gov.au/carbonpricemodelling/content/report.asp

For the "*Net Present Option Value (NPOV)"* calculation the real gas price was escalated at 2% per year real from 2020, the approximate average of the recent Australian Energy Market Operator (AEMO) scenario analyses. The algal oil price was also assumed to escalate at this rate in real terms. The CO_2 price trajectory to 2050 published in a recent Treasury report was assumed, along with the projected linear wholesale electricity price trajectory. This gave a CO_2 price of \$30 real in 2020 escalating at 5% per year to \$130/t CO_2 in 2050 and a wholesale electricity price of \$54/MWh real in 2020 escalating linearly to \$134/MWh in 2050. Further details of these assumptions and the other option value parameters assumed are given in Appendix F. Details on the NPOV option value calculation philosophy and methodology may be found in the 2010 low carbon energy report published by the Australian Academy of Technological Sciences and Engineering (ATSE), while the application of real options theory to investment in a portfolio of new projects is outlined by Luehrman in the Harvard Business Review journal[109,110].

5.3 Price of CO_2 Required

The *"Price of CO_2 Required"* is the value of the CO_2 credits required for the investment in the technology to achieve a return equal to the cost of capital, all other things being equal. The calculated CO_2 price (\$/tCO_2) remains constant in real terms over the life of the facility. This price is adjusted iteratively in the calculation to achieve an NPV of zero at the given cost of capital.

In the case of algae and mineral carbonation technologies the CO_2 credit revenue stream is not the only source of revenue. For algal technologies there are also sources of revenue from production of algal oil and/or methane gas and stockfeed, whereas for mineral carbonation there could be revenue streams from separated iron, nickel and chromium oxide materials. In forestry, the wood could be harvested periodically and sold. Assumptions must be made about these by-products in order to calculate the "Price of CO_2 Required" as the dependent variable.

In this study it has become clear to the taskforce that there is great uncertainty about the financial and process parameters for most of the technologies. This is because the technologies may be characterised as either "conceptual" or "embryonic" at this stage of their development. The "perceived costs" of the technologies, both capital and operating, are no doubt lower than they will eventually become at the time of "First Of A Kind (FOAK)" commercialisation. This is the well-known "Grubb Curve" for technology development.

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[109] Luehrman T, "Investment Opportunities as Real Options: Getting Started with the Numbers", Harvard Business Review, July-Aug, 1998.

[110] Luehrman T, "Investment Opportunities as Real Options: Strategy as a Portfolio of Real Options", Harvard Business Review, Sept-Oct, 1998.

Some of the novel technologies under consideration have sufficient public information to undertake a probabilistic financial analysis as part of this study. These include the growth of algae with CO_2 in power plant flue gas, mineral carbonation based on the unimproved ARC method, and managed growth of forests. However, the state of knowledge of biochar and soil carbon is highly uncertain. As pointed out previously, the permanence level of carbon in soils cannot be adequately assessed for any carbonisation technology as yet and good scientific data on the effects of soil carbon increase on agricultural productivity and therefore revenue streams is not quantitatively available. The economics of biochar pyrolysis at scale from biomass is also uncertain, except in specialised charcoal production. Moreover, agriculture is not included at present in the carbon pricing schemes of the Australian Government. For these reasons, a financial analysis of biochar and soil carbon has not been attempted by the task force.

5.3.1 "Price of CO_2 Required" for Algal Growth using Flue Gas CO_2

Campbell *et al*. (2009)[111] published a financial analysis of an algal growth process using raceway ponds and power station flue gas CO_2 to produce algal oil (bio-oil) and methane. In their work the algal-oil was converted to bio-diesel and the methane was recycled back to the power plant as a fuel. Figure 5.2 shows a schematic diagram of this process. The task force has taken this literature data and analysed it financially in terms of both "Price of CO_2 Required" and Net Present Option Value.

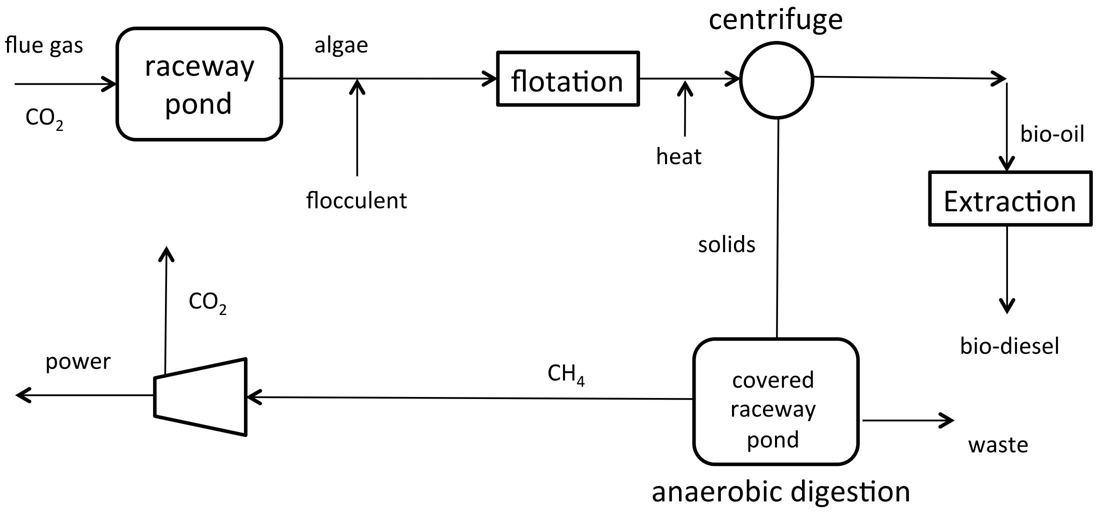

Figure 5.2: Schematic diagram of algae process from Campbell et al. (2009). (Diagram drawn by the task force based on the description in the text of the paper).

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[111] Campbell P K, Beer T, Batten D, "Greenhouse Gas Sequestration by Algae: Energy and Greenhouse Gas Life Cycle Studies", *Sustainability Tools for a New Climate*, Proc. 6th Australian Life Cycle Assessment Conference, Melbourne, Feb 2009.

For the analysis here, it was assumed that the facility would produce a bulk oil product for sales to a petroleum refining operation. This is because the facility processes around 1Mt per year of CO_2 to yield around 240M litres of algal oil (bio-oil), a large operation aimed at bulk commodity products. For the scale-up used in the financial analysis here, a conservative approach whereby the relative cost of land preparation and gas supply and delivery logistics were assumed proportional to the required land area. The weighted average cost of capital (discount rate) was taken as 10%.

In this work, the bare capital cost data from Campbell *et al.* was modified according to the NETL cost estimation process outlined above. The products from the facility were assumed to be algal-oil and methane, and credits for these products formed part of the revenue stream for the facility. Credits for CO_2 in terms of replacement for fossil fuels were also assumed, as were debits for CO_2 release to the atmosphere from inefficiencies and the use of energy for the plant. The iterative calculation of "Price of CO_2 Required" determined the price for these CO_2 credits to achieve a zero NPV over the life of the facility. Operating costs and penalties from waste disposal used the data of Campbell *et al*., which were similar to those reported in the US DOE Algal Species Program report outlined in the literature review of this report[112]. Further details of the costs used in the calculations may be found in Appendix F.

The "Price of CO_2 Required" for algae facilities is a strong function of both the algal productivity and the price of the algal-oil product. These relationships are shown in Figures 5.3 and 5.4, respectively.

Figure 5.3 shows the calculated "Price of CO_2 Required" for an investment in 2020 as a function of the algal productivity in raceway ponds for an algal-oil price of $1.00 per litre ($160/bbl) and a methane price of $5.74/GJ in real (uninflated) 2011 dollars. The natural gas price is taken from the mid-range of a gas price scenario analysis by the Australian Energy Market Operator (AEMO) (2011)[113], while the algal oil price is mid-range between current crude oil[114] and palm oil prices[115].

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[112] Sheehan, J., Dunahay, T., Benemann, J. and Roessler, P., "A look back at the U.S Department of Energy's aquatic species program: biodiesel from algae", National Renewable Energy Laboratory, Report NREL/TP-580-24190, 1988

[113] Australian Energy Market Operator (AEMO): http://www.aemo.com.au/planning/scenarios.html

[114] http://www.oil-price.net/

[115] http://palmoil.com/

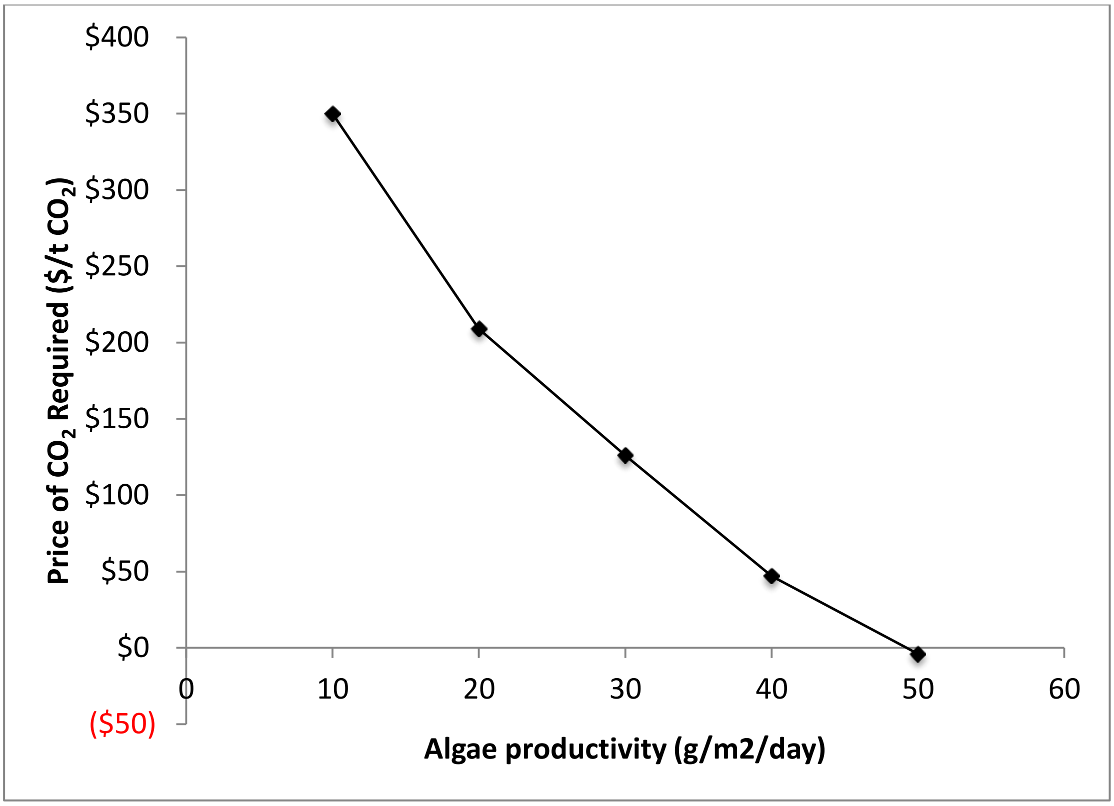

Figure 5.3: Variation of "Price of CO_2 Required" for an algae facility as a function of algae productivity (g/m^2/day)). [Algal oil price is $1.00 per litre ($160/bbl) and natural gas price $5.74/GJ in 2020.]

As can be seen from the figure, "Price of CO_2 Required" is a strong function of algae productivity. As described in the literature review of this report, algal processing costs vary widely as a function of many variables and especially productivity and by-product values. As a result, the parameter "Price of CO_2 Required" is not particularly helpful in the financial analysis of algae capture of CO_2 due to its wide range. The relationship is also strictly speaking only applicable to raceway type algal growth ponds, since other types of photo-bioreactors may be arranged in orientations other than horizontal, making the area term difficult to compare.

Figure 5.4 shows the "Price of CO_2 Required" as a function of the algal-oil price for an algal productivity of 30g/m^2/day, other parameters being the same as Figure 5.3. As can be seen, the "Price of CO_2 Required" is again a strong function of the algal oil price. Given the volatility in global crude oil markets, this means that an investment in a commercial facility to produce algal bio-oil is relatively high risk financially. It is noted that productivities of 30 g/m^2/day are projected to be achievable in the future but are around 50% higher than annual average productivities reported for existing commercial open pond operations.

It is projected by the Australian Government Treasury that CO_2 prices under a global carbon trading scheme will be around $30/t CO_2 in 2020, escalating at 5% per year. As can be seen from the figures, this means that both algal-oil prices and algal productivities will need to be high for a raceway type algal growth project aimed at bulk commodity products and significant CO_2 capture in order to be financially successful in 2020. It is also clear that the economics are driven by the production of algal-oil, not the capture of power station CO_2.

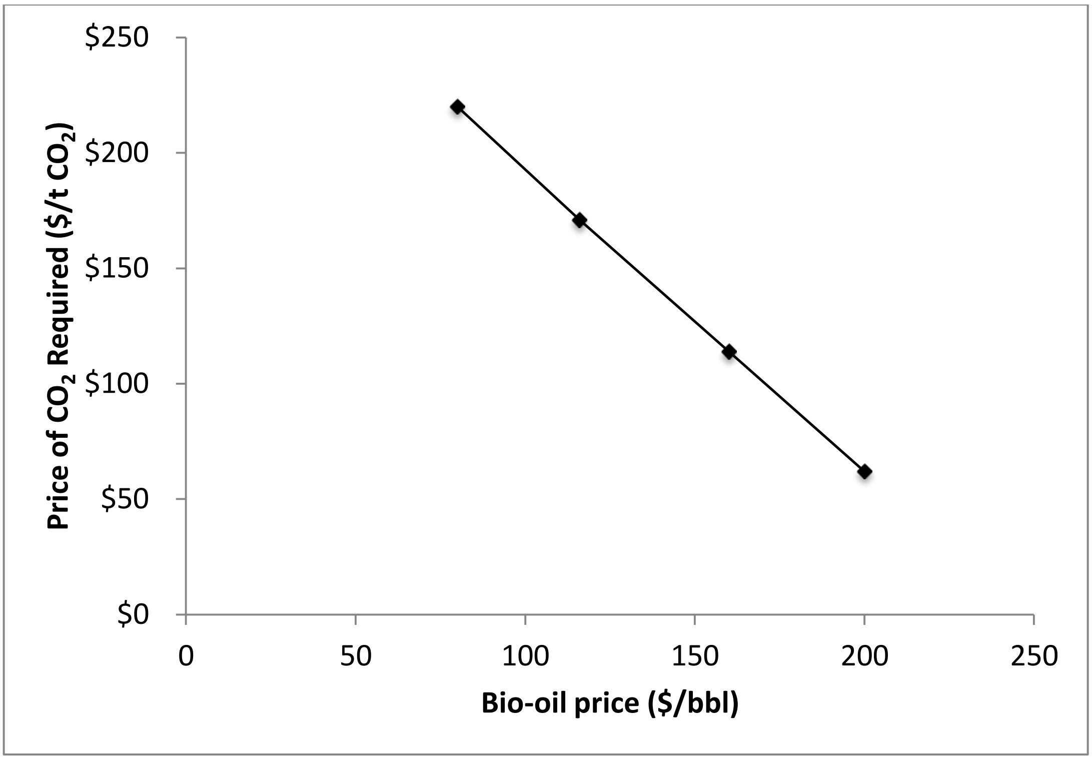

Figure 5.4: Variation of "Price of CO_2 Required" for an algae facility as a function of algal-oil price ($/bbl) [Algae productivity is 30 g/m^2/d and natural gas price $5.74/GJ in 2020.]

By assuming reasonable probability distributions to describe the uncertainty of the input parameters in the financial model, a probability distribution for the "Price of CO_2 Required" was obtained using a Monte Carlo simulation method for the algae processing case above. Details of these input assumptions may be found in Appendix F. It was found that the "Price of CO_2 Required" for the base case for the Campbell *et al.* proposal using the task force model was:

- Price of CO_2 Required = **$126** (range $- 8 to $261, one std. dev.) $/t CO_2 for 10% WACC, 30 g/m^2/d productivity and $1.00/litre ($160/bbl) algal-oil price.

This range in "Price of CO_2 Required" is very large, and is driven by the sensitivity of the investment to algal-oil price and algae productivity probability distributions into the future. These tend to outweigh the potential future CO_2 credits price and will both need to be relatively high to align with a reasonable CO_2 credits price under a carbon-trading scheme.

5.3.2 “Price of CO_2 Required” for a Mineral Carbonation Plant using unimproved ARC Technology

A financial analysis of a large-scale mineral carbonation plant using Albany Research Centre (ARC) technology has been carried out independently by Rayson *et al.* (2008)[116] at the University of Newcastle, NSW and published in a public report. This analysis is reasonably comprehensive and considers both capital and operating costs of a facility to process 11 Mt per year of CO_2 from a power station in the Hunter Valley using 31.5 Mt per year of mined New England serpentine rock and producing 3.465 Mt per year of iron and chromium oxide by-products and 36.5 Mt per year of carbonate waste. Figure 5.5 shows the Rayson *et al.* concept in schematic form, with the information required to draw it taken from the Rayson *et al.* report.

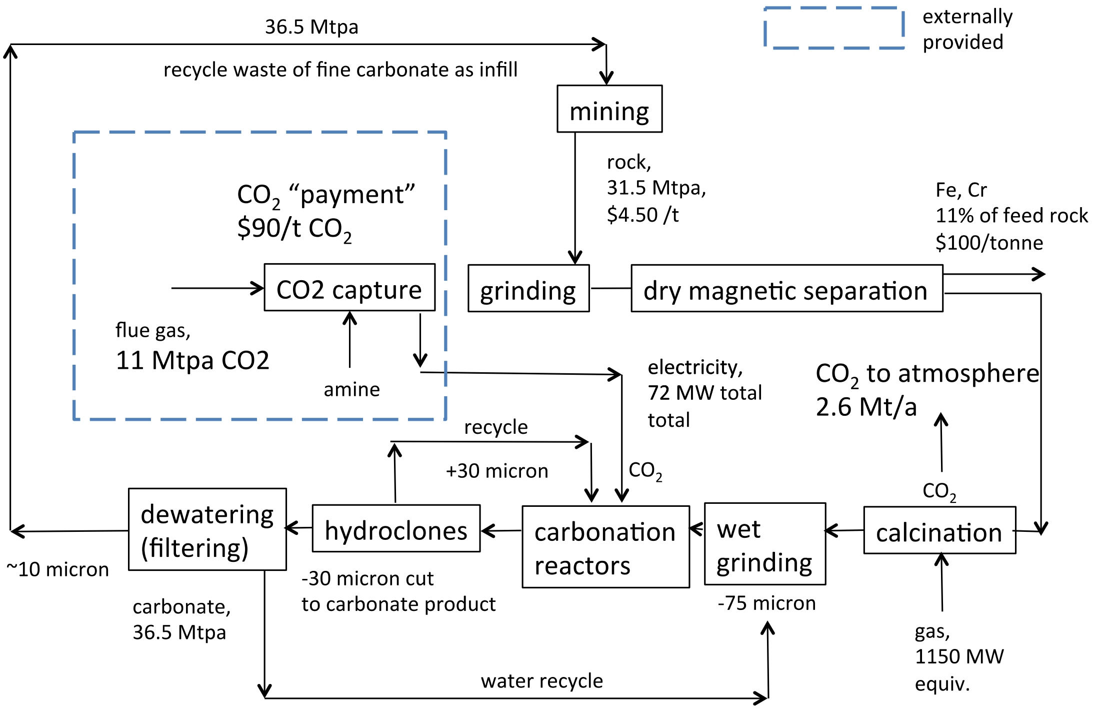

Figure 5.5: Mineral carbonation process proposed by Rayson et al. (2008).). (Diagram drawn by the task force based on the process flowsheet and description in the text of the report)

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[116] Rayson, M., M. Magill, R. Sault, G. Ryan and M. Swanson (2008). “Mineral Sequestration of CO_2 - Group 2, Phase 3”, Discipline of Chemical Engineering, The University of Newcastle, NSW 2308. Report may be obtained by contacting the Discipline Secretary at the University of Newcastle.

The ARC process requires captured pure CO_2 from the power station, so the cost of capture of the CO_2 must be added to the “Price of CO_2 Required” from the facility itself to get the overall “Price of CO_2 Required”. In the Rayson *et al.* report the costs also include the credits from the 11% of iron and chromium oxides extracted at \$100/t and involve a financial calculation that uses a zero discount rate. This gave a minimum “Price of CO_2 Required” of \$70/tCO_2 without the cost of capture of CO_2, or \$160/tCO_2 including the \$90/tCO_2 estimated CO_2 post-combustion capture cost. Rayson *et al.* showed that if a 10% discount rate was used to determine the NPV and a \$90/tCO_2 post-combustion capture charge was added, the effective total “Price of CO_2 Required” was \$200/tCO_2 without further efficiency improvement.

The Rayson *et al*. cost data were adjusted in the present analysis by the task force using the standard NETL method to determine new (higher) capital costs with the NETL contingencies, taking into account the contingencies on some items already assumed by the authors, as outlined in Appendix F. The analysis of “Price of CO_2 Required” was then carried out under the same conditions in terms of CO_2 credits, power prices and cost of capital as the algae example above. However, the cost of CO_2 captured from the flue gases to provide a CO_2 feed to the facility was taken here as \$50/t CO_2 (rather than \$90/t in the Rayson *et al.* report), using updated advice from the CO2CRC[117] and IEA information[118]. Gas and electricity consumption were assumed to be the same as the Rayson *et al*. data, as were the by-product iron and chromium at 11% of the ore mined and \$100/t value. Davies[119] has noted that the cost and development challenges associated with large-scale CO_2 capture should not be underestimated, and the task force notes that the quoted \$50/t CO_2 may be lower than that actually achieved when large-scale CO_2 capture deployment occurs.

By assuming reasonable probability distributions to describe the uncertainty of the input parameters in the financial model, a probability distribution for the “Price of CO_2 Required” was obtained using a Monte Carlo simulation method. Details of these input assumptions may be found in Appendix F. It was found that the “Price of CO_2 Required” for the base case for the Rayson *et al.* proposal (including the costs of CO_2 capture) using the task force model was:

- Price of CO_2 Required = **\$179** (range \$140 to \$217, one std. dev.) \$/t CO_2 for 10% WACC

This compares with the Rayson *et al.* value of ~\$200/t CO_2 for 10% weighted average cost of capital, based on a CO_2 capture cost of \$90/t CO_2. The different (lower) number in this study is essentially due to the \$50/t price for CO_2 capture assumed here and the task force modifications to capital cost due to the NETL methodology. However, at 10% cost of capital the “Price of CO_2 Required” for the mineral carbonation part of the unimproved process would be \$129/tCO_2 (range \$90 to \$167). This compares to the \$70/tCO_2 minimum value reported by Rayson *et al*. for a zero per cent cost of capital, or the \$110/tCO_2 reported by Rayson *et al*. for 10% cost of capital.

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[117] Hooper B, Personal Communication, CO2CRC, August 2011.

[118] “CO_2 Capture and Storage”, IEA Energy Technology Essentials, ETE01, International Energy Agency, 2006.

[119] Davies M., Rio Tinto Plc, Review comments to the task force, October 2011.

The result here shows that mineral carbonation using the unimproved ARC method (as analysed by Rayson *et al*.) will require a relatively high carbon price to be economic at the 10% rate of return level. This agrees with the conclusions of Rayson *et al*. However, as outlined earlier it has been publicly proposed that an effective "Price of CO_2 Required" of \$40/t CO_2 (not including the costs of CO_2 capture from flue gas) can be achieved through further study and improvement of the technology. The task force has financially modelled this case. Our results show that, in order to achieve this, the following (or an equivalent combination) would need to occur, based on the Rayson *et al*. data:

- The rate of financial return (WACC) would need to halve to 5%,
- The capital costs would need to be 50% of Rayson *et al.* and ARC values, and:
- The gas consumption would need to be 50% of the Rayson *et al.* and ARC values.

The task force believes these targets to be very challenging, especially in the light of the current bench-scale scientific information available in the literature on the ARC method.

Hunwick of ICS[120] has proposed a mineral carbonation method based on novel chemistry that integrates CO_2 capture and the carbonation process. The details of this process are commercial-in-confidence. Hunwick has published a "Price of CO_2 Required" for a net 24 Mt CO_2 per year novel facility processing 85-90M tonne per year of serpentine rock[121]. The results from Hunwick's analysis (including 25% estimated contingencies) show a published "Price of CO_2 Required" in the range \$28.50 to \$35/t CO_2. These values are very much lower than the Rayson *et al.* results. This is thought by the task force to be due to the integrated nature of the Hunwick proposal, with CO_2 capture from flue gas part of the process chemistry and no requirement for ore activation by heat. The task force has not verified the capital and operating cost estimates of ICS as part of the present study. The task force believes that the Hunwick ICS proposal should be further analysed independently in terms of an engineering evaluation to fully review the claimed lower capital cost and chemistry claims of the process.

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[120] Hunwick R, "System, apparatus and method for carbon dioxide sequestration", Australian Patent AU 2008217572 B2, 2008.02.20.

[121] Hunwick R., "The ICS Process – Carbon capture and storage by integrated mineralisation", EXPPERTS 2010 Conference, Berlin, September 2010 and Personal Communication to task force, December 2011. (with permission).

5.3.3 "Price of CO_2 Required" for a forestry operation

Hunt (2009)[122] published a financial analysis of a forest-growing operation in Queensland while Polglase *et al*. (2011) undertook a financial analysis of forest plantings across Australia[123]. Unlike the chemical and algae operations considered above, the CO_2 capture from forests is not uniform over time as the forests grow. Data on this non-uniform growth profile provided by Hunt are shown in Figure 5.6.

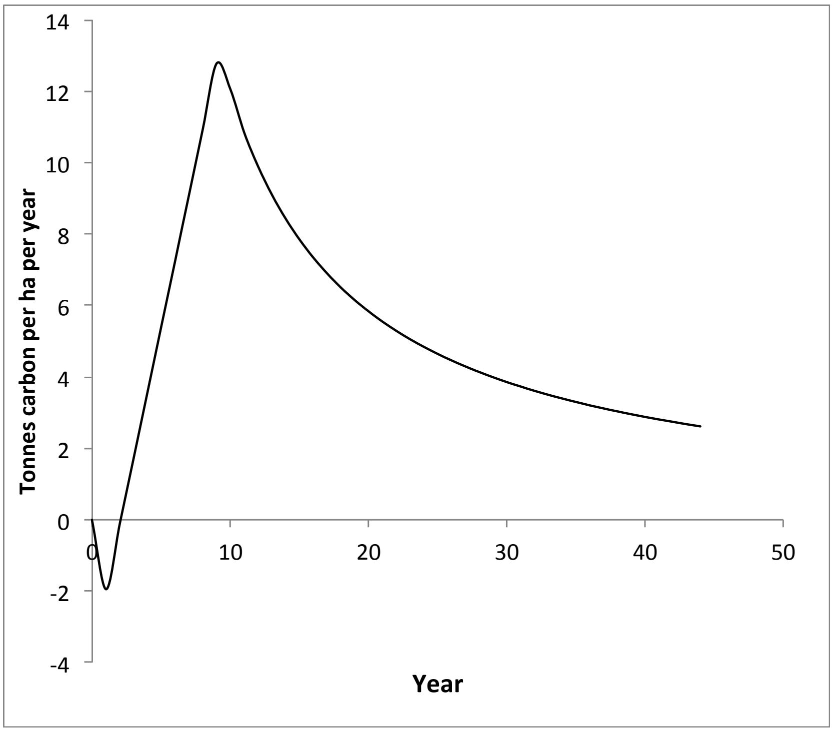

Figure 5.6: Carbon sequestration rate in an unharvested forest (diagram drawn by the task force from interpolated data from Hunt, 2009)

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[122] Hunt C, "Economy and ecology of emerging Markets and credits for bio-sequestered carbon on private land in tropical Australia", Ecological Economics, 66, (2008), pp309.

[123] Polglass P, Reeson A, Hawkins C, Paul K, Siggins A, Turner J, Crawford D, Jovanovic T, Hobbs T, Opie K, Carwardine J, Almeida A, "Opportunities for carbon forestry in Australia: Economic assessment and constraints to implementation", CSIRO National Research Flagships – Sustainable Agriculture. Canberra, ACT, 2011.

The task force has analysed the data of both Hunt and Polglase *et al.* In the Hunt case, the data for carbon sequestration in Figure 5.6 were used to calculate the CO_2 sequestered each year for 44 years and this CO_2 was credited at the "Price of CO_2 Required" in the financial model. In the case of Polglase *et al*., two different CO_2 sequestration rates at opposite ends of the range shown by them in regions in Australia were taken in two sequential twenty year periods. Thus, a low productivity region (generally in more arid areas) was ascribed a carbon sequestration rate of 2.1 t/ha/year in the first 20 years, and 1.4 t/ha/year in the following 20 years. A high productivity region (generally in eastern areas of Australia) was ascribed a CO_2 sequestration rate of 6.1 t/ha/year in the first 20 years and a rate of 4.2 t/ha/year in the following 20 years. In this way, both a low and high productivity region was modelled from the Polglase data, using the 70% "growth decline factor" suggested by the authors for the two 20 year periods[124].

Capital and operating costs assumed by Hunt and Polglase *et al*. were different. Hunt assumed a capital planting cost for an unharvested softwood forest and then applied an opportunity cost associated with the loss of beef cattle grazing as an annual operating cost for the life of the sequestration. The opportunity cost associated with foregone beef cattle husbandry on the newly forested land suggested by Hunt was $4,155/ha in NPV terms at 5% discount rate. Hunt also applied a maintenance cost for the three initial years of operation at $1,100/ha/year and this was also used in this study. Further details on planting cost assumptions ($2,840/ha) for the analysis here are given in Appendix F. These costs were also corrected to 2011 dollars using the CPI.

Polglase *et al*. assumed establishment costs on purchased land of $1,000 and $3,000 per ha, noting that the $3,000 value is more reasonable. In this work this $3,000/ha value has been assumed. For the low productivity case of Polglase *et al*., a land price of $250/ha has been assumed, while for the high productivity case a land price of $3,500/ha has been assumed. Maintenance costs in the first few years are assumed here to be incorporated into the establishment costs.

Like the other technologies, the "Price of CO_2 Required" from a forestry operation is a strong function of the cost of capital assumed. For example, Greenfleet are a charity and presumably achieve a zero return on their capital employed. On the other hand, the costs of forestry should be compared on the same basis as the other technologies such as algal growth and mineral carbonation, namely at 10% return. Table 5.3 below gives the "Price of CO_2 Required" as a function of the cost of capital for a managed forest based on the Hunt and Polglase *et al*. data using the task force model:

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[124] Polglase P, Reeson A, Hawkins C, Paul K, Siggins A, Turner J, Crawford D, Jovanovic T, Hobbs T, Opie K, Carwardine J, Almeida A, "Opportunities for carbon forestry in Australia: Economic assessment and constraints to implementation", CSIRO National Research Flagships – Sustainable Agriculture. Canberra, ACT, 2011, Figure 2 (CO_2 sequestration rates), pp8.

Table 5.3: “Price of CO_2 Required” for a forestry operation

WACC (%)	Hunt	Polglase *et al.* (High Productivity)	Polglase *et al.* (Low Productivity)
15%	\$84	\$58	\$87
10%	\$56	\$40	\$60
5%	\$36	\$24	\$34
0%	\$24	\$11	\$15

The Greenfleet charity operation charges \$12/t CO_2 emitted from cars[125] and this is similar to the value calculated by the task force model for zero return for the Polglase *et al*. data. From the above Table a commercial operation seeking a 10% return, provided that it is included in a carbon credit scheme in the future, gives a \$40 to \$60/t CO_2 avoided value at 10% discount rate. Under the analysis by the task force, this is competitive with the values required by the other technologies to be financially viable.

The CO2 Australia Group has three mallee eucalyptus plantations established near Dubbo and Wagga in NSW, sequestering carbon dioxide for the Qantas Group. More than 200,000 trees have now been planted for Qantas. In October 2011, the cost of CO_2 emission abatement for Qantas passengers was \$9.25 per tonne of CO_2 at the time of purchase of a Qantas ticket. This is the lowest cost option that the task force found during the study.

5.3.4 Comparison of technologies in terms of “Price of CO_2 Required”

Figure 5.7 shows a summary of the range of “Price of CO_2 Required” for the three technologies considered above from the literature, together with a range of values for geological CO_2 capture, transportation and storage (not including power generation):

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[125] Greenfleet: http://www.greenfleet.com.au/ allows car emissions to be offset at a rate approximately equal to \$12/t CO_2.

- The “Price of CO_2 Required” for ***capture*** associated with **geological storage** has been reported by the IEA as \$20-\$80 USD/t CO_2, with a mean value of \$50/t CO_2[126], as also confirmed by Hooper of the CO2CRC[127]. The additional cost of ***transport and storage*** varies with location, and the two values shown in Figure 5.7 are for transportation to the Gippsland basin from the La Trobe Valley and from Northern NSW to the Surat Basin in Queensland[128]. The range for these cases for transportation and storage is from \$10-12/t CO2 to \$22-65/t CO_2, respectively. The range of total “Price of CO_2 required” for capture, transportation and storage for geological storage under these circumstances is thus from \$30-92/t CO_2 to \$42-145/t CO_2 respectively for the two locations.

- The “Price of CO_2 Required” is relatively low for **unharvested forestry** and in the range \$10/t CO_2 to \$55/t CO_2 depending on the type of forestry, location and cost of capital.

- The “Price of CO_2 Required” for **algae** varies widely, from close to zero to over \$250/t CO_2. This large range is a function of the strong dependence of this parameter to the algal productivity and the price of the algal-oil product, both of which are uncertain at this point in time.

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[126] “CO_2 Capture and Storage”, IEA Energy Technology Essentials, ETE01, International Energy Agency, 2006.

[127] Hooper B, Personal Communication, CO2CRC, August 2011.

[128] “National Carbon Mapping and Infrastructure Plan – Australia”, Concise Report, Carbon Storage Task Force, Department of Resources Energy and Tourism, Commonwealth of Australia, September, 2009, pp. 21.

- The "Price of CO_2 Required" for the **conventional, heat activated mineral carbonation** process (as proposed by Rayson *et al*. and including the \$50/tCO_2 costs of providing captured CO_2 from flue gas) is in a narrower band than algae, but relatively high (\$140-\$220/t CO_2) without further process improvement such as increases in reaction rate, decreases in energy consumption and decreases in capital costs. The **novel mineral carbonation process** proposed by Hunwick of ICS potentially has a low "Price of CO_2 Required", based on the proponent's own published and stated claims in the range \$28.50 to \$35/t CO_2[129],[130], depending on transportation method. This may indicate that mineral carbonation processes can be improved in terms of their potential financial performance through innovative chemical and mineral engineering. The task force believes that the ICS claims are worth investigating further. In this context, however, the task force also notes that the ICS cost claims are of the same order or less than the CO_2 capture component only of geological storage (\$50/t CO_2), even though the ICS concept includes a very large mineral processing plant and hard rock mine in addition to the capture of CO_2 from the power station flue gas using ammonia. However, the ICS Process does not include the energy-intensive step of handling and compression of pure CO_2. As noted previously, the cost claims by ICS would benefit from a review by an expert engineering organisation familiar with the costs of new combined chemical engineering, mineral processing and mining operations during scale-up from bench-scale laboratory results to large operations. Because the task force could not independently peer substantiate the cost claims of the ICS process, they are not included in Figure 5.7.

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[129] Hunwick R., "The ICS Process – Carbon capture and storage by integrated mineralisation", EXPPERTS 2010 Conference, Berlin, September 2010. Personal Communication to task force, December 2011.

[130] Hunwick R., "The ICS Process – Carbon capture and storage (CCS) by integrated mineral carbonation", Non-confidential presentation to task force, August, 2011.

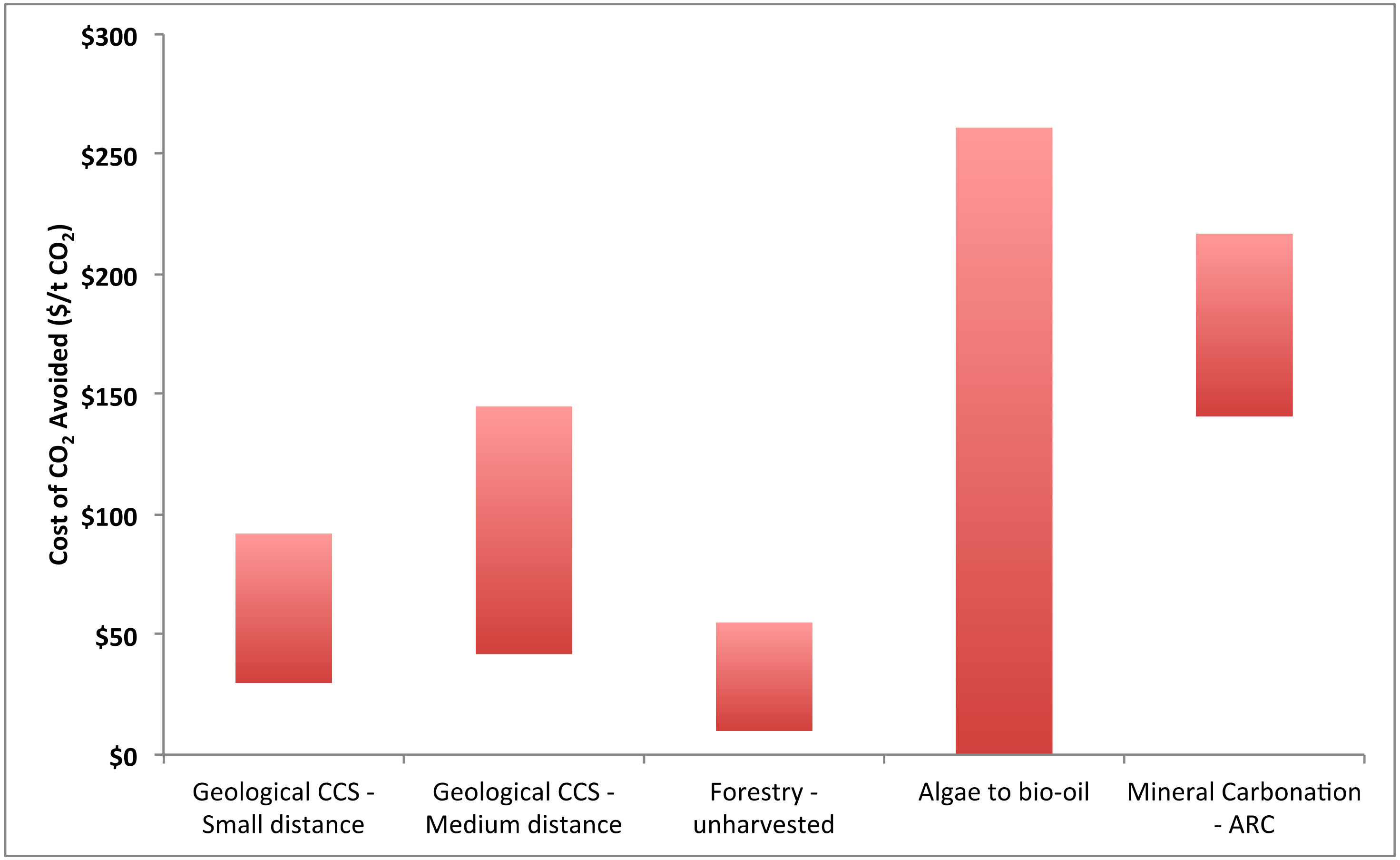

Figure 5.7: Overall comparison of “Price of CO_2 Required” for different technologies at 10% discount rate. “Price of CO_2 Required” only includes the cost components for CO_2 capture, transport and storage, not electricity generation.

5.3 Option Value of Novel Capture Technologies

Luehrman[131] [132] describes the concept of real options and how they might be used to value new technologies in two papers in the Harvard Business Review in the late 1990s. These papers provide informative background for the interested reader on the theory of real options and the idea of business strategy comprising a portfolio of real options. Determination of real options is a useful technique when the uncertainty is high, as in this study. The Australian Academy of Technological Sciences and Engineering (ATSE) took this concept further and calculated the “Net Present Option Value (NPOV)” of new low-carbon power generating technologies in a report released in December 2010. This ATSE report provides a background to the idea of NPOV and methods for its calculation[133]. Basically, the NPOV is calculated from a probabilistic analysis of the NPV distribution expected from an investment in the future, taking into account the uncertainty in the variables involved. The NPOV is the aggregated part of the NPV distribution where the expected NPVs are greater than zero. The idea is that an investor would not invest in the case where the NPV is less than zero when the time comes for the investment. However, viewed from today, there is a possibility of upside NPV and hence wealth creation due to uncertainty or volatility (variance) in the NPV distribution. The Chair of this task force was the author of the ATSE report, and the task force is grateful that ATSE has made the technique available for the present task force analysis. Details of the methodology are fully explained in the ATSE report and are not repeated here.

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[131] Luehrman T, “Investment Opportunities as Real Options: Getting Started with the Numbers”, Harvard Business Review, July-Aug, 1998.

[132] Luehrman T, “Investment Opportunities as Real Options: Strategy as a Portfolio of Real Options”, Harvard Business Review, Sept-Oct, 1998.

[133] “Low-carbon Energy: Evaluation of New Energy Technology Choices for Electric Power generation in Australia, Australian Academy of Technological Sciences and Engineering, Nov. 2010. pp17, pp59. http://www.atse.org.au/resource-centre/ATSE-Reports/Energy/

In the present NPOV analysis, the same financial data for the technologies as the above "Price of CO_2 Required" calculation were used. However, the expected future CO_2 price trajectory was calculated over the life of the investment based on the Australian Government Treasury predictions based on a global carbon price model after 2020[134]. This gave a CO_2 price of $30 real in 2020 escalating at 5% per year to $130/t CO_2 in 2050 and a wholesale electricity price of $54/MWh real in 2020 escalating linearly to $134/MWh in 2050. The natural gas price (where applicable) was assumed to escalate from $5.74/GJ real in 2020 at a rate of 2% per year, the approximate average of the scenario analysis presented by the Australian Energy Market Operator (AEMO)[135]. All these assumptions are almost exactly the same as the assumptions used in the ATSE low-carbon energy study. For each of these price trajectories, an increasing "volatility" or uncertainty was assumed post-2020. This amounted to a 5% per year increase in variance in the probability distributions of these parameters, in a similar fashion again to the ATSE study. Further details on these NPOV calculation assumptions are given in Appendix F and in the ATSE report. The NPOV method used a Monte Carlo method over 5000 iterations to compute the NPV distributions for investment in 2020 and the corresponding NPOV and volatility components from the final NPV distribution for each case.

Luehrman[136] has provided a simple diagrammatic method for displaying the outcome of an option value analysis, the so-called "Options Space Diagram". The "x-axis" of this diagram is "value-to-cost", or the ratio of the future cash flows from the operations (S) to the capital costs invested (X), expressed as S/X in present value terms. A value of S/X equal to 1.0 represents zero NPV, since NPV=S-X. The "y-axis" is the "volatility", or essentially the variance in the (S-X) probability distribution. As either S/X increases, or the "volatility" increases, the option value increases. The interested reader is referred to the Luehrman papers and the ATSE report for further discussion on these parameters. The diagram provides regions where qualitative decisions about investment (or not) may be made. For example, at the time of the future investment if the volatility is low and the NPV is high, then the project should be a good investment then. On the other hand, if the NPV is negative, and the volatility is low, there is little potential for upside in the NPV. If the NPV is moderately low, but there is high volatility, then the investment could be made later after the situation becomes clearer, and so on. In principle, the higher the option value, the better the potential future investment. The option value is increased by both higher values of S/X (NPV) and by higher values of "volatility", the two axes on the Option Space Diagram.

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[134] Australian Government Treasury: http://www.treasury.gov.au/carbonpricemodelling/content/report.asp

[135] Australian Energy Market Operator (AEMO): http://www.aemo.com.au/planning/scenarios.html

[136] Luehrman T, "Investment Opportunities as Real Options: Strategy as a Portfolio of Real Options", Harvard Business Review, Sept-Oct, 1998, pp 93.

In the present study NPOVs have been calculated for the algae [Campbell *et al.*[137]], the conventional mineral carbonation [Rayson *et al.*[138]] and the forestry [Polglase *et al.*[139]] literature data assuming investment (or exercising the option) in 2020. In each case the probability distributions of S, X, and (S-X) were calculated and the "volatility" of the NPV (S-X) distribution was determined in the form of a standard deviation. An Options Space Diagram was then created for the technologies in question by plotting the "volatility" against the "value-to-cost" in Figure 5.8. The size (area) of the bubbles on the diagram is indicative of the magnitude of the option value, and the higher the option value, the better. Note that the diagram as presented **refers to an investment in 2020**. In other years the diagram will be different, since the revenue and cost streams for each investment will be different. Some technologies, for example, may have a higher option value in (say) 2030 due to the expected higher CO_2 price then.

Forestry Case: The high productivity case forestry bubble in Figure 5.8 lies to the right of the NPV=0 line (S/X=1), so has positive NPV. This means that a value-creating investment can be made in forestry in 2020. There is some volatility present because of the uncertain nature of the carbon dioxide price in the future. The carbon dioxide pricing regime would also have to include this agricultural activity for it to receive revenue and therefore have option value in the future. For the low productivity case, the option value is small and the NPV is negative for investment in 2020 under the envisaged CO_2 trading regime. This result essentially agrees with the Polglase *et al*. analysis, where it was found that the area available for sequestration forestry in Australia declines as the productivity falls, unless the CO_2 price is high.

Algae Case: There are three algae option value bubbles shown on the Options Space Diagram. The large orange bubble is for algae converted to stock feed (at $200/t) and bulk algal-oil (at $160/bbl) for 30 $g/m^2/d$ productivity. This option has relatively large value. In purely financial terms, this may indicate a good investment in the future, depending on its by-product prices and algal productivity then. The smaller red bubble adjacent to the orange one is for the algae to power generation case under the same algal-oil and algae productivity conditions. This option is slightly less valuable, depending on CO_2, algal-oil and natural gas prices in the future and the extra capital costs that will be required to generate the natural gas bio-fuel.

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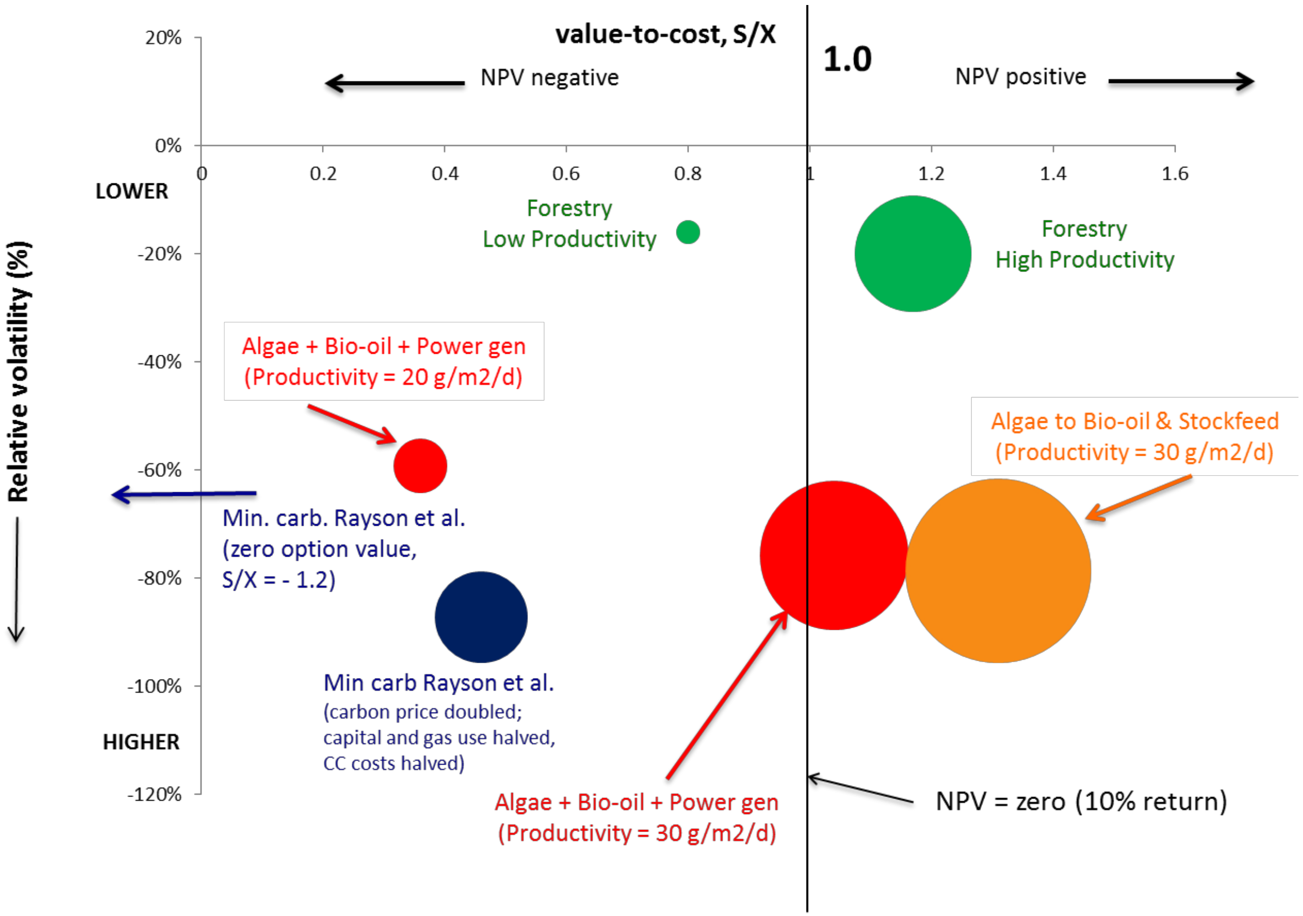
[137] Campbell P K, Beer T, Batten D, "Greenhouse Gas Sequestration by Algae: Energy and Greenhouse Gas Life Cycle Studies", *Sustainability Tools for a New Climate*, Proc. 6th Australian Life Cycle Assessment Conference, Melbourne, Feb 2009.

[138] Rayson, M., M. Magill, R. Sault, G. Ryan and M. Swanson (2008). "Mineral Sequestration of CO_2 - Group 2, Phase 3", Discipline of Chemical Engineering, The University of Newcastle, NSW 2308. Report may be obtained by contacting the Discipline Secretary at the University of Newcastle..

[139] Polglass P, Reeson A, Hawkins C, Paul K, Siggins A, Turner J, Crawford D, Jovanovic T, Hobbs T, Opie K, Carwardine J, Almeida A, "Opportunities for carbon forestry in Australia: Economic assessment and constraints to implementation", CSIRO National Research Flagships – Sustainable Agriculture. Canberra, ACT, 2011



area of bubble proportional to option value

Figure 5.8: "Options Space Diagram" for algae, mineral carbonation and forestry option values ***for investment in 2020****. [The Australian Academy of Technological Sciences and Engineering (ATSE) is acknowledged for making the NPOV calculation methodology available to the task force].*

The small red bubble on the left-hand side of the Figure 5.8 represents the same cost parameters as the larger red bubble, but with the lower algal productivity of 20 g/m^2/d. Under these conditions the NPV (S/X) is negative for investment in 2020, indicating that high productivities will be required to ensure that algal technologies are adopted when it comes time to exercise the commercial option. Alternatively, the by-product from the algae operation will need to be high value to increase the revenue stream.

Mineral carbonation case: The option value for the financial data derived from Rayson *et al.* using unimproved ore activation technology gives zero option value and a strongly negative NPV (S/X ratio) under the Treasury carbon price trajectory from 2020, as shown by the dark blue arrow in the diagram pointing to the left. This is because the carbon dioxide prices envisaged are insufficient to provide enough revenue to create positive NPV values at 10% cost of capital. The "value-to-cost" is simply too low to create any option value due to the requirement for high CO_2 prices to provide reasonable returns. To investigate the sensitivity in this case, the CO_2 price was doubled in its trajectory, the capital cost was halved, the natural gas usage was halved and the costs of carbon dioxide capture prior to the facility were halved in the task force model. This gave rise to some option value due to "volatility", as shown in the dark blue bubble on Figure 5.8. The ARC ore-activation process will clearly need to achieve significant technology improvements, potentially coupled with "public good" subsidies from government, to have future value to investors based on the information published to date in the public domain.

Other technologies that are being proposed could be analysed by the NPOV option value method if the proponents could provide public peer-reviewed process and financial data together with probable ranges. One example of this is the Hunwick ICS novel chemistry process for mineral carbonation, which could possibly have good option value in the light of its claimed low "Price of CO_2 Required". However, much of this data is commercial-in-confidence, or has not been peer-reviewed by scientists and engineers at this stage, or is not backed up by scientific experiments whose results are in the public domain. Over time, it is believed by the task force that the type of options analysis presented here should be undertaken with these new technologies as they are proposed, they evolve and the data becomes publicly available.

6. COMPARATIVE CHARACTERISATION OF TECHNOLOGIES

This section of the report compares at a high level the technologies studied in this report with each other as well as with of geological sequestration of CO_2. The comparison is made, where possible, in terms of items such as the permanence of CO_2 storage, the ability of the technology to capture the CO_2 emitted by fossil fuel combustion during power generation, the requirements for land and other resources, and environmental impact. A comparison of the costs of the technologies has been undertaken in Section 5 of the report above and is not repeated here. Each of the comparison items are considered in turn in tabular form based on the detailed information presented previously in the report and from other sources.

6.1 Permanence of CO_2 Storage

TECHNOLOGY	PERMANENCE OF CO_2 STORAGE
Geological CCS	Geological storage of CO_2 will involve placement of CO_2 in suitable sub-surface geological aquifers. The IPCC[140] has noted that it is "very likely" that 99% of this sequestered CO_2 can be permanently stored in these aquifers for 100 years, and "likely" that 99% can be stored for 1,000 years.
Algal capture	Algal processes for CO_2 capture are analogous to the photosynthetic production of biomass from atmospheric CO_2. This is because is it proposed that the algae will consume flue gas and will then itself be converted to a fuel and/or animal feed for subsequent use. Algal consumption of CO_2 thus displaces fossil fuels that would otherwise be consumed. It can be argued that this displaced fossil fuel is never consumed, and the carbon removal is permanent because this displaced fossil fuel remains in geological structures. However, there is controversy at the philosophic level about whether this once-of, short-term cycle represents permanent removal by algae of CO_2 produced by fossil fuels from the atmosphere.
Mineral Carbonation	The mineral carbonation process mimics the natural process of carbonate rock formation by weathering. The magnesium and calcium carbonate product produced by a mineral carbonation process will be very likely permanent if kept separated from acidic materials (e.g. acid rain) in buried storage.
Biomass growth	Biomass growth consumes CO_2 from the atmosphere by photosynthesis and then deposits this as carbon in the plant structure. The process occurs in a non-linear way for decades for some plants (e.g. trees). If the plant material is left to die the carbon will re-enter the atmosphere by natural processes of decay. The permanence thus depends on the life of the biomass. CO_2 sequestration projects are currently required to guarantee 100 years of carbon storage during tree growth. If the biomass is harvested and then converted into a product that is prevented from decaying (e.g. timber used in structures), then the permanence of carbon storage could be for centuries. If the biomass is grown and then used as fuel (e.g. sugar-cane trash) then the life cycle is short and the same arguments on displacement of fossil fuels apply as for algae above.
Carbon in soils	Farming improvements such as the Carbon Farming Initiative aimed at an increase in soil carbon through change in practices will lead to permanent carbon storage in soil if continued indefinitely. Some dense biomass chars have been shown to have permanence in the soils for centuries when added exogenously. However, many chars produced from different biomass under different conditions have short lifetimes in the soil on decadal or even annual time scales. If the exogenous addition to the soil is char produced from fossil fuels (e.g. lignites), and is in a form that has low soil permanence, then this effectively liberates fossil carbon into the atmosphere unless there is an associated greater permanent increase in endogenous soil carbon. The overall field of carbon in soils and its permanence is at present uncertain and requires more scientific research.

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[140] "Carbon dioxide capture and storage", Intergovernmental Panel on Climate Change (IPCC) Special Report, UNEP, Cambridge University Press, 2005, pp. 14.

6.2 Potential for CO_2 Capture

TECHNOLOGY	POTENTIAL FOR CO_2 CAPTURE IN AUSTRALIA
Geological CCS	The Carbon Storage Taskforce[141] has reported that there is high confidence that the east of Australia has geological aquifer storage capacity for 70-450 years at a CO_2 injection rate of 200 Mt per year. That is, a total storage capacity of between 14 and 90 Gt CO_2. It is envisaged that CO_2 capture technologies could have a CO_2 capture efficiency of around 90% from the flue gas at any particular power-generating site. Depending on CO_2 capture and transportation costs, geological CCS could sequester a large proportion of the CO_2 produced from power generation in Australia for centuries, noting that the amount of CO_2 being stored would be greater than the current amount being emitted due to in energy inefficiencies in the CCS capture process.
Algal capture	Owing to the physics and biology of the photosynthetic process, the present study has found that only around 25% of the total CO_2 produced from power stations can feasibly be captured by photosynthetic algae at good locations. This is because the algal processes require solar energy to capture CO_2 and therefore cannot operate at night. Storage of CO_2 (in flue gas) during the night would require prohibitively expensive flue gas storage for ~18 hours per day. Since algae capture of CO_2 requires very large land resources[142] and good climatic conditions for algal growth, not all power generating sites are suitable for algal capture. It is believed by the task force that algae technologies as they stand now can therefore only potentially capture a small proportion (say 10%) of the total CO_2 produced by power generation in Australia, or around 20 Mt/year CO_2.
Mineral Carbonation	If sufficient resources of magnesium-containing rock are available at low cost, then mineral carbonation could potentially sequester many tens of millions of tonnes of CO_2 from power generation per year at selected locations in Australia. It has been estimated[143]that this could amount to a total of 20Gt CO_2 over 100 years in NSW, involving the mining of hundreds of millions of tonnes of magnesium-containing rock per year from (say) the Great Serpentine Belt in the New England region of NSW. However, it is not clear to the task force that the availability of this or other rock resources in Australia has been fully analysed in terms of geology and minability by scientists and engineers expert in the field.

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[141] "National Carbon Mapping and Infrastructure Plan – Australia", Concise Report, Carbon Storage Taskforce, Department of Resources, Energy and Tourism, Commonwealth of Australia, September, 2009.

[142] Approximately 5,000 ha per 1Mt CO_2/year or approximately 400 km^2 for each 1GW of generator capacity at 1 t CO_2 per MWh.

[143] Davis M. (2008) "The CO_2 sequestration potential of the ultramafic rocks of the Great Serpentinite Belt, New South Wales" Honours Thesis, Dept. of Earth Sciences, University of Newcastle.

	Brine resources required would be very large if this technology was used to capture CO_2. For example, if sea water was used for its Mg content, salt water supply equivalent to about 30 Wonthaggi desalination facilities would be required for a large Victorian power station hub (4 GW) alone to provide sufficient Mg and Ca. This is equivalent to ~70 Dampier Salt facilities in terms of brine supply. It is unlikely that resources of this magnitude will be available in Australia without high sub-surface extraction costs. "Red mud" waste from the alumina production process has been noted as a possible mineral carbonation feedstock for pure CO_2. According to Alcoa[144], who have a patented process to sequester CO_2 with "red mud", about 30 tonnes of "red mud" are required per tonne of CO_2, leading to a total sequestration potential in Australia using all their waste of 300,000 t CO_2. This represents a small fraction of the total CO_2 emitted by power generation in Australia, even if it was financially feasible to transport this material to the sequestration location and convert flue gas into pure CO_2 for the process.
Biomass growth	Forest in Australia occupies 150M ha of land at present, or 19% of Australia's land area. 12Gt of carbon is stored in these forests and forestry operations currently utilise 2M ha. It has been estimated that growing forests could sequester between ~400 Mt and ~800 Mt per year of CO_2[145]. However, to achieve a rate of (say) 200 Mt/year of CO_2 sequestration (at 10 tCO_2/ha/year average sequestration rate over 100 years) would require an extra 20 Mha of forests, containing 12,500 million trees at 4m spacing. This is ten times larger than current Australian forestry operations. Increase in forests in Australia of this scale would also have an unknown but likely beneficial effect on the sub-surface soil storage of endogenous soil carbon. The availability of land and water for this purpose and the need for alternative uses for the land could, however, provide a significant barrier to this expansion.
Carbon in soils	This report has estimated that total biochar production via pyrolysis processes from existing farm residue sources and expansion of mallee plantations could capture of the order 15 Mt per year carbon (equivalent to 55 Mt CO_2 taken from the atmosphere per year). This biochar could be placed exogenously into soils as a form of sequestration. However, commercially viable pyrolysis processes at the scale required do not currently exist. Quantification of the sustainable and permanent increase in soil carbon due to this carbon addition (as well as for addition of fossil-derived chars) is at present uncertain and requires further scientific study. Quantification of increases in soil carbon farming initiatives aimed at sustainably increasing the storage of carbon in soils has not been undertaken by this task force due to the present inherent temporal and spatial uncertainties in the information available on soil carbon levels in Australia. However, since soil carbon levels have historically decreased in Australia over time due to farming, it is likely that improved farming practices that are sustainably applied would have a significant positive effect on the amount of carbon stored in Australian

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[144] http://www.alcoa.com/australia/en/info_page/Residue_Management_Reuse.asp

[145] Garnaut R. (2011) "Transforming rural land use" Garnaut Climate Change Review – Update 2011. (http://www.garnautreview.org.au/update-2011/update-papers/up4-transforming-rural-land-use.pdf)

	soils. Over time, this amount of soil carbon increment could be substantial.

6.3 Use of Resources

TECHNOLOGY	USE OF RESOURCES
Geological CCS	*Land:* The CO_2 capture facility required for geological CCS would vary with the capture technology but would generally comprise a large chemical engineering plant with a footprint similar to the area occupied by the fuel combustion / power generating facility. It would be located on land adjacent to the power generating facility. Easements to land would also be required for the network of supercritical CO_2 pipelines carrying the CO_2 from the generating facility to the geological sequestration site. This could range from several km for sites above a suitable geological formation, to distances of the order a hundred km for nearby sites (e.g. the La Trobe Valley Victoria - Gippsland Basin hub), to a thousand km for generation facilities far from any suitable sequestration site. Access to underground storage aquifers would need to be regulated, controlled and monitored by governments. *Energy:* CO_2 capture and gas compression for geological CCS requires a significant amount of energy for the combined capture and compression operation. This has been estimated as around 25% of the fuel input energy to the power generating unit, depending on the overall design and thermal efficiencies achieved. The IPCC[146] has reported and it may be calculated that the extra energy consumption from fuel for capture under these conditions is around 0.7 MWh/t CO_2 for a pulverised coal power plant. *Water:* Zhai *et al.* (2011)[147] have reported that total cooling water consumption for a pulverised coal supercritical pulverised coal power plant almost doubles with the addition of post-combustion capture CCS from around 120 to 150 tonnes water per tonne of CO_2 generated in the flue gas, noting that greater amounts of flue gas are produced in the CCS case to provide extra energy for the process. Dry cooling of both power plant and CCS plant may be an option for Australia, albeit at reduced overall efficiency and higher cost. *Chemicals:* Makeup amine to a post combustion capture power generation capture facility has been estimated by Zhai *et al.* as 0.1kg/tonne CO_2 captured.
Algal capture	*Land:* The amount of land required for algal consumption of power station CO_2 is large and depends on the algal productivity. At feasible productivities at good sites (30 g algae/m^2/day) the task force estimates that about 5,000 ha per 1M tonnes per year of CO_2 captured are required. A 1GW pulverised coal power station emitting at 1 t CO_2/MWh, emits around 8 Mt CO_2 per year, but the algae will only collect 25% of this during the sunlight hours. Collection of this 2 Mt/yr CO_2 would require a land area of ~10,000 ha or ~100

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[146] "Carbon dioxide capture and storage", Intergovernmental Panel on Climate Change (IPCC) Special Report, UNEP, Cambridge University Press, 2005, Table 8.3a, pp. 347.

[147] Zhai H., Rubin E.S., Versteeg P.L., "Water use at pulverised coal power plants with postcombustion carbon capture and storage", Environ. Sci. Technology, 2011, 45, pp2479.

	km^2 (10km x 10km) for each GW of capacity. For a large (4.5GW) power station hub in NSW, approximately 450 km^2 (21 km x 21 km) would theoretically be required to capture 25% of its CO_2 output at moderately high algal productivity. The availability of land at this scale adjacent to power stations is questionable. Algal productivities at this scale have not been demonstrated, and further studies are required to demonstrate algal productivities using flue gas at different locations and in different seasons at large scale. *Energy*: The electricity requirement for the pumping requirements for algae growth in ponds has been estimated at 0.27 MWh per tonne algae or 0.13 MWh per tonne of CO_2 captured (Appendix F). If anaerobic fermentation of the algae after oil removal is employed, this energy can be recovered. The excess energy from methane combustion has been estimated by Campbell *et al*. as 0.46 MWh/t CO_2 captured. *Water:* The salt water requirement estimated by Campbell *et al*. (2009)[148] for growing algae was 70,000 t/ha/year, or 700 Gl/year for the capture of 25% of a 1GW power station CO_2 output (2Mt CO_2/year). This represents 350t salt water per t CO_2. If fresh water was used for this duty it is assumed that some of this quantity could be recycled after removal of the algal product. The USA Aquatic Species Program assumed for open ponds that the water requirement would be 50% greater than the evaporation rate. For NSW evaporation levels (~1,500 mm/year), this would amount to a new water top-up rate of 200Gl per year for the 1GW power station example. This amounts to 100 t fresh water per tonne of CO_2 captured. Evaporative losses could be minimised if covered photo-bioreactors were used for the algal growth process, at greater capital cost. The amount of water contained in the algal growth ponds for the collection of 2 Mt CO_2 per year from a 1 GW power station would be approximately 50 Gl or 50 Mt. The water used could be waste-water, after treatment for pathogens. *Chemicals:* Nutrient consumption (N, P, K, S) was estimated by Campbell et al. as 3.3 kg/t CO_2, while flocculant consumption was estimated as 1.4 kg/t CO_2. Waste products were estimated as 200kg/t CO_2, or ~400,000 t/year of waste for disposal for the 2 Mt/year CO_2, 1GW power station example.
Mineral Carbonation	*Land:* A mineral carbonation facility for a 1GW power station would be a large mineral processing operation with a footprint size of the same order or larger than the generating plant, not including the rock mine. If the mineral processing facility was situated adjacent to (say) a Hunter Valley power station in NSW, significant infrastructure would be required to transport the required mined rock to the site. A 1 GW power station would require ~23 Mt/year of magnesium-containing rock, while the waste carbonate product would comprise ~28 Mt/year of finely ground carbonate and this would need to be transported back to the mine. Alternatively, if the facility

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[148] Campbell P K, Beer T, Batten D, "Greenhouse Gas Sequestration by Algae: Energy and Greenhouse Gas Life Cycle Studies", *Sustainability Tools for a New Climate*, Proc. 6th Australian Life Cycle Assessment Conference, Melbourne, Feb 2009.

	was located close to the mining area, then either captured CO_2 or chemical reagents would need to be pipelined to, or to and from, the power station to the mineral processing facility at the mine. Land would be required for easements for these pipelines, which could run for hundreds of kilometres. The mining operation would be large, but not exceptional in the Australian context. A 1GW power station would require a hard-rock mining operation similar in scale to many of the iron ore mines in the Pilbara. A 4.6GW two power station hub would need to mine ~100 Mt/year of serpentine rock and dispose of ~125M of fine tailings per year to capture (net) ~70% their CO_2. This would require a mine approximately three times the size of BHP Billiton's Mt Whaleback mine at Newman WA[149] (38 Mt iron ore per year) just for this hub. Processing, dewatering and disposal of 125 Mt/year of fine tailings would present a significant technical challenge, since the volume of this fine wet material is larger than the volume of the original mined rock and would therefore overspill the cavity left by the mining operation. There would be land use issues associated with mine planning and disposal of this material as mining proceeds. *Energy:* Mineral carbonation processes that require pure CO_2 as a feedstock and activation of the rock using heat consumes significant energy. Pure CO_2 feed requires chemical absorption of CO_2 from flue gas, in a similar fashion to that required for geological CCS with a similar energy penalty of around 0.7 MWh/t CO_2 including gas compression. Rayson *et al*.[150] proposed that activation of the rock would be undertaken using natural gas as a fuel, with an extra energy consumption for this purpose of ~3.2 GJ/t CO_2 (~0.9 MWh/t CO_2). Electrical consumption for the mineral processing operation (not including CO_2 capture) was taken by Rayson *et al*. as ~0.06 MWh/t CO_2. Adding these components means that a rock activation process would need more than twice as much fuel (coal and gas) to maintain the same sent-out electricity as a case with no CO_2 sequestration – approximately 1.7 MWh/t CO_2 extra energy. Rayson *et al*. have noted that the net sequestration of CO_2 from the proposed heat activation carbonation process is 76% of the input pure CO_2, or 68% of the power station CO_2 emissions assuming a 90% CO_2 capture efficiency by the CO_2 capture process. This inefficiency in CO_2 sequestered is mainly due to combustion of natural gas for the activation process and subsequent emission of CO_2. These numbers do not, however, take into account the extra CO_2 emitted due to the energy inefficiencies of the CO_2 capture process at the power station. The ICS process is claimed to not require pure CO_2, with attendant energy savings. Hunwick has estimated that the ICS process needs to burn less than 25% extra coal to make up for parasitic losses[151], a value similar to that estimated for geological CCS. Hunwick also notes that 24 Mt CO_2 per year can be sequestered from a 33 Mt CO_2 per year emitting power station using the ICS process, the net CO_2 being dictated by the energy requirements of the ammonia capture and carbonation processes, and materials handling. This

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[149] http://en.wikipedia.org/wiki/Iron_ore_mining_in_Western_Australia

[150] Rayson, M., M. Magill, R. Sault, G. Ryan and M. Swanson (2008). "Mineral Sequestration of CO_2 - Group 2, Phase 3", Discipline of Chemical Engineering, The University of Newcastle, NSW 2308. Report may be obtained by contacting the Discipline Secretary at the University of Newcastle.

[151] Hunwick R., "The ICS Process – Carbon capture and storage by integrated mineralisation", EXPPERTS 2010 Conference, Berlin, September 2010.

	represents an overall CO_2 collection efficiency of 73% for coal-based energy. Brine-based processes would require large consumption of energy for pumping very large quantities of salt water or brines and for Mg+Ca ion upgrading. *Water:* Rayson *et al*. took a water consumption rate of 0.42 kl/t CO_2 in their analysis for the mineral processing part of the operation. This consumption rate was estimated from the water lost in the carbonate product and does not include any cooling water consumption. Hunwick has estimated the net water consumption of the ICS process as 0.167 t water/t CO_2.[152] Brine-based processes require very large quantities of water to provide the necessary Mg and Ca ions (see above). This approach appears to the task force to be infeasible in terms of supply of the necessary water and salt resources. *Chemicals:* Hunwick estimates the ammonia losses for the ICS process as 10 kg/t CO_2 sequestered and common salt requirements as up to 40 kg/t CO_2 sequestered. No information is provided by Rayson *et al*. on the consumption of chemicals for the rock activation process, apart from natural gas. The need for flocculation or other treatment in order to de-water the carbonate product of these processes has not been reported.
Biomass growth	*Land:* Between 50,000 and 200,000 ha are required per million tonnes of CO_2 captured for forestry, depending on the land resource and climate. As noted previously, this is more than an order of magnitude higher than that that for managed algae growth. *Energy:* There is a small energy requirement for sequestering CO_2 in forests, mainly associated with liquid fuels for forestry management. *Water:* Trees grown in forests increase evapotranspiration through their leaves relative to farmed arable lands. Polglase *et al*. (2008)[153] used the analysis by Zhang *et al*. (1999)[154] to determine this difference and to plot maps of variation in water interception by

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[152] Hunwick R., “The ICS Process – Carbon capture and storage (CCS) by integrated mineral carbonation”, Non-confidential presentation to task force, August, 2011.

[153] Polglase P., Paul K., Hawkins C., Siggins A., Turner J., Booth T., Crawford D., Jovanovic T., Hobbs T., Opie K., Almeida A., Carter J., “Regional Opportunities for Agroforestry Systems in Australia”, RIDC Publication No. 08/176, CSIRO Sustainable Ecosystems, October 2008.

[154] Zhang L., Dawes W., Walker G., “Predicting the Effect of Vegetation Changes on Catchment Average Water Balance”, Technical Report 99/12. CRC for Catchment Hydrology, Canberra (1999).

	agroforestry compared to grasslands. This amounted to an extra 60-100t water/tCO_2 sequestered for forests, via evapotranspiration from surface waters. Extensive planting of forests may therefore significantly change the water balance in catchment basins through water evaporation to the atmosphere.
Carbon in soils	*Land:* The managed production of biomass via forestry and pyrolysis would have a similar land requirement to forestry. The land requirements for each pyrolysis facility would be equivalent to a moderately sized chemical plant facility. *Energy:* There would be a small energy requirement for liquid fuels for the forestry component of biomass production. Pyrolysis facilities would produce liquid and gaseous by-products and these could lead the energy self-sufficiency for the pyrolysis process. *Water:* Managed biochar production would have similar water evapotranspiration effects to forestry. Innovation in the pyrolysis process could lead to recovery of water from wet biomass feed without energy penalty, as demonstrated by The Crucible Group. There is general scientific uncertainty about the effects of increases in soil condition and retained water in sub-soil by soil carbon increase, especially in relation to land location and climate.

7. TASK FORCE ASSESSMENT OF INITIAL HYPOTHESES

A number of “hypotheses” regarding the novel capture technologies were proposed at the Task Force initial workshop. It was the objective of the Task Force to answer these hypotheses in either the affirmative or negative as part of the study. The answers to these hypotheses are provided below.

Hypothesis 1: *“***There is sufficient scientific and technical literature on novel carbon capture technologies for the task force to assess the feasibility and develop a ranking of the various processes.”**

Answer: A qualified “YES”.

- There is a large amount of data in the literature on the algal processes and on mineral carbonation. There is conflicting information on the major questions about biochar and soil carbon. Despite the high level of uncertainty the Task Force has been able to make a judgement on the potential of all of the technologies. The Task Force has also been able to make recommendations for further research work that will more accurately predict the potential scale of carbon sequestration.

- Based on some of the published data, the Task Force has developed a financial ranking using financial analysis and incorporating contingencies for the range of research outcomes proposed in the literature.

Hypothesis 2: *“***By 2020, Novel CCS projects will be bankable at commercial scale.[155]”**

Answer: Generally “NO”

- The nearest potentially feasible business model considered is the creation of managed carbon forests, as practiced commercially by CO2 Australia Group. The Task Force analysis shows that these will also need regions of high forest productivity and/or relatively low cost and availability of land.

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[155] For the purposes of the task force report bankability is defined as the potential for a project to raise sufficient **private** finance (**either** debt or equity) to construct and operate a full-scale (>1Mtpa CO_2) sequestration plant.

- Algal technologies may be bankable for a different business strategy by 2020, namely the production of valuable by-products from algae culture. In this regard, they could use a relatively small proportion of the CO_2 being emitted by power stations as a feedstock. They will not be bankable with the aim of achieving a high proportion CO_2 sequestration from power stations at the scale required for a range of reasons, including the fact that they can only sequester a small fraction of the CO_2 being generated due to the physics of solar insolation.

- Mineral carbonation projects are embryonic at this stage, and the Task Force does not envisage them being bankable at the necessary large scale by 2020. Successful larger scale pilot plant studies will be required before then to overcome the second "valley of death" (Fig. 5.1), and the time available before 2020 for these studies to be conducted, the risks reduced and a plant designed and built is judged to be insufficient by the task force.

- Soil carbon enhancement projects such as carbon farming may be financially viable purely in terms of agricultural benefits to framers. Large-scale soil carbon sequestration in soils requires further scientific evaluation in terms of the permanence of soil carbon, both exogenously and endogenously generated. Large-scale use of biomass produced from pyrolysis or other chemical treatment processes is embryonic in terms of the necessary scale required and the life-cycle analysis. It is also embryonic in terms of scientific knowledge of the permanence of biochar in soils.

- Section 5 of the report above shows the funding "twin valley of death" diagram (Fig. 5.1). Most of the technologies under consideration by the Task Force are in the early stages of the funding cycle shown in this diagram. Some are prior to the first "valley of death", and some are approaching the "pilot scale" of development before the second "valley of death". The exception to this is forestry aimed at CO_2 sequestration, which is already commercial.

Hypothesis 3: "**By 2015, scientific consensus will be reached on permanence and sustainability of implementable Novel CCS"**

Answer: Generally "NO"

Algae

- Photosynthetic micro algae cannot sequester an appreciable amount of carbon emissions from industrial sources due to the scale of CO_2 production required and the limitations of algal systems (including fluctuations in diurnal and annual irradiance, gas transfer limitations, process energy requirements and algal growth rate). The CO_2 embedded in many algal products returns to the atmosphere after a relative short period, and as such does not provide long term sequestration, except in the sense that for algal-oil and algal methane production the bio-fuels displace the use of fossil fuels.

Mineral Carbonation

- Mg- and Ca- carbonates are the safest and most stable form of sequestered carbon provided they are isolated from acidic environments. The sustainability of industrial mineral carbonation processes is more controversial due to the uncertainty over the ultimate potential rate of sequestration, the upstream and downstream process energy requirements, and their impact on cost and the logistics of converting accessible cations to appropriately stored carbonate product. The sustainability of the technology in terms of its social acceptance is also in question. It is unlikely that these will be achieved by 2015.

Forestry

- Scientific consensus has been reached on the relevant physical processes of carbon sequestration in terrestrial biomass. Scientific consensus will not be reached on its effect on soil carbon levels until after several long-term field trials which will extend beyond 2015. Consensus on effective protocols and regulation in relation to carbon forestry is also required. It is unlikely that this will be achieved by 2015.

Biochar

- Consensus on the permanence and sustainability of carbon sequestration by biochar requires detailed results from wide-ranging research work. There is no consensus on the permanence of fossil derived biochar in soils in terms of a life-cycle analysis. Due to the diversity of feedstocks and pyrolysis processes and the consequent differences in biochar properties, scientific consensus is critical to accreditation of biochar as a permanent carbon sink. The sustainability of biochar in terms of economic and social viability is also not assured. It is unlikely that this will happen before 2015.

Soil Carbon

- Both the humic/labile soil carbon pool and the amplified effect of soil amendments such as biochar and carbon-based fertilisers are potentially significant forms of carbon sequestration but are potentially volatile in the soil. Scientific consensus on the permanence and sustainability of these forms of carbon storage requires a comprehensive program of long-term field trials. It is doubtful that these will be completed by 2015.

***Hypothesis 4:* "By 2020 coal, together with novel methods for carbon capture and sequestration, will be the lowest cost option for base-load power in Australia at emissions of 150kg/MWh, with sufficient storage capacity to make a material contribution to GHG reduction targets".**

Answer: "NO"

- All of the technologies considered herein have the potential to sequester some carbon emissions directly from coal-fired power. However none of the technologies considered have the capacity to make a material contribution to GHG reduction targets by 2020 at the hypothetical required emissions level.

Algae

- For reasons outlined previously, microalgal bio-sequestration physically constrained in terms of photosynthesis. It therefore cannot achieve CO_2 emissions of 150kg/MWh from coal-fired power stations without expensive flue gas storage. In addition, the business model for algal bio-production systems is essentially based on the production of high value algal products such as nutraceuticals or algal oils to offset fossil fuel use, not CO_2 capture.

Mineral Carbonation

- Mineral carbonation offers the potential to sequester over 100 years of Australia's industrial CO_2 emissions with domestic feedstock reserves, and this sequestration product is almost certainly permanent. Despite this mineral carbonation requires the development and commercialisation of major research and development outcomes and is very unlikely to be operable at scale by 2020.

Forestry

- Sequestration of atmospheric CO_2 by forests to offset industrial carbon emissions is the only novel technology considered by the Task Force that has been and is currently being implemented commercially. The availability of land for forestry will be key to its contribution. Evidence suggests that, by 2020, less than 2Mt CO_2 per year can be sequestered by this method.[156]

Biochar

- As a form of CO_2 storage, biochar can be produced from bio-based waste streams or from dedicated crops. The use of dedicated crops to produce biochar is subject to the same rate and scale limitations as carbon forestry (above). Applicable bio-based waste streams constitute approximately 5-10 Mt per year nationally of carbon that can be potentially sequestered as biochar. It is therefore unlikely that this method can provide a material contribution to CO_2 sequestration from coal-fired power generation by 2020. The permanence of biochar produced from fossil sources (e.g. lignite) has not been scientifically investigated with sufficient rigour to provide assurance that this method can permanently sequester large amounts of power station CO_2 by 2020.

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[156] Polglase P, Reeson A, Hawkins C, Paul K, Siggins A, Turner J, Crawford D, Jovanovic T, Hobbs T, Opie K, Carwardine J, Almeida A, "Opportunities for carbon forestry in Australia: Economic assessment and constraints to implementation", CSIRO National Research Flagships – Sustainable Agriculture. Canberra, ACT, 2011.

Soil Carbon

- The feasibility and permanence of sequestering carbon in Australian soils is uncertain. It is unlikely that long term scientific field trials and adequate remotely sensed carbon flux measurements to assess the permanence of carbon in the variety and range of Australian soils can be undertaken by 2020. The addition of humic materials in soils offers a short-term increase in soil carbon, by it is almost certain that these methods will not offer long-term (millennial) sequestration potential.

***Hypothesis 5:* "By 2015 novel carbon capture and storage will be accepted by the community and regulators through effective consultation and education, through informed social consent".**

Answer: "NO"

- The level of uncertainty regarding all forms of novel carbon sequestration is too high to provide sufficiently accurate information to satisfy true informed consent by the community by 2015.

***Hypothesis 6:* "By 2015, an internationally accepted methodology for quantifying CO_2 sequestration 'reserves', analogous to HC reserve system SPE 2007, will be developed."**

Answer: "NO"

- In light of the current state of development, no internationally accepted methodology for quantifying CO_2 sequestration capacity will be developed by 2015. It is possible to produce an acceptably focussed range of sequestration capacity for carbon forestry, algal bio-sequestration and mineral carbonation, but in a commercial framework the practical limits of these technologies will be determined by the future development of these technologies. This is unlikely to occur by 2015.

***Hypothesis 7*: "A map of the mineralization feedstocks in Australia, graded by desirability, can be produced".**

Answer: A qualified "YES"

- An audit of the accessible mineralization feedstocks from ultramafic rocks in NSW has been produced[157]. Further extensive geological study and analysis of the resource from a mine planning point of view will be required before mining commences.

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[157] Davis M., Honours Thesis, University of Newcastle, (2008).

CONCLUSIONS

The novel carbon capture and storage Task Force was convened to provide an independent assessment of the feasible potential and costs of sequestering coal fired power station CO_2 emissions by methods other than geological sequestration.

The Task Force considered the latest scientific developments in algal bio-sequestration, terrestrial bio-sequestration and mineral carbonation, and compared with them some of the claims and processes proposed by Australian proponents of such technology. Advice was solicited from experts in the field including CSIRO and international researchers and quantitative analysis carried out to the extent that reliable data was available. A qualitative opinion on the current status and prospects of each technology in Australia was formed.

The following conclusions represent the consensus view of the Task Force after consideration of these discussions and analyses. The conclusions include a judgement of the prospects for technological development in each area. Clearly, research breakthroughs and novel approaches to problems are a cornerstone of research and development and cannot be foretold. However, given the time available before 2020 and the amount of time required for a novel concept to be developed to appropriate commercial scale in this field, it is considered likely that the conclusions of this report will remain relevant over that time frame.

Algae

The culture of algae is clearly a feasible commercial venture for the production of very high value products such as nutraceuticals, specialty food products, nutritional supplements and cosmetics. The Task Force also considers that bulk volume production of algae, necessary for any meaningful CO_2 capture, has the potential to produce algal-oil at a competitive cost and scale under certain unique circumstances. Algal culture systems such as these could be deployed using industrial sources of CO_2 such as coal-fired power plants where sufficient land area and water resources are available adjacent CO_2 sources in appropriate climatic areas.

However the weight of experienced expert opinion and the analysis available to the Task Force is conclusive: algae is not a full CO_2 sequestration option for fossil fuel fired power stations. This is for two reasons: firstly, it represents only short-term storage of CO_2 in products that might offset use of fossil resources, and secondly, photosynthetic algal growth could only consume around 20% to 25% of the total CO_2 output.

The culture of algal species is presently:

- More applicable to the production of high value products than CO_2 sequestration
- Mature technology in some areas, mainly in the production of high value niche algal-derived products
- Sensitive to the following economic factors:
    - Algae productivity (lipids & biomass), showing high sensitivity to these factors.
    - Product prices, showing high sensitivity to these factors.
    - Capital including land acquisition and preparation costs.
    - Operating costs, including nutrients and flocculants.
    - The future CO_2 price trajectory under a carbon trading scheme in terms of received CO_2 credits.

- Limited in maximum sequestration potential in Australia due to :
  - Lack of suitable land adjacent to power plants.
  - Poor match between power plant and algal facility diurnal duty cycles.
  - Low winter temperatures in most power station areas.
- Could be financially viable as a bulk producer of algal oil and/or natural gas as a replacement for fossil fuels, and bulk stockfeed, provided product prices are relatively high.

Mineral Carbonation

Sufficient rock mineral resources are indicated to be available in Australia for the sequestration of all coal-fired power plant CO_2 emissions for centuries at current emission rates. In NSW, these resources are relatively close to the upper Hunter coal-fired generating facilities. This CO_2 could then be held in long-term stable carbonate products. However, the Task Force identified major engineering challenges in the upstream and downstream processes employed for mineral carbonation, including the scale of materials processing, handling, transport and disposal. Community acceptance of such large scale mining operations is also not assured. Notwithstanding these issues, the Task Force concludes that innovative solutions to these problems are being developed and could be found over time at the scale required. However, mineral carbonation processes at scale are capital intensive and complex. The time required for development of the complex novel processes from embryonic laboratory scale to meaningful commercial scale in the field will present a time barrier to their implementation. Mineral carbonation is seen by the Task Force to be a high risk, long-term option currently at an embryonic laboratory research stage.

Mineral carbonation presently:

- Requires research breakthroughs, particularly in regard to activation of minerals and the high pressure conditions under which carbonation reactions occur.
- Potentially could be made more cost-effective through novel flowsheeting and integration of process unit operations, including proving of lower cost novel processes at scale that do not require production of pure CO_2 from flue gas.
- Has been investigated only at laboratory bench scale in very small (litre scale) reactors.
- Is assessed to be subject to significant complexity and scale-up issues.
- Has unfavourable economics unless significant process and cost efficiencies are demonstrated through engineering innovation.
- Has economics that are very sensitive to by-product prices, and markets and prices for these products are uncertain at the large tonnage scales involved.

Forestry

Forestry is the only process available to Australia today that offers immediate potential for long-term sequestration of CO_2. Forestry also offers numerous ancillary benefits to the landscape, environment and community. Due to non-linear tree growth rates, forestry does not however have the capacity to make a significant impact to Australia's CO_2 sequestration in the near term (to 2020) but could make a small but meaningful impact in the period 2020 to 2050. The primary factors affecting forestry in the short term are the time required to establish forests and deploy sufficient resources nation-wide, and issues associated with land use change.

Forestry is presently:

- A mature, commercial technology.
- A technology with a non-linear and slow take-up trajectory for CO_2 sequestration.
- Cost-effective under some circumstances, including areas where high productivity and/or low relative land cost exist.
- Capacity-driven by issues of land use change and ability to deploy resources.
- Undeveloped scientifically in terms of knowledge of the carbon balance in soils.
- Not well developed in terms of regulatory framework, including agricultural CO_2 credits.

The Task Force did not assess the relative merits of bioenergy using a forestry estate for offsetting fossil fuel, as opposed to using the same trees for permanent storage. This comparison was beyond the scope of this study.

Biochar

After extensive review of the literature and discussion with leading researchers the Task Force concludes that, while some biochar may be considered permanent for the purposes of sequestration, there is insufficient scientifically validated data presently available to quantify what proportion of biochar may be ascribed that characteristic. In addition the Task Force concludes that the quantity of biochar that could be produced from agricultural and other wastes in Australia is small relative to Australia's carbon sequestration requirements.

Biochar may be used as a beneficial soil amendment, along with other forms of exogenous soil carbon addition, such as the addition of humic substances. However, these beneficial effects still need to be substantiated through long-term scientific experiments, including field trials. At the present time, the carbon permanence of these amendments has not been scientifically verified. Because of this, the life-cycle of carbon associated with biochar amendments is presently unknown and its economics (including verified agricultural financial benefits) cannot be determined.

Biochar:

- Needs substantial biological feedstocks to produce sufficient biochar.
- Needs more scientific research as a soil amendment.
- Has a high uncertainty in terms of carbon permanence in soil, dependent on feedstock and pyrolysis/formation conditions and soil conditions.
- Has the potential to create valuable bio-products as replacements for fossil fuels.
- Is uncertain in regard to scale-up to the size of the pyrolysis facilities required.
- Needs to be accredited in national and international carbon storage protocols and regulations.

Soil Carbon

The Task Force is advised that carbon levels in Australian agricultural soils have been generally declining since European settlement. This trend may have adverse consequences and in theory offers an opportunity to sequester a very significant volume of $CO_{2.}$ However current methods to increase soil carbon levels, including changes in land use practices and the use of additives such as humic acid and biochars, are not well understood and are difficult and expensive to measure. Soil carbon is a dynamic pool and any action to increase soil carbon levels must be maintained over time periods of the order of 100 years to qualify as a sequestration activity.

The Task Force has not formed an opinion on the long-term (2050) capacity of Australian soils to sequester CO_2 and considers soil science, soil carbon measurement and long-term field trials of soil amendments under typical conditions to be key research areas to verify this capacity. Importantly, the use of fossil carbon for soil amendment requires further scientific measurement and life cycle assessment to determine any net CO_2 benefit.

Soil carbon amendment is:

- Yet to be sufficiently scientifically evaluated.
- Uncertain in respect of permanence, effectiveness and potential scale.
- Expensive and time consuming in terms of measurement, needing wide-ranging.scientific research across different soil types, spatial land zones and temporal scales.
- Supported by anecdotal evidence of improvements in soil quality, but this needs to be verified in high quality scientific experiments and field trials.

Financial and other Comparisons between Technologies

The Task Force has undertaken a comparison of the novel technologies and geological CCS in terms of potential contribution to CO_2 sequestration, cost, resources consumption and environmental impact[158]. In terms of **cost** (or “Price of CO_2 Required” for financial viability), geological CCS is of the same order of cost or less than the novel technologies, depending on the location of the storage basin relative to the CO_2 emitter. Managed forestry has the lowest cost, but its development will depend on land availability for the large land areas required. Algae capture of CO_2 could be low cost if algal productivity is high and the revenue received from the algal by-products is high. This will depend on the technical outcomes achieved at large-scale demonstration projects and the global price of (for example) algal-oil. Mineral carbonation by the conventional heat-activated rock process is calculated to have relatively high costs at this stage for unimproved processes. Lower costs could be available through innovation in the process and integration of the CO_2 capture and carbonation steps. The task force did not undertake a cost analysis of the production of biochar or enhancement of soil carbon due to the unavailability of published costs in for this technology.

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[158] Section 5 of the report contains the financial analysis details. The reader is referred to Section 6 of the main body of the report for details on the technology comparisons in dimensions other than financial.

GLOSSARY OF TERMS

Ammonium carbonate, $(NH4)_2CO_3$	Ammonium carbonate; commonly used as a source of bioavailable nitrogen in cell culture media.
ABARE	Australian Bureau of Agricultural and Resource Economics.
abatement	Suppression or termination, specifically a reduction in greenhouse gas emissions compared with business-as-usual case.
ABS	Australian Bureau of Statistics.
acetic acid	Clear colourless pungent organic acid, major constituent of vinegar, used as a solvent for various industrial purposes, CH_3COOH.
ACIAR	Australian Chair for International Agricultural Research.
ACRE	Australian Centre for Renewable Energy.
activation (mineral carbonation)	Converting metal oxides in minerals into a state in which they can react more rapidly with carbon dioxide to form carbonates.
additionality	Reduction in net emissions by sources, or enhancement of removals by carbon sinks, that is additional to the reduction that would occur in the absence of an incentive provided through a program.
adenosine	A nucleoside formed by the condensation of adenine with ribose, a major component of DNA, RNA and adenosine phosphates http://en.wikipedia.org/wiki/Adenosine
ADP	Adenosine Diphosphate; a high energy compound containing adenosine and two phosphates.
adsorptive	To gather on a surface in a condensed layer.
AEMO	Australian Energy Market Operator. http://www.aemo.com.au/
agroecosystem	That part of the biological ecosystem impacted by or impacting on agriculture.
albedo	The ratio of the light reflected by a planet or satellite to that received by it http://en.wikipedia.org/wiki/Albedo
algae	any of numerous groups of chlorophyll-containing, mainly aquatic eukaryotic organisms ranging from microscopic single-celled forms (micro-algae) to multicellular forms 100 feet (30 meters) or more long (macro-algae); distinguished from plants by the absence of true roots, stems, and leaves and by a lack of non-

	reproductive cells in the reproductive structures: classified into the six phyla Euglenophyta, Crysophyta, Pyrrophyta, Chlorophyta, Phaeophyta, and Rhodophyta.
algal oil	Natural storage oils produced by many species of microalgae; similar to vegetable oil.
alkaline earth metals (Ca^{2+}, Mg^{2+})	Group 2 elements on the period table consisting of bivalent metals the hydroxides of which are alkalis.
ammonia	NH_3; a gas at STP and major source of fixed nitrogen for cell culture. Can also be utilised for absorption of CO_2 from flue gas.
amphibole	A category of crystallised silicate minerals.
ANLEC R&D	Australian National Low Emissions Coal Research and Development; national body formed by the National Low Emissions Coal Council (NLECC) to implement a national program for low emission coal research and development to address the research priorities identified in the NLECC strategy. http://www.anlecrd.com.au/
anthropogenic	Caused or produced by humans.
anthrosol	Soil that has been formed or heavily modified by human activity.
aquatic	Of or related to water.
aqueous process	A process performed in a solution or suspension of water.
aquifer	A body of permeable rock that can contain or transmit groundwater.
arable land	Land that can be used for growing crops (as opposed to arid land).
ARC	Albany Research Centre (Oregon), part of the US Department of Energy http://www.netl.doe.gov/about/arc_history.html
asbestos	A refined fibrous mineral derived from amphibole and chrysotile, previously used as a building product; highly heat resistant; has adverse health effects.
aseptic	Free from competing or contaminating organisms, especially pathogens.
ASP	Aquatic Species Program; research program conducted by the National Renewable Energy Laboratory of the US DOE with the goal of producing fuel from cultured algal biomass.
ASPEN	Proprietary process modeling software: http://www.aspentech.com/core/aspen-plus.aspx

associated gas	Natural gas found in a crude oil reservoir, either separate from or in solution with the oil
astaxanthin	A carotenoid used as a nutritional supplement for its antioxidant properties. http://en.wikipedia.org/wiki/Astaxanthin
Atm, atm	Atmospheres; a unit of pressure equal to the normal air pressure at sea level.
ATP	Adenosine Triphosphate; a compound containing greater chemical energy than the related ADP, made up of adenosine and three phosphates.
ATSE	The Australian Academy of Technological Sciences and Engineering.
autotroph	An organism that can produce all the higher-energy compounds it requires for nourishment from inorganic precursors. http://en.wikipedia.org/wiki/Autotroph
bagasse	Fibrous biomass material remaining after sugar cane has been mechanically crushed.
bankability	Characteristics that qualify and enable a project to be successful in applying for finance.
bar	One atmosphere pressure (approximately equal to one Atm).
basalt	Igneous rock derived from lava flows consisting largely of labradorite and pyroxene. http://en.wikipedia.org/wiki/Basalt
Base technology	A stage of technology development described by Arthur D. Little (see section 4.1) as having progressed beyond 'Key' and been adopted as standard industry practice by a large number of companies.
BC	Black Carbon; term to describe carbonaceous biochar.
BCIA	Brown Coal Innovation Australia Limited; not-for-profit company dedicated to developing sustainable processes for exploiting brown coal reserves in Australia by promoting research and development. http://www.bcinnovation.com.au/
BEC	Bare Erected Cost, the capital cost of a facility based on the addition of all the components before adding contingencies and other development costs.
Beta-carotene	A nutraceutical that can be converted by the body into Vitamin A. http://en.wikipedia.org/wiki/Betacarotene
BFS	BioLogic Farming System, marketed by Australian firm LawrieCo. http://www.lawrieco.com.au/

BiG Char	Black is Green; pyrolysis for biochar proponent based in Mackay, Queensland. http://www.bigchar.com.au/
biochar	Charcoal derived from biomass through an applied chemical or physical process.
biodiesel	Diesel fuel derived from a recent biological source rather than refined from crude oil.
biodigestor	A manufactured reactor that creates an environment where biological digestion of feedstocks can be optimised.
biofuels	Fuel products produced from biological feedstock processing, specifically in contrast to fossil fuels.
biological capture and storage processes	Any process using biological systems (specifically photosynthesis) to absorb and store carbon dioxide.
biomass	Biological matter.
Bio-sequestration	See ‘Biological capture and storage processes’.
Biosystem	Interrelated network of biological components.
BoM	Bureau of Meteorology; Australia’s national weather, climate and water agency.
boreal	Ecosystems located in sub-arctic zones.
brackish water	Water with a moderate concentration of salts – between fresh and seawater.
brine	Water with a high concentration of salts – more so than seawater.
broadacre	Description of land suitable for farms conducting large scale crop operations.
buffer	An ionic compound added to solution to resist changes in acidity/alkalinity, or pH.
business as usual	A scenario of future greenhouse gas emissions that assumes that there would be no major changes in policies on mitigation.
^{o}C	Degrees Centigrade.
Ca	Calcium; an element in the alkaline earth group with atomic weight 20; soft grey metal. http://en.wikipedia.org/wiki/Calcium
Ca^{2+}	Calcium ion, counter ion to carbon dioxide to form calcium carbonate.
$CaCl_2$	Calcium chloride.
$CaCO_3$	Calcium carbonate.

CaO	Calcium oxide.
cap and trade scheme	A regulated system which sets a quantitative limit on emissions of carbon dioxide by issuing credits and allowing trade of credits to accommodate changes in emissions.
capacity factor	The relationship between actual power produced from a generation system compared with full nameplate capacity over a given period of time. Also defined in this report in terms of CO_2: Actual CO_2 absorbed by algae compared with the amount captured at full algal productivity.
Carbon capture	A process which removes carbon dioxide from the atmosphere, most commonly by transferring it from a gaseous state into liquid or solid products.
carbon cycle	The term used to describe the movement of carbon in various forms (for example, as carbon dioxide or methane) through the atmosphere, ocean, plants, animals and soils.
carbon dioxide fertilization	Increasing plant growth or yield by elevated concentrations of atmospheric carbon dioxide.
carbon price	The price at which emissions permits can be traded, nationally or internationally, or the tax charged per tonne of CO_2 emitted.
carbon sink or reservoir	The parts of the carbon cycle that store carbon in various forms.
carbon storage	The separation of carbon from atmospheric carbon dioxide and its sequestration for extended periods of time.
carbon tax	A tax levied on emissions of CO_2 and other greenhouse gases.
carbonaceous	Containing carbon.
carotenoid	Any of a group of red and yellow pigments contained in animal fat and some plants. http://en.wikipedia.org/wiki/Carotenoid
cation	A positively charged ion that is attracted to the cathode in electrolysis. http://en.wikipedia.org/wiki/Cation#Anions_and_Cations
CCS	Carbon Capture and Storage; processes which together remove carbon dioxide from a mix of gases and separate it from the atmosphere for an extended period of time.
CDM	Clean Development Mechanism; a flexibility mechanism under the Kyoto Protocol that allows Annex I countries to meet part of their obligation to reduce emissions by

	undertaking approved emissions reduction projects in developing countries. Emissions reductions under the CDM can create tradable permits offset credits, called certified emission reductions or CERs.
cellulose	Structural component of the cell walls of green plants.
CFI	Carbon Farming Initiative; a program by the Australian Government.
CH_4	Methane; the simplest alkane and major constituent of natural gas, a powerful greenhouse gas.
charcoal	Carbonaceous material produced by heating organic substances in the absence of oxygen.
chelators, EDTA	Ethylenediaminetetraacetic acid; one of a group of chemicals (chelators) used as a ligand to prevent metals from reacting with surrounding reactants. http://en.wikipedia.org/wiki/Chelator
chrysotile	A common form of natural asbestos (fibrous serpentine). http://en.wikipedia.org/wiki/Chrysotile
citric acid	$C_6H_8O_7.H_2O$, an intermediate in the metabolism of carbohydrates naturally occurring in many fruits. http://en.wikipedia.org/wiki/Citric_acid
climate change	A change in the state of the climate that can be identified (for example, by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer.
climate sensitivity	A measure of the climate system's response to sustained radiative forcing. Climate sensitivity is defined as the global average surface warming that will occur when the climate reaches equilibrium following a doubling of carbon dioxide concentrations.
CMAR	CSIRO Centre for Marine and Atmospheric Research. http://www.cmar.csiro.au/
CO_2	Carbon Dioxide; gas at STP; commonly formed from the combustion of a fuel with oxygen.
CO2CRC	The Cooperative Research Centre for Greenhouse Gas Technologies; a joint venture comprising participants from Australian and global industry, universities, and other research bodies. http://www.co2crc.com.au/

CO_2-e	Carbon Dioxide Equivalent; the power of a climate forcing effect expressed as that amount of carbon dioxide required to create the same result.
coal	Geological residue partially decayed plant matter rich in carbon; fossil carbonaceous material tens to hundreds of millions old.
commercial scale	A process operating at such magnitude that it can form the basis of a viable business and have a discernable impact on an industry.
comminution	the action of reducing a material, an ore, to minute particles or fragments.
conceptual	A stage of technology development preceding the 'embryonic' stage defined by Arthur D. Little (see section 4.1). Conceptual stage technologies have not been tested experimentally and are merely concepts.
coppice	To harvest a plant above the roots so that new growth can sprout from the stump. http://en.wikipedia.org/wiki/Coppice
counter-ions	Ionic component that can form a compound with a specified element.
counter-party risk	(also default risk); the risk that an organization does not pay out on a credit derivative, credit default swap, credit insurance contract, or other trade or transaction when it is contracted to.
CPI	Consumer Price Index.
Cr	Chromium; a grey, lustrous hard metal. http://en.wikipedia.org/wiki/Chromium
crustal	Related to the earth's crust, the upper layers of geological formations.
CSIRO	Commonwealth Scientific and Industrial Research Organisation.
CSLF	Carbon Sequestration Leadership Forum.
cytosol	The solution of proteins and metabolites inside a biological cell, in which the organelles are suspended .
D	Debt.
daf	Dry ash free.
DAFF	Department of Agriculture Fisheries and Forestry.
DCC	Department of Climate Change.

deforestation	The decline in regions of natural forest.
dewatering	Process of removing water from a target material.
diatom	Algae species containing silica in their cell walls.
diffusion	The spreading of free molecules from a region of high concentration to a region of lower concentration under the influence of only the concentration gradient.
direct emissions	Emissions from sources within the boundary or control of an organisation's or facility's (or individual's) processes or actions. They can include emissions from fuel combustion (for example, in transport) and non-combustion emissions arising from physical or chemical processes (for example, in agricultural production or industrial manufacturing).
diurnal	Following a daily cycle.
DNA	Deoxyribonucleic Acid; molecular constituents of genetic material. http://en.wikipedia.org/wiki/DNA
DOE	Department of Energy (United States).
DPI	Department of Primary Industries, Victoria.
dunaliella	Genus of green microalgae common in marine waters.
dunite	A green to brownish coarse-grained igneous rock consisting largely of olivine.
E	Equity.
EBIT	Earnings Before Interest and Taxes.
EBITDA	Earnings Before Interest, Taxes, Depreciation and Amortization.
ecosystem	The macro-scale biological network of organisms and processes.
electrolytic cell	Apparatus for decomposition of chemical compounds by the application of electrical current.
embryonic	A stage of technology development described by Arthur D. Little (see page 4.1) as having been tested by some experimental procedures but requiring extensive further development.
endogenous soil carbon	Organic carbon pre-existing or generated in soil as a result of natural processes.
Enhanced Oil Recovery (EOR)	Method of extracting the final parts of a volume of oil from a reservoir by the injection of CO_2 gas.
enzyme	Proteinaceous structure that catalyzes biological

	reactions. http://en.wikipedia.org/wiki/Enzyme
EPC – contractor services	Engineer/Procure/Construct services; various subcontracted responsibilities for a project taken as a single cost.
ex-situ	Out of its natural place.
exogenous soil carbon	Carbon added to soil by artificial means such as spreading carbon-based fertilizers over the surface or addition of biochar.
exothermic	Yielding energy in the form of heat.
FCF	Free Cash Flow.
Fe	Iron, a silver grey metal that is rapidly oxidised in air to form a brown-orange oxide coating. Exists in different oxide forms in nature, including hematite and magnetite. http://en.wikipedia.org/wiki/Fe
Fe_3O_4	Magnetite, an oxide of iron.
feedstock	Material required by a process for conversion to products.
FFICRC	Future Farm Industries Cooperative Research Centre – Australian research group dedicated to the development of farming technology.
FGD	Flue gas desulphurization; processes designed to remove sulphur-containing contaminants from flue gas.
fibre optic	Thin artificial tubes that conduct light with no loss.
Fischer-Tropsch (FT) synthesis	Chemical process converting synthesis gas to hydrocarbons.
flocculation	The process by which dispersed objects in solution combine to form masses (flocs); flocculant is a chemical compound that promotes flocculation. http://en.wikipedia.org/wiki/Flocculant#Flocculants
flue gas (coal-fired flue gas)	Gas resulting from the combustion of coal, predominantly nitrogen with around 12-13% CO_2 and trace oxygen.
flyash	Fine particulates produced from coal ash during combustion; generally removed from flue gases by physical means.
FOAK	First Of A Kind (specifically in terms of industrial products).

fossil fuel	Any combustible organic material derived from the remains of former life.
fulvic acids (fulvic pool)	A yellow to yellow-brown humic substance that is soluble in water under all pH conditions. Fulvic acids have lower molecular weight and higher oxygen than other humic acids. http://en.wikipedia.org/wiki/Humic
g	Gram; a unit of weight equal to one thousandth of a kilogram.
G	A unit of acceleration equal to the acceleration of gravity.
gamma radiometric	A process that uses gamma radiation to measure phenomena.
Global CCS Institute	Global Carbon Capture and Storage Institute Limited. http://www.globalccsinstitute.com/
GCTB	Green Cane Trash Blanketing; a method of distributing trash on sugar can field for agricultural purposes.
gel	Semirigid colloidal dispersion; a gel is mainly liquid, but behaves like a semi-rigid solid. http://en.wikipedia.org/wiki/Gel
geochemical capture and storage processes	The capture and storage of CO_2 in the earth after chemical conversion to another compound (e.g. carbonates, biochar).
geophysical capture and storage processes	Geological sequestration; the capture and storage of CO_2 in the earth as a liquid without chemical conversion.
GHG	Green House Gas. http://en.wikipedia.org/wiki/Greenhouse_gas
GJ	Gigajoule; One thousand million Joules.
glucose	A simple sugar used by cells to provide energy.
GM	Genetically modified (as in GM organisms).
GMO (Genetically Modified Organism)	An organism containing genetic material originating from human action; genetic engineering. http://en.wikipedia.org/wiki/GMO
greenhouse effect	The trapping of the sun's warmth in a planet's lower atmosphere due to the greater transparency of the atmosphere to visible radiation from the sun than to infrared radiation emitted from the planet's surface.

groundwater	Water sourced from subsurface natural reservoirs.
Grubb curve	Mathematical trajectory described by Michael Grubb, Cambridge University, to illustrate the firstly increased and then reduced cost and effort required for processes as their understanding increases from the conceptual level.
Gt	Gigatonne; one thousand million tonnes.
GWh	Gigawatt Hour; 1000 MWh.
H_3PO_4	Phosphoric acid; a common source of phosphates for use in cell culture media.
ha	Hectare; a unit of area equal to 10,000 square metres.
Harzburgite	A plutonic rock of the peridotite group consisting largely of orthopyroxene and olivine. http://en.wikipedia.org/wiki/Plutonic http://en.wikipedia.org/wiki/Peridotite
HC reserve system SPE	Hydrocarbon reserve system of the Society of Petroleum Engineers. http://www.spe.org/index.php
HI	Harvest Index
HPAL	High Pressure Acid Leaching; industrial process typically used for processing nickel laterite ores involving the high pressure contacting of the ore with acids.
humic acids (humic pool)	Component of soil which decomposes at an intermediate rate resulting in a turnover time of decades (from humus; a heterogenous mixture of decomposing biomass).
humified	That component of organic breakdown material converted to humic acid.
hydrocarbon	A compound containing only hydrogen and carbon, commonly found naturally in crude oil. Hydrocarbons form the basis of most of the fuel sources used.
hydrocarbon exuding algae	Algae such as certain green algae *botryococcus* strains or genetically modified organisms that can produce and export hydrocarbons into the surrounding media.
hydroxide	A chemical compound containing the hydroxyl group, OH.
ICS	Integrated Carbon Sequestration Pty Ltd; An Australian company promoting mineral carbonation processes.
IEA	International Energy Agency.

	http://www.iea.org/
IER	Ignite Energy Resources; an Australian company promoting the processing brown coal (lignite) resources.
IGCC	Integrated Gasification Combined Cycle: a fuel gas combustion process involving both a gas turbine and a steam turbine to improve overall heat efficiency. http://en.wikipedia.org/wiki/CCGT
IMF	International Monetary Fund. http://www.imf.org/external/index.htm
in-situ	In its original place.
informed consent	Permission granted in the full knowledge of the possible consequences.
inoculum	A small volume of highly concentrated microorganisms for transfer into a larger volume of media to generate a large homogenous population (*pl*. inocula).
insolation	The amount of solar radiation reaching a given area in a given time.
interstices	An intervening space, especially a very small one.
ion	An electrically charged atom formed by the loss or gain of an electron.
IP	Intellectual Property; legally recognised property resulting from original creative thought.
IPCC	Intergovernmental Panel on Climate Change. http://www.ipcc.ch/
IRR	Internal Rate of Return: the rate of return used in capital budgeting decisions to measure and compare the profitability of investments. The rate of return that yields zero Net Present Value (NPV).
Joule, J	Unit of energy in the SI system of units; the energy expended in applying a force of one Newton through a distance of one metre.
K	Potassium, an alkali metal that oxidises rapidly in air. http://en.wikipedia.org/wiki/Potassium
Key	A stage of technology development described by Arthur D. Little (see section 4.1) as having progressed beyond pacing and been fully commercialised by a small number of companies, giving them a competitive advantage over the rest o their industry.

kg	Kilogram; one thousand grams.
kha	One thousand hectares.
KH_2PO_4	Potassium Phosphate; soluble salt used as a fertilizer and rich source of potassium and phosphate for cell culture.
KNO_3	Potassium nitrate (saltpetre); component of fertilizer that is rich in potassium and fixed nitrogen.
kWh	Kilowatt-hour; a unit of energy equal to a power of one thousand watts operating for one hour.
Kyoto protocol	An amendment to the United Nations international treaty on global warming in which participating nations commit to reducing their emissions of carbon dioxide, negotiated in Kyoto, Japan, in 1997.
labile pool	Component of soil which decomposes rapidly resulting in a turnover time of 1-5 years.
LCA (Life Cycle Analysis)	Technique used to assess and quantify the overall effects of a product including production, operational life and disposal.
leaching	Method of removing solids from a mixture by dissolving them in a solvent and extracting the required component from the solid phase.
lignite	Brown coal; coal resulting from the decomposition of biomass in the absence of high pressure (as compared with black coal) consequently demonstrating a higher moisture content. A fossil material younger than black coal. http://en.wikipedia.org/wiki/Lignite
lignotuber	A starchy swelling of the root crown of a plant containing buds from which new stems may sprout and to provide a store of nutrients in the absence of photosynthesis. A protection of the plant from fire.
limestone	Sedimentary rock consisting predominantly of calcium carbonate. http://en.wikipedia.org/wiki/Limestone
lipids	One of three chief structural components of living cells (along with carbohydrates and proteins); esters of fatty acids. http://en.wikipedia.org/wiki/Lipid
Liquefied Natural Gas (LNG)	Natural gas (predominantly methane) in compressed liquid form.
m^2	Metres squared; a unit of area equal to a square one metre by one metre.

magnetite, Fe_3O_4	Black iron oxide mineral that is magnetic.
mallee	Low, shrubby eucalyptus trees that flourish in desert regions of Australia. http://en.wikipedia.org/wiki/Mallee_%28habit%29
MEA	Monoethanolamine; a weak base used as a solvent to remove carbon dioxide from flue gas in a carbon capture process . http://en.wikipedia.org/wiki/Monoethanolamine
Mg	Magnesium; an element with atomic number 12 in the alkaline earth group; grey reactive metal. http://en.wikipedia.org/wiki/Magnesium
$Mg(OH)_2$	Magnesium hydroxide; inorganic alkaline compound reactive with acids including carbon dioxide to form Magnesium carbonate.
Mg^{2+}	Magnesium ion; counter-ion for the formation (with carbon dioxide) of magnesium carbonate.
MgCl	Magnesium chloride; salt of magnesium.
$MgCO_3$	Magnesium carbonate; a stable product of the reaction of magnesium with carbon dioxide.
MgO	Magnesium oxide; compound readily forming magnesium carbonate but rarely found in natural formations.
microalgae (microalgal)	Microscopic, usually single-celled, algae (and the products of them).
microbial	Related to microbes; microscopic organisms, typically bacteria and yeasts.
mineral sequestration	Conversion of gaseous carbon dioxide to carbonates by reaction with metal oxides, especially Mg and Ca.
MIT	Massachusetts Institute of Technology; university in Boston, USA. http://web.mit.edu/
MJ	Megajoule; one million joules.
mm	Millimetre; one thousandth of a metre.
Monte Carlo method	Class of computational algorithms that rely on repeated random sampling to compute their results.
MRET	Mandatory Renewable Energy Target; an increasing target for deployment of renewable energy by the Australian Government.

Mt	Megatonne; One million tonnes.
MW	Megawatt; a unit of power equal to one million watts.
MWh	Megawatt-hour; a unit of energy equal to a power of one million watts operating for one hour.
N_2, N	Nitrogen; a colourless gas occupying 79% of the atmosphere.
N,P,S	Nitrogen, Phosphorous (as phosphate), and Sulphur – essential micronutrients for organic growth and development in soils.
N_2O	Nitrous oxide (gas), commonly produced in the breakdown of nitrogen compounds; 310 times more powerful than CO_2as a greenhouse gas.
NaCl	Sodium chloride; common table salt.
$NaHCO_3$	Sodium bicarbonate; baking soda.
Nannochloropsis	Genus of alga used for the production of Astaxanthin.
NaOH	Sodium hydroxide; caustic soda or lye, common source of alkalinity or high pH.
natural Gas	Flammable gas (predominantly methane, CH_4) often found in association with oil and coal, and used as a fuel. http://en.wikipedia.org/wiki/Natural_gas
NBT	Nature Beta Technologies; Israeli proponent of algal products.
NCTF	Novel Carbon Task Force (Novel carbon capture and storage task force) – group commissioned by the sponsors to produce this report.
NETL	National Energy Technology Laboratory, part of the United States Department of Energy. Conducts and coordinates a diverse range of research relevant to fuel and energy systems. http://www.netl.doe.gov/
neutron scattering	Experimental technique that uses the phenomena of the scattering of free neutrons by matter to investigate the properties of materials. http://en.wikipedia.org/wiki/Neutron_scattering
NGO	Non-Governmental Organisation.
NH_4NO_3	Ammonium nitrate; commonly used in fertilizer as a rich source of fixed nitrogen.
Ni	Nickel, a silvery-white lustrous metal.

	http://en.wikipedia.org/wiki/Nickel
niche	A small specialised section of a wider system.
novel carbon capture	For the purposes of this report any form of carbon capture other than geological sequestration.
novel carbon storage	For the purposes of this report any form of carbon storage other than pure compressed CO_2 in underground formations (geological sequestration).
NO_x	Oxides of nitrogen; common contaminants in coal-derived flue gas.
NPOV	Net Present Options Value; the current value of options to own future property, based on net present value probability distribution of an investment.
NPP	Net Primary Productivity; the total biological productivity of an area accounting for production and loss.
NPV	Net Present Value; an economic standard of evaluating a time series of cash flows, discounted from future years at the weighted average cost of capital (WACC).
nutraceutical	A food with both nutritional and medicinal benefit.
nutrient	A substance that provides nourishment to living organisms.
obduction	A geologic process in which the edge of a tectonic plate consisting of oceanic crust is thrust over the edge of an adjacent plate consisting of continental crust.
offgas	The crude gaseous components released by chemical processes.
OH^-	Hydroxide ion that may complex with a metal to form a metal hydroxide.
olivine	An olive-green, gray-green, or brown mineral occurring widely in basalt, peridotite, and other basic igneous rocks. It is a silicate containing varying proportions of magnesium, iron, and other elements. $(Mg,Fe)_2SiO_4$.
organic	Class of chemical compounds containing carbon.
overnight costs	The cost of construction of a project if no interest was incurred during construction.
OREC	Oxidative Resistant Elemental Carbon.
P	Phosphorous, an element with atomic number 15. Phosphorus is found in its oxidised state in nature due to its high reactivity.
Pacing	A stage of technology development described by Arthur D. Little (section 4.1) as possessing the potential to radically change the basis of competitiveness but has not

	yet come into use across an entire industry.
Pareto analysis	Identification of the most effective tasks for achieving the greatest effect with minimal resources. (based on the Pareto principle expressed by Vilfredo Pareto).
passivating	Tendency to resist or reduce a specific chemical process.
PCC	Post Combustion Capture; the capture of carbon dioxide from flue gas after combustion in a boiler or gas turbine.
permanence	Perpetual or continued existence; specifically in the case of carbon storage, the length of time storage can be considered permanent. The task force considers periods over 100 years a *minimum* prerequisite for permanence.
permeability	A measure of the resistance of a material to the flow of liquid or gas through it.
pH	A measure of acidity or basicity of an aqueous solution. http://en.wikipedia.org/wiki/PH
pharmaceutical	A medicinal drug.
photo-bioreactor	A vessel in which photosynthetic organisms can be cultured using light.
photosynthesis	The process by which photoautotrophic organisms use light energy and chemical building blocks to produce higher-energy compounds. http://en.wikipedia.org/wiki/Photosynthesis
PJ	Petajoule; 10^{15} Joules.
polycyclic aromatic hydrocarbon, PAH	PAH; hydrocarbons in the form of fused stable continuous rings that enable electrons to cycle throughout the molecule; potent atmospheric contaminants and high energy fuels.
porosity	A measure of the volumetric concentration of pores in a material suitable for the passage of liquids or gases.
porosity (geological porosity)	Measure of the void space available in a given volume of geological media, particularly with respect to that available for passage and storage of gasses and liquids.
ppb	Parts per billion.
ppm	Parts per million.
process intensification	Steps taken to reduce the resource requirements and optimising the production of valuable products of a given process for commercial optimisation.
protozoa	Single cell eukaryotic organisms; primitive superphylum

	of organisms in the kingdom Protista. http://en.wikipedia.org/wiki/Protozoa
PUFA	Poly Unsaturated Fatty Acids; fatty acids that contain more than one double bond in their chemical structure. http://en.wikipedia.org/wiki/PUFA
pyrolysis	Decomposition of organic materials brought about by high temperatures, specifically in the absence of oxygen.
raceway pond	A biological reactor system using a liquid medium (water) circulating along a large continuous open channel by paddles, allowing low-cost movement and mixing.
rangelands	Open vegetated country commonly devoted to grazing for farmed cattle.
RCO_2	value used in the field of mineral carbonation to describe the ratio of material to the volume of CO_2 it can absorb
RD&D	Research, Development and Demonstration.
reafforestation	Conversion of previously deforested land back into forested land.
renewable energy	Sustainable sources of energy that may be replenished within a reasonable amount of time.
RNA	Ribonucleic Acid; genetic material. http://en.wikipedia.org/wiki/RNA
S	Future cash flows of a project from its operations.
saline	A solution that contains a high concentration of salts – similar to seawater.
salinity	A measure of the concentration of salts in solution; also used to describe the salt content of soils
sapwood	Part of the wood of a living plant where sap flows.
savannah	Open country commonly dominated by grasses with few trees.
scenario	An analysis dataset based on a consistent set of assumptions.
scientific consensus	Agreement among a majority of experienced research scientists on a specific topic.
sequestration	Removal and permanent emplacement of a part of a mixture, especially gaseous components; see carbon capture and storage.
serpentine	Dark green mineral derived from serpentinite consisting largely of magnesium oxides.

	http://en.wikipedia.org/wiki/Serpentine_group
serpentinite	A dark, typically greenish metamorphic rock, consisting largely of serpentine or related minerals, formed when mafic igneous rocks are altered. http://en.wikipedia.org/wiki/Serpentinite
Si	Silicon, a metalloid element, atomic number 14. http://en.wikipedia.org/wiki/Silicon
silica	Natural source of silicon dioxide, SiO_2.
silicate rocks	Rocks containing silicon and oxygen and specifically in this report those also containing magnesium and/or calcium.
soil amendment	A component of soil externally applied to produce a specific effect, commonly increasing soil productivity.
soil carbon accounting methodology	A systematised and widely accepted process for measuring and expressing the amount of carbon contained within soils.
solar aperture	The area of an opening allowing solar radiation to pass.
SO_x	Oxides of sulphur; common contaminants in coal-derived flue gas.
sp.	Species; a class of individuals having common characteristics, subset of genus.
spectroscopic	Process of measurement using light.
stockfeed	Source of nutrients and food for farm stock including cattle and sheep.
stover	Leaves and stalks of maize, left in the field after harvest.
supercritical	Condition of temperature and pressure at which a specific material exists beyond its critical state, intimating a change in physical properties; a supercritical fluid has the properties of both a liquid (density) and a gas (viscosity).
syngas	Synthesis Gas; purified off gas generally comprising a mixture of carbon monoxide (CO) and hydrogen (H_2).
TASC	Total As Spent Costs; current measure of capital invested in a project at any one time.
technoeconomic analysis	Quantification of the feasibility and cost of a technology.
technology risk	The chance that a given product or process on which operation relies will not achieve the expected results.
temporal	Of time. Temporal variability – a difference in properties of a studies object at different times.

TWh	Terawatt-hour, 1000 GWh or 1 million MWh.
terrestrial plants	Organisms from the plant kingdom which grow on land.
TJ	Terrajoule, 1000 GJ, or 1 million MJ, or 10^{12} Joules.
topographical	Describing landscape features.
TPC	Total Project Costs; equals BEC+ process contingency + EPC + project contingency.
transesterification	In organic chemistry, a reaction where the organic unit of an ester is exchanged with the organic unit of an alcohol; that is, between one ester and another alcohol to form the ester of the alcohol and the alcohol of the ester (e.g. reaction between methyl acetate and ethyl alcohol to form methyl alcohol and ethyl ester); inter-esterification.
trash	Biomass material (leaves and stalks) left on field after sugar cane harvesting.
triglyceride	An ester of glycerol and a carboxylic acid.
ultramafic rocks	Igneous rocks composed chiefly of mafic minerals; a silicate mineral that is rich in magnesium and iron (hence “mafic”).
volatility	A financial measure in this report; a measure of the standard deviation of the probability distribution of the net present value of an investment.
WACC	Weighted Average Cost of Capital; the average of the cost of both debt and equity components of capital, weighted for the leverage or debt to equity ratio.
Wollastonite	A naturally occurring calcium silicate mineral.
X	Capital costs invested in a project; in options theory the “exercise price” of the option.

APPENDICES

APPENDIX A: Novel CO_2 Capture Task Force Scope of Work

A.1 Context

There are an increasing number of proponents of non-geological capture of CO_2 from power generation, including technologies such as bio-sequestration and mineral sequestration. The Australian Government under the National Low Emissions Coal Initiative established the Carbon Capture Task Force (CSTF) in October 2008 to develop the Carbon Mapping and Infrastructure Plan for geological storage of CO_2. This plan was delivered in September 2009. However, the science and technology of non-geological sequestration of CO_2 is often not as well developed and some of the proponents are making claims that may be unsubstantiated by the science and engineering as it stands. The objective of the present project is to prepare a report similar to that delivered by the CSTF on non-geological capture of CO_2 using a Novel Capture Task Force (NCTF).

Bio-sequestration is the capture and storage of atmospheric CO_2 by biological processes. This may be by increased photosynthesis (through re-forestation, or decreased de-forestation); by enhanced soil carbon trapping in agriculture; or by the use of algal bio-sequestration to absorb CO_2 from industrial processes. *Mineral sequestration*, or mineral carbonation, involves reaction of CO_2 with metal oxides that are present in common, naturally occurring rocks. This process mimics natural weathering phenomena, and results in natural carbonate products that are stable on a geological time scale. The report will consider both bio-sequestration and mineral sequestration opportunities.

Objective

Given the range of non-geological storage techniques and the number of proponents promoting them, the study will provide an independent assessment that ascertains the feasible potential and costs in Australia of novel CO_2 capture and sequestration techniques. The concise report and supporting comprehensive analyses will be delivered within six months of the commencement of the study.

Sponsors

The project will be sponsored and funded equally by:

- Australian Low Emissions Coal Research and Development Limited (ANLEC R&D)
- Brown Coal Innovation Australia Limited (BCIA)
- Global Carbon Capture and Storage Institute Limited

Representative of these three organisations will form a Project Steering Committee to whom the NCTF will regularly report progress and to which the NCTF interim and final reports will be presented.

ANLEC R&D will, on behalf of the sponsors, contract with members of the NCTF and other service providers to undertake the project, and will account to BCIA and Global CCS Institute for receipt and expenditure of funds for the project.

The Task Force (NCTF)

The Task Force (NCTF) will comprise a small number of members with wide-ranging experience:

Chair:	Dr. John Burgess
Members:	Jeffery Lewis
	Dr. Allan Lowe
	Dr. Stephen Schuck

These members have experience in the fields of industrial R&D, project investment, mining, environmental and safety management, power generation, biotechnology and engineering and process plant engineering. Their input to the project will be of a leadership, judgment and editorial nature.

A secretariat for the Task Force will be provided by the University of Melbourne's *Melbourne Energy Institute*. A post-graduate fellow with qualifications in biotechnology will provide full time to provide scientific support and technical services to the Task Force. Some secretarial support and other resources as necessary will also be provided.

CSIRO will provide expert resources to the project from the following personnel, who will assist with scientific advice on the various proposed technologies:

Co-ordination	Dr. John Carras
Soil Carbon	Dr Michael Battaglia
Mineralisation	Dr Greg Duffy
Algal fixation	Dr Victoria Haritos
Novel coal processes	Dr Louis Wibberley

Other expertise will be accessed for the study. This will include Fellows of the learned Academies and university academics, as appropriate.

A.2 The Task Force Process

The Task Force will undertake the following steps to progress the study:

1. Strategy Workshop

A strategy workshop for the study will be held soon after commencement of the project. It will involve all the key players, plus some appropriate invitees. The workshop will be interactive and participative. The key technologies with their current issues, and their potential impact on novel CO_2 sequestration, will be discussed and noted. A set of hypotheses will be developed for each of the technologies and their issues. These hypotheses will need to be answered by the study in either the affirmative, or not. Project work will be required to answer the hypotheses developed, and this will form the basis of the action plan for the project. The strengths, weaknesses, opportunities and threats of each technology, and their sustainability, will also be developed as part of this analysis.

2. Literature Analysis

A literature review of the science and technology underpinning the technologies will be undertaken, including existing reports from organisations such as the CO_2CRC and IPCC. The proposals of key proponents of the technologies will also be examined and cross-referenced to the scientific review. This will involve interviews with the technology proponents and disclosure by them of the non-confidential information they are prepared to reveal. A gap analysis will be undertaken between the claims and the known science and technology. This will assist in answering the hypotheses developed as part of the strategy workshop.

3. Descriptions of the Technologies

A qualitative description of all the technologies considered will be provided in the report.

4. Cost Analysis

A preliminary cost analysis of each of the identified technologies will be developed. The analysis will be based on the literature review and verified claims of the technology proponents. Factors such as the chemical and biochemical kinetics will be used to size equipment and to forecast the capital investment required. Operating costs will be estimated, based on requirements such as energy, water, algal nutrient, biomass production, labour, mining costs, multi-phase separation technologies, and so on. Any positive revenue streams associated with by-products will be evaluated in terms of potential markets and prices, as well as their costs of production. These independent analyses will be compared with the claims of the various technology proponents. Issues associated scale-up and operation of large-scale equipment will be identified. If possible, a learning curve trajectory for each of the technologies will be determined. It is proposed that an estimate of the technology cost in terms of \$/t CO_2 captured will be provided as part of the study. However, in view of the uncertainty of many of the costs associated with these technologies, the cost analysis outcome is likely to be probabilistic with ranges of expected values. A Pareto analysis of the major engineering constraints faced by each solution and suggestions as to the “best possible” outcome for each constraint will also be provided. The cost analysis models will be available to sponsors of the report.

5. Expert Opinion and Recommendations

A qualitative expert opinion, taking into account the results of the analysis, will be provided in the form of Conclusions to the study. This will include the prospects of each of the technologies to provide a significant contribution to CO_2 capture and storage needs in Australia and internationally. Recommendations for further study on the prospective technologies not yet underpinned by rigorous science will also be made.

A.3 List of People the Task Force Engaged in the Study

Proponent advice

Enrico	Bombardieri	MBD Energy
Geoff	Brent	Orica

Bob	Davis	C2HT
Rocky	de Nys	MBD/JCU
Bogdan	Dlugogorski	University of Newcastle
Sara	Gipton	Greenfleet
Kirsten	Heimann	MBD/JCU
Joe	Herbertson	The Crucible Group
Richard	Hunwick	Hunwick consultants (ICS)
James	Joyce	Black is Green
Chris	Kelleher	Newcastle Innovation
Eric	Kennedy	University of Newcastle
Andrew	Lawson	MBD Energy
Nicholas	Paul	MBD/JCU
Tony	St. Clair	MBD Energy
Alex	Stefan	Miltex Timber Products
Marcus	St. John Dawe	GreenMag Group
Les	Strezov	The Crucible Group
John	White	Ignite Energy Resources

Expert scientific advice

Tony	Bacic	UoM/Bio21
Jeff	Baldock	CSIRO
Michael	Battaglia	CSIRO
Robin	Batterham	ATSE
Snow	Barlow	University of Melbourne
Tom	Beer	CSIRO
Ami	Ben-Amotz	Seambiotic
John	Benemenn	Benemenn and Associates
Michael	Borowitzka	Murdoch
John	Carras	CSIRO
Tim	Cavagnaro	Monash University Centre for Green Chemistry
Annette	Cowie	DPI
Jiri	Doucha	Academy of Sciences of the Czech Republic
Greg	Duffy	CSIRO
David	French	CSIRO
Victoria	Haritos	CSIRO
Brian	Haynes	University of Sydney
Milton	Hearn	Monash University Centre for Green Chemistry
Barry	Hooper	CO2CRC
Sandra	Kentish	University of Melbourne
Evelyn	Krull	CSIRO
Frank	Larkins	DPI (Vic)
Kurt	Liffman	CSIRO
Karel	Livansky	Academy of Sciences of the Czech Republic
Greg	Martin	University of Melbourne
Deborah	O'Connell	CSIRO
Ian	Olmstead	University of Melbourne/Victor Smorgon Group/Greenfuel Technologies
Tony	Patti	Monash University Centre for Green Chemistry
Philip	Polglase	CSIRO
Peter	Rayner	University of Melbourne
Fiona	Robertson	DPI (Vic)

Mike	Sandiford	University of Melbourne
Balwant	Singh	DPI (NSW)
Bhupinderpal	Singh	DPI (NSW)
Rajinder	Singh	CO2CRC
Charlie	Speirs	Vic DPI
Dianne	Wiley	CO2CRC
Ron	Zevenhoven	Abo Akademi (Finland)

Project Finance advice

Rob	Fowler	Booz and Co.
Jason	Coonan	Melbourne Ventures
Peter	Hanley	Macquarie
Tara	Martin	Deloitte Touche Tohmatsu
James	Price	PP&E Valuations
Andrew	Ristrom	Domain Capital
Ric	Symes	Domain Capital
Julian	Turecek	Cleantech Ventures

Independent industry advice

James	Baird	Clinton Foundation
Bruce	Fox	CSIRO
Geoff	Gay	TruEnergy
Bruce	Godfrey	BCIA
Matthew	Gordon	EPA
Ian	Harper	Melbourne Business School
Tom	Holden	Vic Environment and Natural Resources committee
Michael	Hutchinson	TruEnergy
Brent	Jenkins	Newcastle Innovation
John	Karas	DRET
David	Lamb	Greenfleet
Andrew	Roden	Global CCS Institute
Karen	Taylor	Vic Environment and Natural Resources committee
Matthias	Raab	CO2CRC
Caroline	Williams	Vic Environment and Natural Resources committee
Tony	Wood	Clinton Foundation

Sponsors

Bruce	Godfrey	BCIA
Phil	Gurney	BCIA
Edlyn	Gurney	Global CCS Institute
Kathy	Hill	Global CCS Institute
Noel	Simento	ANLEC R&D

Task Force / Administrative

John	Burgess	Taskforce (chair)
Lewis	Jeffery	Taskforce
Allen	Lowe	Taskforce
Steve	Schuck	Taskforce
Dylan	McConnell	Melbourne Energy Institute (Secretariat)
Susannah	Powell	Melbourne Energy Institute (Secretariat)
Jemma	Stefanou	Melbourne Energy Institute (Secretariat)

Warren	Flentje	Melbourne Energy Institute (Secretariat)
Lauren	Estabillo	ANLEC R&D
Merinda	Woodburn	ANLEC R&D

APPENDIX B Novel CO_2 Capture Task Force Strategy Workshop

A one-day strategy workshop was convened by the Task Force immediately following the commencement of the study.

B.1 Workshop Process

The intent of the one-day strategy workshop was to identify key challenges and issues for the novel CO_2 capture technologies and to develop a prioritised list of actions to address them. Key independent experts in the relevant fields, mainly from CSIRO and universities but also from government, participated in the workshop. The workshop attendees went through a process to identify the issues and develop statements about several hypothetical future situations in which the technologies could find themselves in the future. The issues and challenges raised were wide-ranging, and encompassed the scientific, technological, financial, environmental and social areas. An action plan for the Task Force was then developed to undertake work to establish whether the hypothetical statements for the future of the technologies are realistic in these dimensions.

B.2 Major Issues Identified by the Workshop

- The environmental, economic and social sustainability of novel capture processes has not been assessed. Full economic analyses including all inputs and outputs have not been made.
- The potential contribution by novel methods to CO_2 capture and storage in Australia is not known.
- Scientific and technical knowledge and data for minerals sequestration is needed, including review potential locations in terms of their suitability.
- Engineering design optimisation for capturing CO_2 from various gas streams by algae is not well understood, as is land use by biological capture systems under different land and climate conditions.
- The community has not yet granted a licence-to-operate for commercialisation of novel CO_2 capture and storage technologies.
- The feasibility of scale-up of novel CO_2 capture and storage processes to commercial size has not been confirmed.
- The life cycle and permanence of storage of CO_2 by bio-sequestration is not well understood. The area of arable land that can be used is not known due to uncertainties about current and future land use.

Hypothetical Futures and Action Plan

Following the discussion and listing of the issues, the participants re-convened to articulate the possible futures for the novel carbon capture and storage technologies. For each postulated future, the whole group then listed the potential actions that the Task Force could take to either prove or disprove the “hypotheses”. Following the workshop, the suggestions for action were taken by the Task Force and edited to form the action plans, accompanied by the suggestions by the workshop participants for the resources available to advise the Task Force. Seven hypotheses were developed, as listed below:

Hypothesis 1: “There is sufficient scientific and technical literature on novel carbon capture technologies for the Task Force to assess the feasibility and develop a ranking of the various processes.”

Hypothesis 2: “By 2020, Novel CCS projects will be bankable at commercial scale.”

Hypothesis 3: “By 2015, scientific consensus has been reached on permanence and sustainability of implementable Novel CCS”.

Hypothesis 4: “By 2020 coal, together with novel methods for carbon capture and sequestration, will be the lowest cost option for base-load power in Australia at emissions of 150 $kgCO_2/MWh$, with sufficient storage capacity to make a material contribution to GHG reduction targets”.

Hypothesis 5: “By 2015 novel carbon capture and storage will be accepted by the community and regulators through effective consultation and education, through informed social consent”.

Hypothesis 6: *“*By 2015, an internationally accepted methodology for quantifying CO_2 sequestration 'reserves', analogous to HC reserve system SPE 2007, will be developed”.

Hypothesis 7*:* *“*A map of the mineralization feedstocks in Australia, graded by desirability, can be produced”.

B.6 List of Workshop attendees

The following people participated in the Task Force Strategy Workshop at the start of the project. The Task Force acknowledges with thanks the input of these people to the study.

Professor Snow Barlow, University of Melbourne, Chair DAFF, Expert Panel on Climate Change R&D
Dr. Michael Battaglia, CSIRO, Senior Principal Research Scientist and Theme Leader
Professor Robin Batterham, President, ATSE
Dr. John Burgess, Director, BCIA, Chair of Task Force
Dr. Greg Duffy, CSIRO, Research Program Leader
Warren Flentje, University of Melbourne, Research Officer and Secretariat for Task Force
Dr. David French, CSIRO, Principal Research Scientist
Dr. Bruce Godfrey, CEO, BCIA
Dr. Victoria Haritos, CSIRO, Principal Research Scientist
Kathy Hill, Global Carbon Capture and Storage Institute, Principal Manager (Carbon Storage)
John Karas, DRET, General Manager-Low Emissions, Coal Allocation & Storage
David Lamb, Director, Greenfleet
Professor Frank Larkins, DPI Victoria, Chief Scientist (Energy)
Lewis Jeffery, Task Force, Consultant
Dr. Allen Lowe, Task Force
Dr. Stephen Schuck, Task Force, Managing Consultant, SSA
Dr. Noel Simento, ANLEC R&D, Acting CEO
Charlie Speirs, DPI Victoria, Director (Clean Coal Victoria)
Professor Dianne Wiley, CO2CRC, Capture Program Manager

APPENDIX C: Potential for algae to capture CO_2 from a power plant

A number of studies have proposed the integration of algae based bioreactors with coal fired power stations as a route to CO_2[159,160] mitigation. A theoretical study has also been undertaken by Liffman of the CSIRO[161] (2011) on open pond solar physics. However, there appears to have been little work on the practical issues involved with integration of the operations of these industries. The following paragraphs discuss some of the issues involved in developing such a practical approach. The assessment is thus centred on CO_2 capture rate rather than biomass productivity.

Effect of Solar Flux Variation on Carbon Capture from Power Stations

Base load power stations operate on a 24 hour/365 day per year duty cycle. Any carbon capture technology intended to work in close coupling with a power station must match that duty cycle. This poses a problem for technologies based on solar energy such as algae based bioreactors that directly utilise flue gases due to the impracticality of storing large quantities of flue gas[162]. Bioreactors that absorb CO_2 directly from the air do not suffer from this problem.

The ability of a bioreactor to consume CO_2 is determined by numerous factors such as the algae species involved, light energy input, availability of nutrient, bioreactor conditions such as temperature and pH and the presence of any pathogens within the medium. In the absence of other limiting factor then the output of the reactor will increase with the light input (solar energy) to the point where photo saturation is observed. If radiant flux increases beyond this level then photo-inhibition may occur where photosynthesis is reduced to below that achieved at moderate flux levels.[163,164] As the solar energy input varies with the time of

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[159] Zeiler K.G., Heacox D.A., Toon S. T., Kadam K.L. and Brown L.M. (1995) "The use of microalgae for assimilation and utilisation of carbon dioxide from fossil fuel fired power plant flue gas" Energy Conversion Management V36. No 6-9, pp 707 – 712.

[160] Nakamura T., Senior C.L., Olaizola M., Bridges T., Flores S., Sombardier L. and Masutani S.M. (2005) "Recovery and sequestration of CO_2 from stationary combustion systems by photosynthesis of microalgae". Final Report, DOE Contract No. DE-FC26-00NT40934, National Energy Technology Laboratory.

[161] Liffman K., "A Review of Thin Film Open Pond Physics - A Path Forward Towards the Optimal Algal Growth System", CSIRO Materials Science and Engineering, Personal Communication, 2011. http://www.csiro.au/people/Kurt.Liffman.html

[162] A 660 MW generating unit burning Australian black coal produces approximately 3.3 x10^6 m^3/hr of flue gas or 565 t/hr of CO_2 at pipeline conditions when operating t full load. Allowing a minimum of 16 hr of storage to cover overnight emissions in winter then requires a volume of some 50 x10^6 m^3 for flue gas or 1.1 x10^4 m^3 for CO_2 compressed to pipeline requirements (10 MPa, 30˚C).

[163] Richmond A., Kichtenberg E., Stahl B. and Vonshak A. (1990) "Quantitative assessment of the major limitations on productivity of Spirulina platensis in open raceways". Journal of Applied Phycology V2, pp195-206.

[164] Benemann J.R., Oswald W.J. and Bergman P. (1996) "Systems and economic analysis of microalgae ponds for conversion of CO_2 to biomass". Final report to Dept of Energy, Pittsburgh Energy Technology Centre. Grant No DE-FG22_93PC93204.

day and season then the output of the bioreactor will similarly vary. This will affect the maximum proportion of the power station emission that can practicably be sequestered by the bioreactor.

In order to quantify this effect it is necessary to compare the expected profile of CO_2 emissions from the power station against that of the solar flux at the location of the bioreactor. For simplicity it is assumed here that photosynthesis increases proportionally with increase in incident radiant flux, to the point where saturation and then photo-inhibition occur. In practice photosynthetic efficiency reduces as the saturation point is approached[164]. The following calculation will therefore overestimate the amount of CO_2 captured by a bioreactor.

Base load power stations are conventionally assumed to run at full load whenever in service. However, in Australia, this is difficult due to a relatively small system and the large capacity of commercial base load coal fired units. It is therefore more common for such units to broadly follow the system demand curve with high to maximum load being delivered during peak hours and reduced load during the late evening/early morning period.

Figure C.1 illustrates diurnal cycles for system load in winter (July averaged data) and summer (January averaged data) for the NSW region of the Australian National Grid. On this basis a unit loading profile of full load operation from 7:00 am to midnight with reduced load (70%) from 1:00 am to 6:00 am has been assumed for the following calculations.

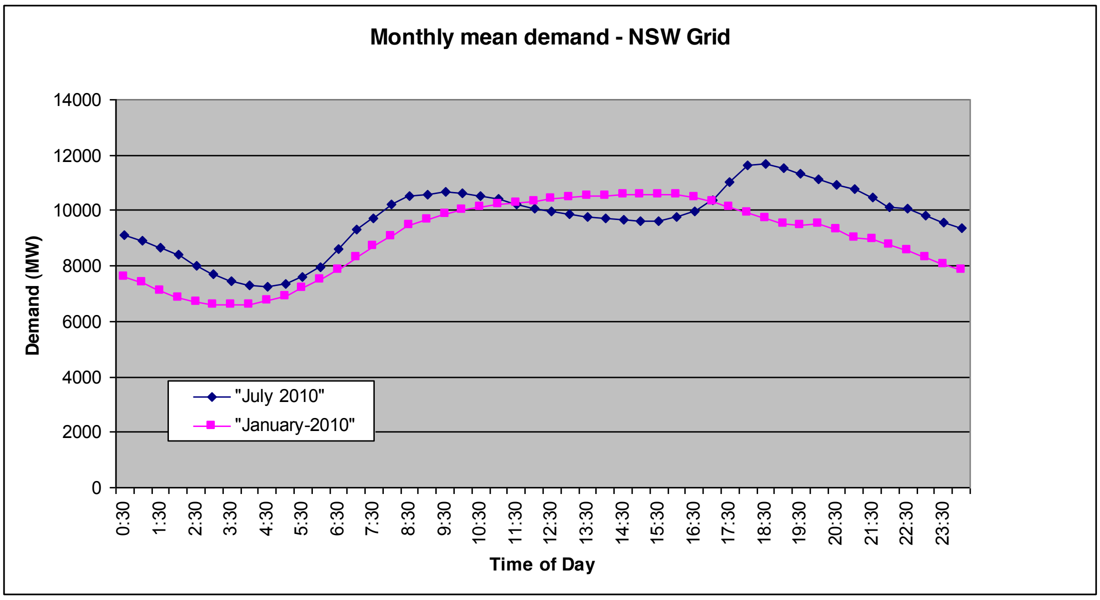

Figure C.1. Thirty one day averaged demand for the National Grid - NSW region for months of January 2010 and July 2010, daily data sourced from http://www.aemo.com.au/ .

Solar insolation comprises both direct beam and diffuse components and varies with time of day and season. The maximum insolation occurs with a clear sky. In this case the insolation to a horizontal surface may be estimated from knowledge of the extra-terrestrial solar insolation, the orientation of the sun in respect to the surface and the transmissivity of the atmosphere.

Figure C.2 shows clear sky insolation to a flat surface at a latitude of 32.26 ºS as a function of solar time and for representative summer (16th January) and winter (16th July) days. The latitude corresponds to that of the Bureau of Meteorology monitoring station at Lower Hill St. Muswellbrook in NSW, which is near to the Bayswater power station site. The data were calculated using equations of solar position given by Duffie and Beckman[165], atmospheric transmissivity from Remund *et al*.[166] and a simplified correlation of diffuse radiation by Bason[167].

Flue gas emission is closely proportional to unit load. Assuming the loading profile discussed above for a base loaded plant then a CO_2 emission profile can be drawn against time of day as also illustrated on Figure C.2. Further, as the ability of a bioreactor to capture CO_2 is assumed proportional to insolation, the CO_2 capture profile will be directly proportional to the insolation curves.

If, for example, the bioreactor is designed to process 100% of CO_2 emissions at an insolation of 1.1 kW/m^2 then CO_2 in excess of the capability of the bioreactor to sequester it will be produced whenever insolation falls below 1.1 kW/m^2. This is illustrated on Figure C.2 by the area below the power station loading curve and above the respective insolation curves.

From this data it is calculated that the maximum capture potential for a bioreactor designed to an insolation of 1.1 kW/m^2 at this location would be 33 % of the power station emissions, assuming that the bioreactor achieves a constant photosynthetic efficiency from 0 to 1.1 kW/m^2.

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[165] Duffie J.A. and Beckman W.A. (1974) “Solar Energy Thermal Processes” John Wiley and Sons.

[166] Remund J., Wald L., Lefevre M., Ranchin T. and Page J. (2003) “Worldwide Linke Turbidity Information” Proc. ISES Solar World Congress, 16 – 19 June, Goteborg, Sweden.

[167] Bason F. “Linke’s Turbidity Factor Applied to Worldwide Global Horizontal Irradiance Measurements” available from www.soldata.dk/PDF/Paper%20FB%20Lisbon%202008.pdf – accessed 20/5/2011) .

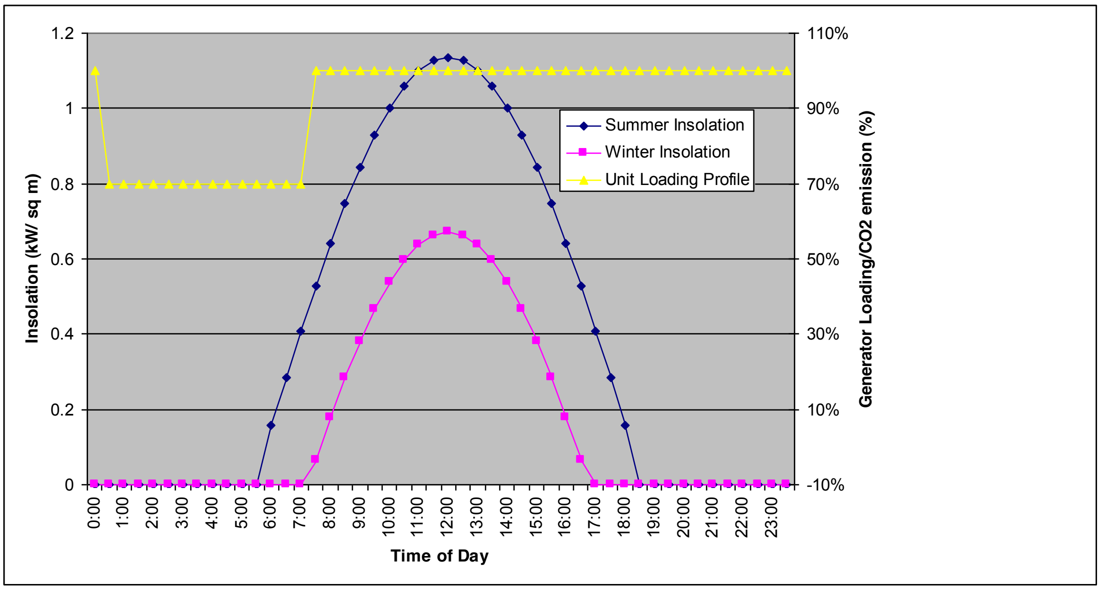

Figure C.2: Diurnal summer and winter insolation vs. indicative base load generator loading profile

In practice many algae species are found to exhibit a decline in photosynthesis and productivity as light increases above about 10% of full sunlight levels with saturation occurring by 25% of full sunlight[168] (for C3 photosynthesis which includes most algae).

Approaches proposed to overcome this limitation, and an assessment of their efficacy, include:

- Use of high turbulence to cycle cells between light and dark regions (energy intensive and damaging to cells to provide the required microsecond scale light change frequencies)
- Use of light diffusers to channel light deep into the culture (expensive)
- Identification of, or genetic modification to, algae adapted to the high light levels (algae cells typically spend most time in low light regions of media and therefore low light adapted cells will out compete high light adapted cells)

Benemann (1996) concludes that “none of these has yet proved feasible for economic applications”.

This implies that bioreactors must in practice be designed to capture 100% of power station emissions by the time light levels reach say 20% of full sunlight strength. This will increase the maximum capture potential to some 55% of emissions but at the cost of a 5 fold increase in surface area (and assuming that no photo inhibition occurs at higher light levels).

Figure C.2 and the above discussion assume a clear sky. However, cloud cover will, on average, reduce the insolation and therefore the bioreactor output. The Bureau of Meteorology provides measurements on daily global solar exposure to a horizontal surface for a number of sites in Australia. Five year average data from the Muswellbrook site has been plotted on Figure C.3 against day of the year. The daily exposure under a clear sky,

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[168] Jansson C., Wullschleger S.D., Kalluri U.C. and Tuskan G.A. (2010) “Photosequestration: Carbon biosequestration by plants and the prospects of genetic engineering” BioScience Vol. 60 No. 9 pp685-696.

calculated by integrating area under daily insolation curves such as illustrated in Figure C.2, is also plotted.

As expected the average insolation falls below the clear sky model as, averaged over time, all days will show some cloud activity. However, data for individual years (not shown here) does show instances where measured data closely matches the clear sky prediction.

It is noted that the insolation varies by around a factor of 4 between a clear day in summer and a cloudy day in winter and photosynthesis is then expected to vary proportionally. Short term test data can therefore be strongly misleading and it is essential that bioreactor performance be assessed on annual averaged data.

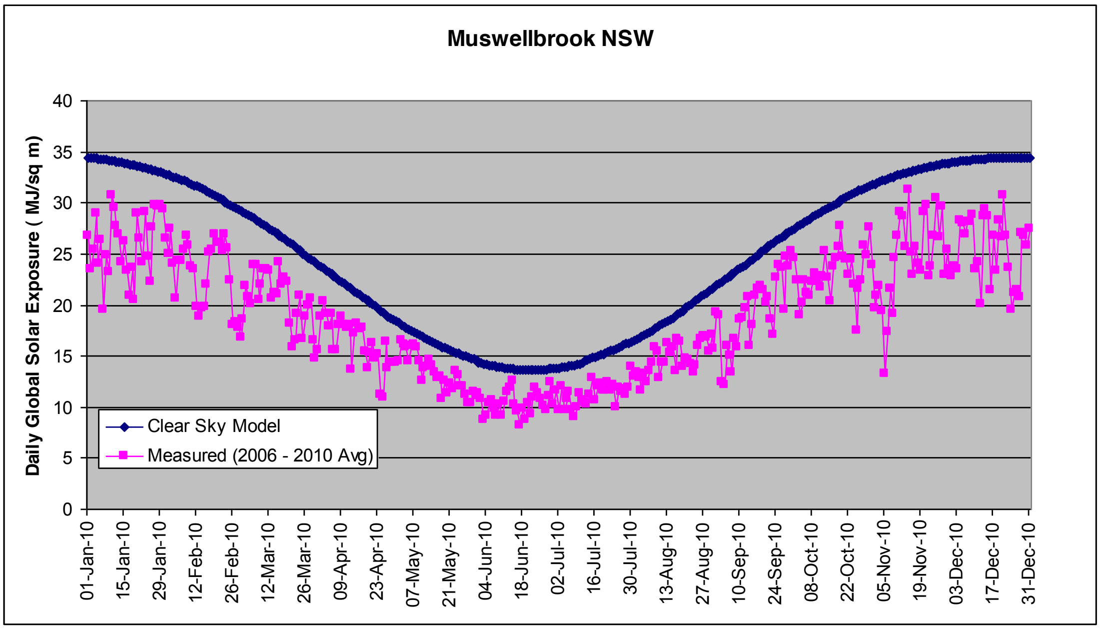

Figure C.3: Daily global solar exposure from clear sky vs. measured data for Lower Hill St. Site in Muswellbrook, NSW. Measured data is average of 2006 to 2010 exposure data available from www.bom.gov.au.

Integrating the averaged global exposure data yields an annual solar input of 6890 MJ/m^2 per annum for this site, as compared to the clear sky input of 9070 MJ/m^2 per annum. This will reduce the maximum collection efficiency of the bioreactor sized to process 100% of full load CO_2 emissions at solar insolation of 1.1 kW/m^2 to 22 % and at insolation of 0.22 kW/m^2 to 42 % respectively.

Thermodynamic assessment of algal production limits

The production of all biomass is ultimately dependent on photosynthesis where solar energy input in the form of photons is consumed to convert CO_2, H_2O plus small amounts of minor elements to carbohydrate and protein. The first law of thermodynamics requires that energy output must exactly equal energy input. In a prefect process all photon energy input will convert to energy stored in biomass. In practice some energy will be lost to heat, reemitted as different wavelength photons or consumed by the life processes of the biomass.

Photosynthesis utilises only radiation with wavelengths between approximately 400 and 700 nm, termed Photosynthetically Active Radiation (PAR). The quantity of PAR incident at a particular site will depend on the location and orientation of the collector with respect to the sun and on the optical properties of the atmosphere which will attenuate the solar radiation.

PAR incident on a flat surface can be calculated from satellite based spectral analysis of radiant flux leaving the atmosphere and data is available for monthly mean values of PAR on a 2.5 degree grid over the globe for the years between 1983 and 1994[169]. Selected data for locations of Bureau of Meteorology (BOM) monitoring station site close to three Australian power station sites is given in Table *C.* C.1. These data were obtained by linear interpolation of down welling PAR given at the four grid point nearest the respective BOM sites.

BOM Site	Stanwell Power Station	Muswellbrook Lower Hill St	Latrobe River
Power Station	Stanwell	Bayswater	Yallourn
Latitude	23.51°S	32.26°S	38.17°S
Longitude	150.32°E	150.88°E	146.34°E
Annual PAR	3401.8 MJ	3091.3 MJ	2819.1 MJ
Annual Solar Exposure	7512.6 MJ	6931.3 MJ	6146.6 MJ
PAR	45.3%	44.6%	45.9%

Table C.1: Annual PAR at three power station sites in Australia, PAR data averaged over years 1983 to 1986 , Annual solar exposure data averaged over 2005 to 2010 obtained from Australian Bureau of Meteorology.

While the data available at each source do not overlap in terms of time and the period of averaging is short, the ratio of annual PAR with the annual solar exposure is consistent with values generally accepted[170]. The data is taken here as indicative and primarily to illustrate the effect of latitude on annual PAR values.

Energy content of the dry biomass produced by photosynthesis will depend on its composition. Miyamoto[171] presents data on range of carbohydrates, proteins and lipids for a number of algae species. These vary widely, however the data indicates protein content typically ranges from 30 to 60%, carbohydrate from 20 to 30% and lipid from 10 to 20%. It is

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[169] http://www.atmos.umd.edu/~srb/par/05datadistri.htm, accessed 2/6/2011

[170] Weyer K.M., Bush D.R. Darzins A. and Willson B.D. (2010) “Theoretical maximum algal oil production” Bioenergy Research V3, pp204-213.

[171] Miyamoto K. (1997) Renewable biological systems for alternative sustainable energy production (FAO Agricultural Services Bulletin -128) http://www.fao.org/docrep/w7241e/w7241e00.htm (accessed 3/6/2011)

likely that a cultivated species would be selected for protein and lipid production, on that basis an analysis of 40% protein, 40% lipid and 20% carbohydrate is assumed.

Amthor[172] has summarised heats of combustion for a range of carbohydrates, amino acids (proteins) and lipids relevant to photosynthesis. Mean values of 16.5 MJ/kg for carbohydrate, 24.0 MJ/kg for protein and 38.0 MJ/kg for lipids are obtained from this data. Combining these heats of combustion with the indicative algae composition assumed above allows a heat of combustion for the algae of 28.1 MJ/kg (dry basis, HHV) to be determined. The maximum quantity of biomass that could be produced at each site while obeying energy conservation principles is then as given in Table C.2.

BOM Site	Stanwell Power Station	Muswellbrook Lower Hill St	Latrobe River
Power Station	Stanwell	Bayswater	Yallourn
Annual PAR	3401.8 MJ/m^2	3091.3 MJ/m^2	2819.1 MJ/m^2
Annual biomass production	121 kg/m^2	110 kg/m^2	100 kg/m^2
Daily biomass production	330 g/m^2	300 g/m^2	275 g/m^2

Table C.2: Thermodynamically limited biomass production per m^2 of reactor exposed to sunlight at three Australian power station sites assuming perfect conversion of incident PAR to stored biomass energy.

Mechanistic Assessment of maximum biomass production rate.

An improved estimate of CO_2 capture rate may be made from knowledge of PAR levels through application of current understanding of the mechanism of photosynthesis[170,172]. This expresses CO_2 reduction and biomass production in terms of the number of photons required to drive the process. Photosynthesis may be described by the following equation

$$CO_2 + H_2O + Q_r \rightarrow CH_2O + O_2 \qquad \text{(C.1)}$$

where Q_r indicates number (quanta) of photons required per molecule of CO_2 fixed.

Following the principles of Weyer *et al*. (2010) the CO_2 capture rate of a solar bioreactor may be written as

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[172] Amthor J.S. (2010) From sunlight to phytomass: on the potential efficiency of converting solar radiation to phyto-energy" New Phytologist 188 pp 939 – 959.

$$C = \frac{I.L}{E_P} \quad \frac{U_P}{Q} \quad E_B \tag{C.2}$$

Where:

C	Carbon fixed (mol CO_2/m^2 annum)
I	PAR insolation on bioreactor (kJ/m^2 annum)
L	Fraction of incident PAR reaching algae
E_p	Average energy of photo active photons (kJ/mol)
U_P	Efficiency of utilisation of incident photons by biomass cell
Q_r	Number of photons required to convert one mol of CO_2 to biomass under lossless photosynthesis(-/mol)
E_B	Biomass accumulation efficiency

The fraction of incident PAR reaching the algae allows for losses due to reflection and absorption of light by any reactor walls and interfaces in the path of the light. For example a bioreactor comprising a trough covered by a clean cylindrical polycarbonate cover (refractive index 1.6) would be expected to lose approximately 10% of light energy through absorption and reflection by the cover. In addition, if there is a layer of air between the cover and the water then energy will be reflected by air/water interface, Weyer *et al*. (2010) estimates an annual average of 6% loss at latitude 20º and 10% at latitude 40º due to this interface reflection. Photons may also be absorbed or reflected by the water, bubbles or particles in the water or may be reflected from the algal cell itself (the colour of algae is due to its partial reflectance of light). A maximum fraction of incident PAR reaching algae is then taken here as 90%.

The average energy of photo active photons may be estimated from the spectral energy distribution of solar radiation at ground level and Plank's law expressing photon energy in terms of wavelength. ASTM[173] provide a standard spectrum for solar energy at ground level ground assuming a clear sky and air mass of 1.5. This spectrum provides a weighting term for the photon energy at each wavelength allowing a weighted mean PAR photon energy to be determined. This yields an E_P of 222.6 kJ/mol, in good agreement with published data.

Photons collected by the algae cell may be used to photosynthesise CO_2, by pathways that consume O_2 and release CO_2 (photorespiration), converted to heat or reemitted as

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[173] ASTM G173 - 03(2008) Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

fluorescence. The proportion of photons successfully consumed in photosynthesis is termed photon utilisation efficiency (U_P). U_P has been found to range from 50 to 90% under low light conditions but reduces to 10 – 30% under high light. Weyer (2010) assumes a median value of 50% however a level of 80% is assumed here as potentially available, for example with genetic modification or bioreactor design.

Studies of the molecular processes involved in photosynthesis allow Q_r, the number of photons required to drive the process, to be calculated. In a recent review Amthor (2010) concluded that to convert CO_2 to sucrose requires either 8.2 or 9.2 photons per molecule of CO_2 fixed, depending on the reaction path assumed and assuming no consumption of photons by competing processes (lossless photosynthesis). This is consistent with others, e.g. Weyer (2010) assumes 8 photons per CO_2 molecule fixed. A value of 8 photons per CO_2 molecule is assumed here.

Biomass accumulation efficiency E_B quantifies the percentage of primary photosynthate that remains after requirements of the organism for life functions such as growth, reproduction and synthesis of proteins, lipids and carbohydrates from sucrose are satisfied. Weyer (2010) quotes published values for E_B ranging between 11% and 87.5% and assumes a mean value of 50%, here a figure of 80% is assumed to be achievable.

From these data the maximum annual average CO_2 capture rate at the three power station sites are calculated and given in Table C.3. For this level of capture to be achieved it would be necessary for the bioreactor to be designed to limit loss of incident photons to a practical minimum, to obtain dramatic improvements over general experience in photon utilisation efficiency at high incident flux levels and to reduce internal consumption by the algae of photosynthetic product to a minimum.

BOM Site	Stanwell Power Station	Muswellbrook Lower Hill St	Latrobe River
Power Station	Stanwell	Bayswater	Yallourn
Annual PAR	3401.8 MJ/m^2	3091.3 MJ/m^2	2819.1 MJ/m^2
CO_2 fixed in biomass	1100 mol/m^2 a	1000 mol/m^2 a	910 mol/m^2 a
CO_2 fixed, annual average basis	130 g/m^2 day	120 g/m^2 day	110 g/m^2 day

Table C.3: Maximum potential biomass production at three Australian power station sites.

Amthor (2010) provides carbon contents for a range of carbohydrates, amino acids and lipids. The data provides a mean of 0.44 kg C /kg carbohydrate , of 0.46 kg C/kg amino acid and 0.74 kg C/kg lipids respectively. Assuming an algae composition of 40% protein, 40% lipid and 20% carbohydrate allows a mean content of 0.57 kg C/kg algae to be calculated. As each kilogram of CO_2 contains only 0.27 kg of elemental carbon, this indicates a requirement of 2 kg CO_2 fixed per kg of algae produced, in good agreement with Ben-Amotz (2010). On that basis the maximum potential annual average biomass production rate at the Australian power station sites would be around 55 to 65 g/m^2 day.

Surface area requirements

To determine the bioreactor area required to process direct feed power station flue gas it is necessary to match instantaneous emissions from the power plant with the maximum sequestration rate of the bioreactor. The maximum insolation to a flat surface at the Muswellbrook Lower Hill St site adjacent Bayswater power station is estimated from solar position algorithms at 1140 J/s.m^2 at noon in mid-summer. Assuming the photo inhibition issues discussed above can be resolved then the maximum potential rate of CO_2 consumption by a bioreactor is 1.7 x 10^{-6} mol CO_2/s m^2 (7.3 x 10^{-6} kg/s m^2) (eq. (C.2), I = 45% of incident radiation, L=90%, U_P = 90%, E_B = 80%).

The Australian Government Generator Efficiency Standards[174] provide analyses for a range of Australian coals used in power generation. Assuming the medium ash, medium volatile (Hunter Valley) domestic coal then stoichiometric calculations give a CO_2 production of 0.9 kg CO_2/MJ heat release from coal. Allowing a generator efficiency of 38% then an emission of 900kg CO_2/MWh is determined[175], resulting in a 660 MW unit releasing 615 t/h of CO_2 (171 kg/s) when operating at full load. At the maximum conversion rate estimated above then a collecting surface area of approximately 24 x 10^6 m^2 is required.

It will be necessary to allow for service area between collectors for harvesting equipment and access for cleaning and maintenance as well as for supply of CO_2, water and other nutrients. Assuming a land utilisation effectiveness (pond area/total area occupied) of 80%[176] yields a requirement of 30 km^2 to service one of the four generating units at Bayswater power station.

As noted above most algae use the C3 photosynthesis route and become light saturated at 10 to 25% of full sunlight levels. Assuming a mid-range saturation level of 20% full sunlight then the bioreactor surface area required to treat the flue gas output from one Bayswater unit will increase by a factor of 5 to around 150 km^2.

Flue gas distribution and disposal

Combustion of Hunter Valley bituminous coal in a power station boiler[177] produces approximately 16 mols of gas per MJ of heat in the coal. The gas at exit of the boiler will contain some 13% CO_2, 4.5% O_2, 7.8% H_2O, with the remainder being primarily N_2. Minor constituents will include between 300 to 500 pm SO_2, depending on the sulphur content of the coal, 300 to 800 ppm NOx depending on the combustion conditions, and trace amounts of HCl, HF, fine particulates and other species. The gas will leave the boiler at a temperature of 130 to 150ºC, depending on ambient temperature and plant design details.

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[174] Australian Greenhouse Office (2006) "Technical Guidelines, Generator Efficiency Standards". Commonwealth of Australia

[175] Note that this is slightly less that the annual average value of 930 kg/MWh quoted for Bayswater by Macquarie Generation (Macquarie Generation, Annual Report 2010), the annual average value will include allowance for part load and restart conditions when emissions are relatively higher.

[176] Benemann J.R. and Oswald W.J.(1996) Systems and economic analysis of microalgae ponds for conversion of CO_2 to biomass." Final Report under USDOE Grant No DE-FG22-93PC93204, (http://www.osti.gov/bridge/product.biblio.jsp?query_id=0&page=0&osti_id=493389&Row=1)

[177] Babcock and Wilcox (1992) Steam, its Generation and Use.

A generating unit of 660 MW gross output and 38% efficiency will require a heat input of 1740 MJ/s. This amount of coal will result in a gas flow leaving the boiler of approximately 28 kmol/s (925 m^3/s at 130ºC and 1 atm pressure).

The flue gas will require cooling to near ambient temperature to minimise pumping energy requirements, insulation requirements and reduce ducting size. This could be achieved by a recirculating scrubber system. At scrubber exit the flue gas will be saturated and, at a temperature of 40 ºC, the moisture content will be approximately equal that leaving the boiler. Cooling system water makeup requirements will be required to cover blowdown required to manage chemistry of the cooling system water.

However, further drying of the flue gas would require refrigeration of the flue gas, which is energy intensive. The preferred alternative requires the design of the gas distribution system to cater for the wet flue gas, which will be corrosive due to CO_2 and SO_2/SO_3 contents.

At 40°C the flue gas volume is around 720 m^3/s, requiring a duct cross section of 36 m^2 to satisfy typical duct velocities of 20 m/s.

To distribute gas across the minimum area of some 30 km^2 will require substantial lengths of ducting. Assuming an array of 6 km x 5 km with ponds of 1km length, and with the first pond located 1 km from the power station, then an arrangement with bus ducts serving two pond arrays each would require a minimum of 20 km of large scale ducting.

As noted above power station flue gas contains significant levels of a number of pollutants including SO_2 and NOx. Industry proponents seeking to release gases containing these substances to the atmosphere must demonstrate that they satisfy regulations including meeting ambient air quality standards.

These specify maxima (0.12 ppm and 0.20 ppm for NO_2 and SO_2 respectively, one hour averaging periods[178]) which are more than three orders of magnitude lower that than in the original flue gas. This indicates a need for the CO_2 depleted flue gas to be collected from the exit of the bioreactor and returned to the power station for disposal through the original stack. This will involve duplication of the gas distribution ducting, provision of additional gas recirculation fans and reheating of the waste gas to ensure proper dispersion of the plume.

Summary

Solar powered bioreactors directly coupled to a base loaded power station may be expected to collect not more that 25% to 50% of the CO_2 emitted by the power station, depending upon insolation design point and bioreactor surface area. This is due to imbalance between the 24/7 operating cycle of the power plant and the diurnal cycle of the bioreactor.

All else being equal then the impact of latitude on bioreactor performance is small (± 10 %) within the latitude range of Australian coal fired power stations.

The maximum potential CO_2 capture rate for a solar powered bioreactor located adjacent the Bayswater power station site is estimated at around 120 g/m^2 day (annual average). This assumes the reactor can operate without photo inhibition or saturation to a solar insolation level of 1100 J/m^2, that no other factor such as temperature, pH, nutrient level including CO_2 supply, O_2 concentration or contamination are limiting, that the algae consistently maintain

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[178] Ambient air quality standards

http://www.environment.gov.au/atmosphere/airquality/standards.html#air a performance equivalent to the best reported in the literature in terms of photon collection efficiency and biomass accumulation efficiency and no diffusion of other limit prevents absorption of all CO_2 in the flue gas.

Many algae are reported to experience photo inhibition or saturation at light levels in excess of 25% of maximum solar flux. This suggests a likely maximum possible capture rate of around 30 CO_2 g/m^2 day or a bioreactor surface area of the order of 150 km^2 per 660 MW unit, assuming all environmental conditions including water temperature are maintained at optimum value.

APPENDIX D: Biochar production from agricultural waste streams

Biochar potential of broadacre crop stubble.

Waste from broadacre crops has been proposed as a source of biomass for the production of biochar[179]. Following harvest, the stubble would be collected, baled and transported to a biochar facility for processing.

Australia currently produces around 35 Mt/a of wheat, coarse grains and oil seeds (10 year average from 2001 to 2010). Wheat is the dominant crop, averaging 57% by weight of the total harvest followed by barley at 21%, the remainder comprising primarily oats, sorghum, maize, canola and triticale[180]. The annual production depends on weather patterns and varies widely with production between 21Mt and 48Mt being observed over the past ten years.

Australian productions of crops such as rice and cotton are relatively small in comparison (ten year average production of 0.56 Mt/a and 0.42 Mt/a respectively).

Field crops can be characterised by the Harvest Index (HI) which is the ratio of the grain yield to the above ground plant material (including grain) at harvest[181]. The above ground biomass may then be written as;

$$Y_{Bio} = Y_{Gr}\left[\frac{1}{HI} - 1\right] \qquad \text{(E.1)}$$

Where

Y_{Bio} : Above ground biomass (t)

Y_{Gr} : Grain yield (t)

HI : Harvest Index

HI varies with plant type and has generally increased over time as semi dwarf varieties have been developed that maximise grain production with limited water availability[182]. Johnson *et al*. (2006) indicate an HI for wheat of 0.45, for barley of 0.50 and 0.44 for oats, based on data

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[179] Burns K and Herbertson J. (2010) “Update on Commercialisation of the Crucible Carbon Pyrolysis Process” Presentation to Bioenergy Australia Annual Conference, Manly, Australia.

[180] Australian Bureau of Statistics “Agricultural Commodities – Australia” ABS 7121.0 www.ausstats.abs.gov.au

[181] Johnson J.M., Allmaras R.R. and Reicosky D.C. (2006) Estimating source carbon from crop residues, roots and rhizodeposits using the national grain-yield database” Agronomy Journal 98 pp622–636.

[182] Richards R.A. (2004) “Physiological traits used in the breeding of new cultivars for water-scarce environments” Proceedings of the 4th International Crop Science Congress, Brisbane, Australia.

from USA farms. Australian experience suggests slightly lower HI values of around 0.36 for wheat[183,184,185].

Assuming an average HI of 0.4 for Australia's broadacre crops would give the above ground biomass of production of 1.5 t/t of harvested grain, or a total average production of 45 Mt/a across Australia.

To ensure the lowest growing grain is collected, the combine harvester used to reap the crop will cut at some distance below the average head height. The biomass in the stems plus husk is then shattered to release the grain and returned to the field. Because to the breakage it is difficult to envisage the collection of much of this material. Similarly, traffic through the field during harvest will result in the crushing of some standing stubble while any stubble harvesting machine must cut at a certain distance above the ground level, leaving further biomass in the field. It will therefore not be possible to collect all residual stubble in a field.

Little data on proportion of stubble that can be harvested could be found. However, Glenvar in WA report a harvest of 0.8 tonnes of hay per tonne of wheat[186], the Government of Saskatchewan suggests 0.6 to 0.8 t/t harvested grain is practical[187]. This suggests that 50% of above ground biomass may be amenable to collection, or a total of 22 Mt/a across Australia.

Ultimate analyses for a number of biomass materials is available[188,189], these data suggest a typical as received moisture content of wheat (and other cereal) straws of about 10% and carbon content of about 42 - 45%. However, the conversion of the straw to char will result in the loss of some carbon, for example Bridgeman *et al*. (2008)[190] found that loss of carbon from wheat straw heated in nitrogen was strongly dependent on temperature with up to

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[183] Dunlop M., Poulton P., Unkovich M., Baldock J., Herr A., Poole M. and O'Connell D. (2008) "Assessing the availability of crop stubble as a potential biofuel resource" Proc 14th Australian Agronomy Conference (available http://www.regional.org.au/au/asa/2008/concurrent/emerging-opportunities/5842_dunlopm.htm accessed 22/7/2011)

[184] Zhang H., Turner N.C. and Poole M.L. (2004) "Crop production potential and constraints in the high rainfall zone of southwestern Australia: Yield and yield components" Proc 4th International Crop Science Congress, Brisbane, Australia.

[185] Li G. and Conyers M. (2004) "The effects of weeds on wheat yield in limed and unlimed soils" Proc 4th International Crop Science Congress, Brisbane, Australia.

[186] http://www.glenvar.com/Production/Straw/WheatStraw (accessed 30/6/2011)

[187] Anon (2006) "Best management practices when harvesting surplus cereal straw" http://www.agriculture.gov.sk.ca/Default.aspx?DN=9d0653b7-9839-42e5-9a72-c5f678834165 (accessed 30/6/2011)

[188] Phyllis, the composition of biomass, http://www.ecn.nl/phyllis/ (accessed 30/6/2011)

[189] BIOBIB - A Database for biofuels, http://www.vt.tuwien.ac.at/biobib/biobib.html

[190] Bridgeman T.G., Jones J.M., Shield I, and Williams P.T. (2008) "Torrefaction of reed canary grass, wheat straw and willow to enhance solid fuel qualities and combustion properties" Fuel 87 pp 844–856

35% loss recorded on heating to 290 °C, Mulligan *et al.* (2010)[191] found 46% and 49% loss on heating wheat char to 500 ºC and 1000 ºC respectively.

On the basis of this data it is therefore likely that the maximum potential production of biochar from cereal crop stubble, assuming full utilisation of all Australian stubble, is of the order of 5 Mt C/a (equivalent to18 Mt CO_2/a).

However, much of Australia's grain crop is produced on mixed sheep/wheat farms where stubble offers a valuable source of feed for sheep, also where crop is produced in marginal areas then plant numbers per unit area will be low relative to the average. The practical potential for harvestable stubble appears likely to be rather less than the maximum potential. It is therefore concluded that annual potential for production of biochar from broadacre stubble will be less than 5 Mt/a carbon.

Biochar Potential of Sugar Cane Farming

The average sugar cane crop in Australia between 2001 and 2010 was 34 Mt/a (varying between 28 and 37 Mt/a)[192]. This material is processed at regional sugar mills to produce around 4.5 to 5 Mt/a of sugar and a fibrous reside termed bagasse.

It is estimated that around one tonne of bagasse is produced from 4 tonnes of sugar cane, resulting in a production of around 11 Mt/a of wet bagasse in Australia[193]. Alternatively, Rainey (2009)[194] suggests an Australian production of bagasse of around 10 Mt/a. The bagasse is indicated to have an energy content of 19 MJ/kg and carbon content of 48.6%, both expressed on a dry basis[193]. This is consistent with overseas data e.g. 45.9 % C and 18.2 MJ/kg, dry basis[195] and 49.7 % C and 19.2 MJ/kg, dry ash free basis[196]. The bagasse is quoted as having an as-received moisture content of 55%[195] or 46% to 52%.

The energy content of this bagasse is significant, calculated at 105 PJ/a assuming 50% moisture and 19.25 MJ/kg energy content in dry bagasse. Stucley *et al.* (2998) state an energy content of 120 PJ/a for bagasse produced in Australia.

The bagasse is presently used primarily to generate steam for the sugar refining process and electricity for export. However, substantial improvements to the efficiency of use of this

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[191] Mulligan C.J., Strezov L. and Strezov V. (2010) "Thermal decomposition of wheat straw and mallee residue under pyrolysis conditions" Energy & Fuels 24: pp46-52.

[192] ABS 7121.0 - Agricultural Commodities

[193] Stucley C.R., Schuck S.M., Sims R.E.H., Larsen P.L., Turvey N.D. and Marino B.E. (2008) "Biomass energy production in Australia. Status, costs and opportunities for major technologies" Rural Industries Research and Development Corporation. Commonwealth of Australia Publication No 04/031.

[194] Rainey T. (2009) "A study of the permeability and compressibility properties of Australian bagasse pulp" PhD Thesis, Queensland University of Technology, Brisbane.

[195] Phyllis, the composition of biomass and waste. Electronic data base maintained by ECN Biomass (http://www.ecn.nl/phyllis/info.asp. accessed 22/7/2011)

[196] Domalski E.S., Jobe T.L. and Milne T.A. (1986) "Thermodynamic data for biomass conversion and waste incineration" report for the National Bureau of Standards under contract to the Solar Technical Information Program of the Solar Energy Research Institute.

energy are possible with current technologies and it is estimated that up to 4000 GWh of electric energy could be exported to the grid by the Queensland sugar industry through the retrofit of such equipment[197].

In addition to the sugar cane that is removed from the field, the sugar cane crop produces trash comprising leaves and growing tips of the cane. Cane trash is estimated at approximately 15% by weight of the above ground biomass at harvest time and with a similar energy content to bagasse[198], or about 6 Mt/a across Australia. Traditionally sugar cane trash was burnt prior to harvest to facilitate manual harvesting. However the development of mechanical harvesters and considerations of crop sustainability and environmental impact have reduced this practice in most parts of the sugar industry in Australia. Where the cane is not burnt prior to harvest some trash reports to the mill with the harvested cane, while the majority is returned to the field.

The recovery of sugar cane trash could therefore effectively double the amount of biomass available from the sugar industry. However, Pankhurst (2005) concluded that " the long-term benefits of GCTB (green cane trash blanketing) to soil health and crop productivity throughout most of the Australian sugar industry far outweigh any negative impacts, and are a solid argument for not recovering cane trash for use as a biofuel". Further, certain regions recommend the return of the trash to the fields as best management practice[199] although in the cooler southern regions there is concern that the trash may suppress yields[200]. It is therefore not clear that full retrieval of trash is likely or desirable.

Residues from sugar cane farming including bagasse and trash therefore total around 10 to 12 Mt/a (dry weight). Depending on charring conditions this may be expected to produce some 2 to 4 Mt/a of biochar. However, recognising the need to provide steam to the sugar refining process and the established cogeneration practice in the sugar milling industry it appears likely that only a fraction of this potential production could in fact be realised as biochar. The potential biochar production from the sugar industry therefore appears to be less than 4 Mt/a.

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[197] Australian Sugar Milling Council submission to Garnaut review. (http://www.garnautreview.org.au accessed 22/7/2011)

[198] Pankhurst C. (2005) "Should sugarcane trash be used as a biofuel for cogeneration or left in the field for its long-term benefits to soil health and crop productivity?" A report prepared for the Sugar Yield Decline Joint Venture

[199] Roebeling P.C. and Webster A.J. (2007) "Review of current and future best-management-practices for sugarcane, horticulture, grazing and forestry industries in the Tully-Murray catchment" A report to FNQ NRM Ltd CSIRO and FNQ NRM Ltd.

[200] Ridge D. (1998) "Farming systems for green cane trash blankets in cool wet conditions". SRDC Final Report SD98010. Sugar Research and Development Corporation. Bundaberg Queensland.

Biochar Potential of Mallee Tree Plantations

The incorporation of mallee tree plantations within normal dryland farming practices has been proposed as a means of capturing carbon, diversifying farm incomes and addressing land degradation issues such as salt accumulation[201].

A mallee oil industry development plan has been produced based around this concept[202]. A two tree row strip planting in 10% of suitable land was assumed such that normal farming would continue unhindered on the remaining land, it was also assumed that 50% of cleared land in Western Australia comprises soil types suitable for mallee planting. A mature yield of 8.6 to 15.5 green t/ha per annum (300 – 400 to 500 - 600 mm/a rainfall respectively) is projected, with the biomass expected to contain 42% moisture. A total tree crop area of 830,000 ha is calculated for Western Australia, producing a total of 8.5 Mt/a of green biomass.

Table E.1 indicates current land use statistics for Australia. Assuming mallee planting on 10% of suitable land (taken as 50% of current cropping and improved pasture area in Western Australia) would give a total mallee planting of 765,000 ha, close to that assumed in the development plan. Applying similar factors across the southern states that may be suitable for mallee planting suggests a total area of 2,900,000 ha of mallee is possible. Assuming similar productivity to Western Australia yields a total production of 32 Mt/a of green biomass (18.6 Mt/a dry biomass) potentially available.

Table E.1. Current land use in Australia[203]

Main Land Use	New South Wales	Victoria	South Australia	Western Australia
Cropping	9,341 kha[204]	4,740 kha	5,155 kha	10,524 kha
Grazing improved pastures	14,060 kha	6,098 kha	3,532 kha	4,779 kha
Total	23,421 kha	10,838 kha	8,687 kha	15,303 kha

The productivity of mallee plantations is presently not well defined. For example Bartle *et al.*[205] have developed a model for mallee production based on water use efficiency and

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[201] Future Farm Industries Cooperative Research Centre (2010) "Energy tree crops" University of WA, Stirling WA.

[202] URS Australia Pty Ltd (2008) "Oil mallee industry development plan for Western Australia"

[203] Australian Bureau of Statistics (2011) "Land Management and Farming in Australia, 2009-10" Doc No 46270DO001_200910.

[204] kha = 1000 ha

[205] Bartle J., Olsen G., Cooper D. and Hobbs T. (2007) "Scale of biomass production from new woody crops for salinity control in dryland agriculture in Australia" Int J. Global Energy Issues Vol 27, No 2.

rainfall statistics for southern Australia where water use efficiency is defined as the quantity of biomass produced per unit of available water. This data was combined with data overlays of soil and vegetation type to provide an estimate of biomass productivity at each point. An economic model was then generated which compared returns from biomass production with that from conventional farming practices to identify the quantities of mallee biomass that could be economically produced.

It was found that the total biomass production was sensitive to assumptions of water use efficiency and biomass price. The standard case indicates production of 8.2 Mt/a (dry) with the optimistic case suggesting 38.8 Mt/a (dry).

Biomass productivity assumed by Bartle *et al*. (2007) is substantially greater than that of URS Australia (2008) as indicated in Table E.2. Bartle *et al*. (2007) base their estimates on a model of water use efficiency in biomass due to Cooper *et al.* (2005)[206]. However, URS Australia (2008) state that more recent data from a study established to provide mallee harvest information across a representative range of soils and climates indicates Cooper's model overestimates actual productivity at all sites by more than 50%, actual yields being based on above ground biomass at plantation ages of 7 to 11 years. More recent data has also become available[207]. This data, from 19 sites with plantings from 1996 to 2001 suggests productivity intermediate between that assumed by Bartle *et al*. (2007) and URS Australia.

Table E.2 Mean annual increment at harvest

Annual Rainfall (mm)	Bartle et al (2007)	URS Australia		Bartle et al (2011)	
300 – 400	13.28 dt/ha[208]	8.6 gt/ha[209]	5.0 dt/ha	11 gt/ha	6.4 dt/ha
400 - 500	14.85 dt/ha	12.1 gt/ha	7.0 dt/ha	19 gt/ha	11.0 dt/ha
500 - 600	19.86 dt/ha	15.5 gt/ha	9.0 dt/ha	14 gt/ha	8.1 dt/ha

Applying the current assumptions of productivity would be expected to reduce the amount of land converted to biomass cropping as estimated by Bartle *et al*. (2007).

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[206] Cooper D., Olsen G., Bartle J.R. (2005) "Capture of agricultural surplus water determines the the productivity and scale of new low rainfall woody crop industries" Australian journal of Experimental Agriculture, 45, pp1369 – 1388.

[207] Bartle J and AbADI a. (2011) " The economics of the industry: future drivers and barriers to the bioenergy and mallee industries" Presented to Oil Mallee Industry Conference Perth. http://www.oilmallee.org.au/index.php/site/media-centre, accessed 6/7/20110.

[208] dt/ha = dry tonnes per hectare

[209] gt/ha = green tonnes per hectare. Data provided as green tonnes/ha converted to dry basis by assuming 42% moisture in biomass; productivity data from Bartle *et al*. (2011) assumes 4 year harvest cycle.

Abdullah and Wu (2009)[210] report that pyrolysis of mallee chips at 450 °C gives a yield of 27% char with a carbon content of 78.8%. This is in reasonable agreement with Lehmann and Joseph (2009)[211] who suggests char yields of from 10% for fast, high temperature (>750 ºC) pyrolysis to 35% for slow heating, moderate temperatures (500ºC) and long gas residence times. Similarly Mulligan *et al*. (2010) report 33.4% and 26.3% dry char residual on pyrolysis at 10 °C/min to 500 and 1000 ºC respectively of steamed mallee leaves, twigs and bark. In this experiment 56% (500 ºC) and 48% (1000 ^{o}C) of carbon reported to char

Taking the productivity data of URS Australia (2008) as a basis, assuming a biochar productivity of 25% by weight of original biomass and a carbon content of biochar of 85% suggests that carbon may be stored at a rate of around 4 Mt/a (displacing emissions of 15 Mt/a CO_2).

In addition to the harvested biomass, carbon will be stored below ground in the root system of the tree. Bartle *et al*. (2011) indicate that over a period of 30 years some 40 green tonnes of root system biomass will be accumulated per ha. This converts to 1.3 green t/ha per annum when averaged over the full 30 year term. Assuming 42% moisture and 50% carbon in dry biomass suggests a total storage in root systems across Australia of around 0.8 Mt/a (displacing emissions of 3 Mt/a CO_2)

The pyrolysis of biomass will provide a combustible gas which may be converted to electricity and potentially displace fossil fuel fired generation. The quantity and quality of the gas will vary with the pyrolysis conditions. The Abdullah and Wu (2009) data allows an order of magnitude estimate of energy content of the volatilised product under slow pyrolysis of mallee wood at a range of temperatures, Table E.3.

Table E.3 Energy content of pyrolysis gas under slow pyrolysis

Pyrolysis Temperature	Mallee wood	Char energy content	Char yield	Heat to char	Heat to volatiles
n/a	18 MJ/kg				
300 ºC		22 MJ/kg	56%	12.3 MJ/kg$_w$[212]	5.7 MJ/kg$_w$
350 ºC		28 MJ/kg	32%	8.9 MJ/kg$_w$	9.1 MJ/kg$_w$
500 ºC		32 MJ/kg	27%	8.6 MJ/kg$_w$	9.4 MJ/kg$_w$

Taking the biomass productivity assumed by URS Australia of an average 11 tonnes of green wood per hectare per annum then heat to volatilised product is of the order of 100 GJ/ha/a. Allowing an efficiency of converting heat to electricity of 30% and an emission rating of 0.9

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[210] Abdullah H and Wu H. (2009) “Biochar as fuel: 1 – Properties and grindability of biochar produced by pyrolysis of mallee wood under slow heating conditions” Energy and Fuel V 22, pp4174 – 4181.

[211] Lehmann J. and Joseph S. (2009) “Biochar for environmental management” Earthscan London.

[212] MJ/kg$_w$ = MJ gas per kg of dry wood delivered to pyrolysis process

tonnes of CO_2/MWh for coal fired electricity then full utilisation of the heat in volatile products would displace generation of 8.3 MWh, thereby displacing fossil fuel emissions of the order of 7.5 tonne CO_2 per hectare per annum. Applied over the 2.9 M ha suggested as achievable for mallee planting across Australia would result in avoided emissions of the order of 22 Mt CO_2/annum. To deliver this amount of electricity into the grid implies centralised pyrolysis and generation facilities, the analysis neglects emissions related to collections and transport of the biomass.

This suggests a total direct emission offset available from implementing mallee plantations across Australia to around 5% of cropping and improved pasture land is around 40 Mt CO_2 per annum.

APPENDIX E: Persistence of biochar in soils

It is well documented that carbonaceous residue from partial combustion or pyrolysis of biomass, termed biochar or Black Carbon (BC), can persist in soils for thousands of years. However, there is also strong evidence that charred organic material in soils can decay over time. Assessing the contribution that BC can make to carbon sequestration in Australia requires that BC decay rates be quantified under local field conditions.

The present review of the published literature was undertaken to gather and analyse information on the level of confidence that may be placed on claims made by various pyrolysis technology proponents of long persistence of BC in soils. The task force is aware that long-term measurements of BC persistence in soils for a range of well-characterised chars are underway in Australia.[213] [214] That data, when available, will provide a marked improvement in the confidence with which biochar technologies may be assessed in terms of permanence of carbon in soils.

A convenient simplification is to assume that the BC comprises one or more fractions that each decay at a constant rate[215]. The BC residual after time t years can then be described by eq. F.1:

$$C_{remaining} = \sum_i C_i . e^{-k_i t} \qquad \text{(F.1)}$$

where

$C_{remaining}$: fraction of original BC after t years
C_i : initial fraction of BC component i
k_i : exponential decay constant for the ith fraction (per year)
t : decay period (years)
i : number of BC components with discrete decay rates

This allows the definition of alternative characteristic times for each fraction such as

- Mean residence time: average time that the fraction exists ($=1/k_i$).
- Half life: elapsed time to 50% reduction of fraction ($C_{remaining} = 0.5$).

Decay constants of BC have been assessed by a number of authors. Nguyen *et al.* (2008)[216] measured BC carbon in 18 samples of agricultural soils from Kenya at a location with a mean

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[213] Singh B.P., Cowie A.L., Smernik R.J. (2011) "A novel 13C natural abundance approach for measuring biochar's stability and priming effect on 'native' soil carbon. 11th Australasian Environmental Isotope and 4th Australasian Hydrogeological Research Conference, Cairns, July 12-14.

[214] Singh B., Singh B.P., Cowie A.L. (2010) "Characterisation and evaluation of biochars and their application as a soil amendment". Australian Journal of Soil Research, 48(7), 516-525.

[215] Lehmann J., Czimczik C., Laird D. and Sohi S. (2009) "Stability of Biochar in the Soil" in Biochar for Environmental Management, Lehmann J and Joseph S. (eds) Earthscan London

annual temperature of approximately 19 ºC. The farms had been established on land cleared by slash and burn of original forests over periods of 2 to 100 years prior to sampling. BC in soil was correlated as a function of time by the relation $BC = 3.51 + 9.16e^{-0.12 \cdot years}$. This indicates two fractions, one with negligible decay over the experimental period and one with an exponential decay rate of 0.12 per annum.

Nguyen and Lehmann (2009)[217] measured decay rates for BC produced by slow heating to 350 and 600 ºC of corn stover and oak wood chips under nitrogen. Sized char particles (+ 0.5mm, -2 mm) were then incubated in sand doped with microbial inoculant and nutrient solution for one year under saturated, unsaturated and alternating moisture conditions. Carbon loss varied between 21.2% for 350 ^{o}C corn stover BC under unsaturated conditions to 6.15 % for 350 ^{o}C oak char under saturated conditions. In general the low temperature chars exhibited greater carbon loss than did the high temperature char, particularly in the case of corn stover char.

Nguyen *et al.* (2010)[218] further investigated the effect of temperature on decomposition rates of BC produced from corn stover and oak chips as described by Nguyen and Lehmann (2009). The BC types were incubated for a period of one year in inoculated sand cultures, at six different temperatures and using eight replicates.

All BC types were found to mineralise to CO_2 more rapidly as temperature increased, with the low temperature chars mineralising more rapidly than high temperature chars and corn stover char more rapidly than oak chip derived materials at any temperature. The impact of incubation temperature change was found to decrease as temperature increased.

Data is provided on residual carbon at one year for each char type and at six temperatures between 4 and 60 ^{o}C in an electronic supplement to the paper. Residual carbon is correlated against temperature using eq. F.2 and the parameter values for each char type are tabulated.

$$f = Const + a.e^{-bT} \qquad (F.2)$$

where

f : fraction residual carbon at end of experiment

T : temperature (^{o}C)

a : pre exponential factor

b : exponential temperature weighting factor

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[216] Nguyen B.T., Lehmann J., Kinyangi J., Smernik R., Riha S.J. and Engelhard M.H. (2008) “Long term black carbon dynamics in cultivated soil” Biogeochemistry 89: pp 295-308

[217] Nguyen B.T. and Lehmann J. (2009) “Black carbon decomposition under varying water regimes” Organic Geochemistry 40: pp846-853.

[218] Nguyen B.T., Lehmann J., Hockday W.C., Joseph S., and Masiello C. (2010) Temperature Sensitivity of Black Carbon Decomposition and Oxidation” Environ. Sci. Technol. 44; pp 3324–3331.

Residual carbon at a temperature of 18 ^{o}C is here calculated for each char using eq. F.2, and the equivalent exponential decay rate and half-life calculated. Results are listed in Table F.1.

Table F.1

Char Source	Char temperature	Char$_{\text{resid 18ºC}}$	Exponential decay constant	Half life
	(^{o}C)	(%)	(per annum)	(years)
Corn stover	350	83.8	-0.177	4
Corn stover	600	85.8	-0.153	5
Oak Chips	350	90.7	-0.098	7
Oak Chips	600	92.8	-0.075	9

Kuzyakov *et al*. (2009)[219] have measured carbon loss from soil and loess samples doped with ^{14}C labelled BC. The BC was produced by slow heating of perennial ryegrass followed by heat soaking (13 hours) at 400 ºC. The BC was incubated for 1181 days at 20 ^{o}C and saturation to 70% water holding capacity. CO_2 emitted by the samples was measured at intervals by absorption into NaOH solution and microbial biomass determined at the end of the experiment. Samples were subject to agitation and to dosing with glucose solution (to stimulate microbiological activity) on a number of occasions.

It was found that BC decomposition rates decreased from an initial rate of 0.016%/day and 0.024%/day (soil and loess respectively) to a constant rate over the final two years of 0.0013 to 0.0015 %/day (both substrates). This decrease in rate with time was taken as evidence of depletion of more reactive components in the BC. Agitation of samples had minimal effect but stimulation of biological activity in the samples caused a short term increase (< one month) in decomposition by about a factor of 3 in the soil and somewhat higher in the loess. This was taken as confirming that biological activity is important in the decomposition of BC. It was concluded that under field conditions of 7 ^{o}C mean temperature and mean precipitation of 600- 700 mm, decomposition rate would decrease in proportion to decrease in biological activity to about 10% of that measured.

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[219] Kuzyakov Y., Subbotina I, Chen H, Bogomolova I and Xu X (2009) “Black carbon decomposition and incorporation into soil microbial biomass estimated by 14C labelling”. Soil Biology & Biochemistry 41:pp 210–219

Chung *et al.* (2008)[220] have measured decomposition of BC residue from 16 historical sites. The BC was originally produced by charring of woods such as oak, chestnut and hickory to produce a high strength, high density charcoal suitable for blast furnace use. Samples of BC containing soils were obtained from the historical storage sites plus from non BC containing soils adjacent the storage sites as reference material.

BC containing and non BC containing soils were incubated at 30 °C and 60% water holding capacity for a total of 177 days. Separately, selected BC particles (+1mm – 2mm) immersed in inoculated sand with added nutrient were incubated for 50 days. Evolved CO_2 was collected in NaOH solution and analysed at intervals during the incubation period. Data from the soils was fitted by a double exponential decay model (a labile and a recalcitrant component) for the soils and a single exponential for the BC particles.

Mineralisation rates of the recalcitrant component of the soils was determined to range between 0.15×10^{-4} and 5.02×10^{-4} per day (mean of 0.43×10^{-4}/day). While the quantity of BC in soils (assumed to be the recalcitrant material) was not determined directly, the mean difference in organic carbon between BC containing soils and their respective reference samples allowed a half- life of 80 years to be determined for the BC component. The data also indicated that an increase in temperature by 10 °C would produce a 3.38 times increase in mineralisation rate and a half life at 10 °C mean average temperature of 925 years is proposed. Cheng *et al.* note that the more labile fractions of the BC will likely already have been lost over the average 130 year life of the samples.

Decomposition rate constants determined for the BC particles were much higher than for the recalcitrant component of the soils. Measured decomposition was assumed due entirely to contamination of the particles with labile organic carbon. It is noted that, if the alternative assumption, that the measured mineralisation is from the BC particles, in made then decay rates and half-life of the BC particles can be calculated from the data provided. The half-life is here estimated to range between 23 and 206 years for these particles. Accepting labile carbon contamination in at least some of these particles then these data provide minimum values for half-life of the BC particles and varying contamination may account for the large spread in the data.

Bird *et al.* (1999)[221] measured oxidative resistant elemental carbon (OREC) in soil plots in Zimbabwe that had been exposed to fire at regular periods of 1, 3 and 5 years respectively, or alternatively protected from fire since 1947. OREC in samples was determined by chemical oxidation of the labile proportion of carbon in the soil followed by combustion to determine residual (OREC) quantities.

Total OREC in the protected plots averaged 2.0 ± 0.5 mg/cm^2 as compared to that of the burnt plots of 3.8 ± 0.6 mg/cm^2, with only minor differences (± 10%) between different burning treatments. This data suggested a half-life for natural degradation of OREC of < 100 years. Further, larger char particles (>2mm) were common at the burnt sites but largely absent in the protected sites. This indicated a half-life of < 50 years for these particles which

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[220] Cheng C.H., Lehmann J., Thies J.E., Burton S.D. (2008) "Stability of black carbon in soils across a climatic gradient" Journal of Geophysical Research V113; G02027.

[221] Bird M.I., Moyo C., Veenendaal E.M., Lloyd J. and Frost P. (1999) "Stability of elemental carbon in a savanna soil" Global biogeochemical cycles 13(4); pp923-932

appear to progressively move to smaller size fractions. It was concluded that only a small fraction of OREC is likely to be sequestered into a slow cycling geological carbon reservoir at these well aerated savannah sites.

Baldock and Smernik (2002)[222] investigated the chemical changes and resistance to decay of charred samples of red pine sapwood. Samples were heated in air to constant weight at temperatures of 150 to 350 ºC. The resultant chars were then analysed for chemical structure and bioavailability of carbon. Bioavailability was assessed by incubating the samples in a sand medium in air at 25 °C. Water, microbial inoculum and nutrients were added to the sand with the objective of determining the bioavailability of carbon in the heated samples relative to that of the original material and to glucose and cellulose. Residual carbon was determined after 120 days by combustion and the fraction of biological available material determined as the fraction of initial organic carbon respired.

Approximately 85%, 74% and 20 % of the organic carbon in glucose, cellulose and original sapwood respectively were mineralised to CO_2 over the period of incubation. This reduced to 13% for sapwood heated to 150 °C and to <2% for sapwood heated to temperatures ≥200 ºC respectively. Samples heated to ≥200 °C all showed some loss of material but differences were not statistically different. This reduction in bioavailability coincided with significant changes in chemical composition of the sapwood observed at temperatures ≥200 °C.

Harmer *et al*. (2004)[223] measured decomposition rates of BC material produced by heating charred maize and rye straw to 350 °C in closed stainless steel containers for two hours. Oak wood was charred at 800 °C for 20 to 24 hours. The BC samples were mixed with sand, microbial inoculum, nutrient solution and moisture sufficient to reach around 60% of water holding capacity and then incubated for 60 days at 20 °C. Samples were primed by the additional of ^{14}C labelled glucose at day 1 and day 25 and BC mineralised determined from measurement of CO_2 released with adjustment of that derived from the labelled glucose.

Mean residence times of 39 and 76 years respectively were calculated for charred straw and charred wood respectively using a two component first order decay equation. Due to the short time of the experiment it may be expected that this will be a minimum value due to the likely early loss of easily degradable fractions. However, while high initial decay rates were observed, decay rates had stabilised by the end of the experiment. The addition of glucose was seen to accelerate decomposition of the char indicating a contribution to decay by microbial action.

Gavin *et al*. (2003)[224] collected multiple core samples for 75 sites in forest in Vancouver Island and analysed these for BC that had been produced by past wildfire activity. Care was taken to identify sites where BC was unlikely to be affected by lateral transport mechanisms. BC content of samples was determined by manual isolation under a binocular microscope and weighing of separated BC particles. Ages of the BC samples were determined by

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[222] Baldock J.A. and Smernik R.J. (2002) “Chemical composition and bioavailability of thermally altered Pinus resinosa (Red pine) wood” Organic Geochemistry 33; pp 1093–1109.

[223] Hamer U., Marschner B., Brodowski S.and Amelung W. (2004) “Interactive priming of black carbon and glucose mineralisation” Organic Geochemistry 35; pp 823–830

[224] Gavin D.G., Brubaker L.B. and Lertzman K.P. (2003) “Holocene fire history of a coastal temperate rain forest based on soil carbon radiocarbon dates” Ecology, 84(1) pp. 186–201.

radiocarbon dating, correlated against tree ring data where available. It was found that content of BC in soil varied greatly between sites and decreased only slightly with time, content of >0.5 mm particles in soil was expressed in first order exponential form with an exponential decay rate of -0.000151 %/year (R^2 = 0.09).

Preston and Schmidt (2006)[225] interpret this data as indicating an average half-life of 6623 years for the BC. However half-life, defined as time to 50% residual carbon, is 4590 years using the correlation provided in Gavin *et al*. (2003) while mean residence time, defined as the inverse of the decay constant is 6623 years. The low coefficient of determination (R^2) for the original data also suggest high uncertainty in this conclusion.

Wardle *et al*. (2008)[226] measured decay rates for laboratory produced char, forest litter and a 50:50 mix of char and litter, buried in mesh bags at three sites in a boreal forest. Average temperature for the sites are not given but are expected to be low. Weight loss measurements were carried out at intervals over 10 years. The char exhibited a small weight loss over the first four years but then showed a small weight gain for the final (10 year) measurement. The cumulative carbon release over 10 years for the char is indicated as of the order of 5 mg/g carbon with an uncertainty of ±5 mg/g.

It was noted that the char accelerated decomposition of the litter in the char /litter mix, suggesting that char additional to soil may result in increased mineralisation of labile carbon in soils. The char containing samples were both found to have accumulated nitrogen at 10 years.

Lehmann *et al*. (2008)[227] used measured data on BC and soil organic carbon in two savannah regions in northern Australia as a basis for estimating the decay rate of BC produced by wild fire at these locations. Estimates of fire frequency, proportion of biomass converted to BC and decay rates for soil organic carbon allowed determination of BC decay rates that allowed predicted BC contents to match the measured values. Mean residence times of from 718 to 9259 years were determined, depending on assumptions made about fire frequency and proportion biomass conversion to BC.

Hammes *et al*. (2008)[228] measured BC in samples of Russian steppe soil samples taken approximately 100 years apart. The steppes were previously frequently exposed to fire, however the initial sample was taken near to the time that regular fire was controlled by agricultural activity. The more recent sample was taken from the location identified in records as that of the initial sample while supporting samples were taken in the near vicinity. The topography and stability of soil type over large areas in this location is expected to reduce impact of potential differences in location of original and more recent samples.

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[225] Preston C.M. and Schmidt M.W. I. (2006) “Black (pyrogenic) carbon: a synthesis of current knowledge and uncertainties with special consideration of boreal regions” Biogeosciences, 3; pp 397–420.

[226] Wardle D.A., Nilsson M. and Zackrisson O. (2008) “Fire-Derived Charcoal Causes Loss of Forest Humus” Science 320(2) pp629.

[227] Lehmann J., SkjemstaD J., Sohi S., Carter J., Barsons M., Falloon P., Coleman K., Woodbury P. and Krull E. (2008) “Australian climate–carbon cycle feedback reduced by soil black carbon” Nature Geoscience Letters 1; pp832-835.

[228] Hammes K., Torn M.S., Lapenas A.G. and Schmidt M.W.I. (2008) “Centennial black carbon turnover observed in a Russian steppe soil” Biogeosciences Discussion 5; pp 661–683.

The rate of decay of BC was modelled using the concept of turnover time τ as defined in eq. F.3, τ reduces to mean residence time (= 1/exponential decay rate) when modern BC contribution is zero.

$$\tau = -T/\ln\left(F - B/\left(F-1\right)\right) \qquad \text{(F.3)}$$

where

τ : turnover time (years)

T : time elapsed between samples (years)

F : ratio of modern BC contribution to historical rate

B : fraction of original BC stock remaining after T years

Turnover time was calculated to range between 212 to 541 years depending on choice of times between sampling and soil bulk density. The best estimate, assuming a 90% reduction in BC contribution rate over the experimental period, was 293 years.

Liang *et al*. (2008)[229] measured decay rates from BC in anthrosols collected from four sites in Brazil and from four adjacent non BC containing sites for comparison. Samples were incubated for 532 days at 30 °C with moisture maintained at 55% of field capacity. Decay of carbon was determined by measurement of CO_2 evolved during the experiment. A double exponential decay model was fitted to the data, assuming a large slow turnover pool (BC) and a smaller more labile component.

Turnover times ranging between 9 to 20 years were calculated for the control samples and between 44 to 52 years for the BC containing anthrosols. However, it was concluded the double curve fit approach overestimated the proportion of stable carbon in the soils. It was however concluded that the turnover time for the BC would be centuries to millennia based on a more than order of magnitude difference in decay rates of the labile and slow turnover components. In view that the double decay model was considered not to properly represent the decay of the different carbon fractions this conclusion must be considered tentative.

Biochar clearly decays with time. To recognise biochar as a carbon sink then requires that a minimum storage time period be ascribed, carbon lost due to decay prior to this time cannot be considered as sequestered. A precedent for minimum storage time is contained in the Australian carbon farming initiative draft guidelines[230] which indicate a requirement for a minimum 100 years storage period.

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[229] Liang B., Lehmann L., Solomon D, Sohi S., Thies T.E., Skjemstad J.O., Luiza F.J., Engelhard M.H., Neves E.G., Wirick S. (2008) "Stability of biomass-derived black carbon in soils" Geochimica et Cosmochimica Acta 72; 6069–6078

[230] Dept of Climate Change and Energy Efficiency "Carbon farming initiative - Draft Guidelines for Submitting Methodologies. Commonwealth of Australia (http://www.climatechange.gov.au/government/submissions/~/media/publications/carbon-farming-initative/draft-methodology-guidelines-pdf.pdf - accessed 12/7/2011))

A summary of the literature data on BC decay rate is given in Table F.2. Different authors have provided decay rate data in various forms. Here it is converted to a constant base of percent carbon remaining after 100 years as determined when applying the decay rates assessed by the various studies. Where incubations were carried out at temperatures above 25 ºC, decay rates were corrected to 18 °C[231] using an average of correlations for different char types from Nguyen *et al.* (2004).

Care must be exercised in extrapolating short term incubations studies to life of BC materials under field conditions. In particular many incubations use high temperatures and constant moisture to accelerate decay rates, many use sand as a medium which maximises aeration but minimises the potential for soil components such as clays to bind with and protect BC particles from decay. The short term of these experiments will also mean that results will be biased toward properties of the more degradable fractions. Conversely, examination of aged soil and BC samples will be biased toward fractions that have high resistance to decay.

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[231] Based on mean of long term annual average maximum and minimum temperatures at 13 locations across NSW, Vic, SA and WA. Farming regions. Data from Australian bureau of meteorology (http://www.bom.gov.au/climate/data/ assessed 12/7/2011)

Table F.2 Literature data on BC decay

Reference	Char type	$C_{remaining,\ 100y}$
Nguyen *et al*. (2008)	Char produced by slash and burn clearing of land	28%
Nguyen and Lehmann (2010)	Corn stover and oak chips, charred at 350 and 600 ºC, varying moisture of incubation	<1%[a]
Nguyen *et al*. (2010)	Corn stover and oak chips, charred at 350 and 600 ºC, varying temperature of incubation	0[a]
Kuzyalov *et al*. (2009)	Perennial rye grass char in soil and loess	60%[b]
Cheng *et al*. (2008)	Old charcoal from blast furnace operations	56%[c]
Bird *et al*. (1999)	Savannah combustion	29%
Baldock and Smirnik (2002)	Pinus sapwood charred at 150 C	0%
Baldock and Smirnik (2002)	Pinus sapwood charred >200 ºC	>0.2%
Harmer *et al*. (2004)	Maise and Rye residue 350 ºC	17%
Harmer *et al*. (2004)	Oak wood residue ºC	40%
Preston and Schmidt (2006)	Aged charcoal from forest fires, data from Galvin et al.(2003)	98.5%
Wardle *et al.* (2008)	Lab charcoal[d]	95%
Lehmann *et al*. (2008)	BC from burning of savannah	87 – 99%
Hammes *et al*. (2008)	BC from burning of Russian steppe	71%

a: decay rate measured at 30 °C adjusted to 18 °C using data from Nguyen *et al*. (2010)
b: estimate based on constant decay rates over final two years of experiment
c: estimate based on half-life inferred by authors at 30 °C, adjusted to 18 °C using data from Nguyen *et al*. (2010)
d: Temperature not given, expected to be low in boreal forest.

It must be further recognised that BC properties can depend strongly on the source biomass, it's preparation including activation, grinding and previous exposure to weathering, and the pyrolysis conditions. These latter conditions could include, for example, the presence during heating of oxygen, moisture and other contaminants; heating rate; final temperature and the period of soaking at the maximum temperature. Few of the publications discussed above provide such details and it is likely that none of these chars is representative of that produced from commercial pyrolysis equipment.

The data reviewed above shows little consistency, although it is clear that some chars do indeed persist for periods well in excess of 100 years. There appears to be a trend with high temperature chars exhibiting greater decay resistance that low temperature chars, and chars sourced from wood appear to be more persistent than BC from more friable sources.

APPENDIX F: Financial analysis assumptions

NETL methodology additional detail

EPC Contractor services: estimated by NETL at 8 to 10 % BEC and taken by the task force to be 10% of BEC.

The NETL methodology assumes that the plant construction is managed by an Engineer/Procure/Construct (EPC) contractor who carries certain limited responsibilities for the project delivery and utilises a multiple subcontract strategy. In particular, the plant owner assumes plant performance, schedule and cost escalation risks. This approach is assumed by NETL on the basis of current utility industry experience in USA where EPC contractor margin to carry full plant delivery risks has become excessive. In general the multiple subcontract strategy allows these risks to be managed over time to the benefit of the owner.

Project Contingency: estimated at 15 – 30% of (BEC + EPC fees + process contingency) and taken by the task force as 15%.

NETL have adopted this contingency level for budget type estimates of AACE Class 4 or 5 as recommended by the AACE International Recommended Practice No 16R-90.

Economic Analysis Factors.

A number of factors are important in assessing the economic performance of the project in addition to the capital cost. These relate primarily to the need to reflect the fact that money has a time value and therefore equal amounts of money spent at different times may not have the same impact on project viability or profitability. In addition it is necessary to recognise the impact of the financial system in which the project operates, in particular tax and accounting issues.

The Task Force has adopted the principles set out in Table G.1

Table G.1: Project economic analysis factors applied by Task Force.

Income Tax Rate[232]	30%
Capital depreciation[233,234]	30 years, 200% diminishing value
Project life	30 years
Discount rate[235]	base rate: 10% real, sensitivity tests at different rates
Project financing	100% equity (implicit)
Capital expenditure period	5 years for mineralisation and algae sequestration, 2 years for forestry projects
Economic analysis period	Project life + capital expenditure period
Distribution of total overnight capital (before escalation)	5 year period: 10%, 30%, 25%, 20%,15% 2 year period: 40% and 60%
Total of overnight capital depreciated	100%
Cost base	$AUD 2011.

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[232] Australian company tax rate 2011/12 FY

[233] Indicative of electricity generating plant equipment as defined under Australian Tax Office (2011) "TR 2011/2 Income tax: effective life of depreciating assets (applicable from 1 July 2011)" Commonwealth of Australia.

[234] Australian Tax Office (2011) "Guide to depreciating assets 2011" Commonwealth of Australia.

[235] Discount rate is commonly determined as weighted average costs of equity and debt, which in turn depend on project financing and proponent risk measures. In view of the developmental status of these technologies and the unknown characteristics of likely proponents, discount rates in keeping with commercial practice for developed technologies were adopted.

Cost Estimate Classification

The American Association of Cost Engineers has developed guidelines for classification of cost estimates[236]. The broad characteristics of these classifications is shown in Table G.2 while some of the key defining requirements for each category are included in Table G.3.

Table G.2: Characteristics of AACE Cost Estimate Classifications[237]

Estimate Class	Typical application	Typical estimating methodology	Expected accuracy
Class 5	Concept screening	Factor models, expert judgement	L: -20% to -50% H:+30% to +100%
Class 4	Feasibility study	Equipment factored or parametric models	L: -15% to -30% H:+20% to +50%
Class 3	Budget authorisation	Semi detailed unit costs with assembly level line items	L: -10% to -20% H:+10% to +30%
Class 2	Control or tender	Detailed unit costs with forced detailed take-off	L: -5% to -15% H:+5% to +20%
Class 1	Check estimate or tender	Detailed unit costs with detailed take-off	L: -3% to -10% H:+3% to +15%

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[236] AACE International Recommended Practices No. 17R-97 - Cost Estimate Classification System. Association for the Advancement of Cost Engineering International

AACE International Recommended Practices No. 18R-97 - Cost Estimate Classification System – As Applied in Engineering, Procurement and Construction for the Process Industries. Association for the Advancement of Cost Engineering International

[237] Adapted from AACE International Recommended Practices No. 18R-97. The +/- value represents typical percentage variation in actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for a given scope.

Table G.3: Illustrative estimate category definition checklist[238].

	Class 5	Class 4	Class 3	Class 2	Class1
Project scope	General	Prelim	Defined	Defined	Defined
Capacity	Assumed	Prelim	Defined	Defined	Defined
Location	General	Approx.	Specific	Specific	Specific
Work breakdown structure	None	Prelim	Defined	Defined	Defined
Block flow diagrams	S/P	P/C	C	C	C
Process flow diagrams		S/P	P/C	C	C
Utility flow diagrams		S/P	P/C	C	C
Piping and instrument diagrams		S	P/C	C	C
Heat and mass balances		S	P/C	C	C
Process equipment list		S	P/C	C	C
Mechanical drawings			S	P	P/C
Electrical drawings			S	P	P/C
Civil/structural/site drawings			S	P	P/C
Control/instrumentation drawings			S	P	P/C

It is common to assume cost estimates follow a log normal distribution as actual costs are usually higher, rather than lower, than estimated and there is no probability of costs being less than zero, as is possible at low probability with a normal distribution. If it is assumed that the cost estimate including contingency is the mean of the distribution then it is possible to estimate the standard deviation by normalising the cost and taking the expected accuracy limits to indicate the 10% or 90% points on the cumulative probability distribution as appropriate. Applying this approach here provides the log normal distribution parameters as indicated in Table G.4.

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[238] Adapted from AACE International Recommended Practices No. 18R-97, S indicates work started, P indicates work is advanced with final reviews and approvals outstanding, C indicates work review and approval is complete.

Table G.4: Parameters for log normal distribution satisfying high and low range for expected accuracy in Class 4 estimate[239].

Expected Accuracy	Distribution mean	Standard Deviation
-15% - + 30%	1	0.134
-20% - + 50%	1	0.297

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[239] A single value of standard deviation does not exactly satisfy both end points of the expected accuracy range, assumed to be due to rounding of the expected accuracy range values.

Capital Costs employing the NETL method

Two examples of the application of the NETL method are given below for data from the literature – algae growth with anaerobic fermentation (Campbell *et al.* (2009))[240] and Mineral Carbonation (Rayson *et al.* (2008)). Costs of some inputs (e.g. electricity and natural gas) were assumed by the task force in 2020, as given in the tables and outlined at the end of this Appendix. Costs of other capital items and operating costs and were adjusted to 2011 dollars and these were assumed to be the same in 2020 in real terms.

Algae Growth with Anaerobic Fermentation (Campbell *et al.* (2009))

Capital costs were taken directly from the Campbell *et al*. publication for the individual process items. Process contingency was taken as 30% for harvesting settlers, flocculation and centrifuges and 15% for all other items. Other costs, as outlined by the NETL approach, were applied and the costs adjusted by inflation to 2011. This gave the following inputs to the financial model, in $/ha:

Bare erection costs (BEC)	$105,848
Process contingency (PROC)	$ 22,405
EPC Contractor Services (EPC)	$ 10,585 (10% of BEC)
Project Contingency (PRC)	$ 20,826 (15% of BEC + PROC + EPC)
Total Project Costs (TPC)	$159,664 (BEC + PROC + EPC + PRC)
Start up Costs (SUC)	$ 5,518
Inventory Capital (IC)	$ 1,355
Financing Cost (FC)	$ 4,311 (2.7% of TPC)
Other Owners Costs (OC)	$ 23,950 (15% of TPC)
Total Overnight Cost (TOC)	$194,798 (TPC + SUC + IC + FC + OC)
TOC in 2011 dollars	$212,329 per ha

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[240] Campbell P K, Beer T, Batten D, "Greenhouse Gas Sequestration by Algae: Energy and Greenhouse Gas Life Cycle Studies", *Sustainability Tools for a New Climate*, Proc. 6th Australian Life Cycle Assessment Conference, Melbourne, Feb 2009.

1.2 Mineral Carbonation (Rayson *et al.* (2008))[241]

Capital costs were taken directly from the Rayson *et al*. report for the individual process items. A variety of process contingencies were assumed in the NETL method, as follows:

Items allocated a 37% contingency by Rayson et al.	37% (CFB, HP grinding rolls)
Reactor	40%
Magnetic separation, tubular pulse filters	30%
Other common mineral processing items	15%

Other costs, as outlined by the NETL approach, were applied and the costs adjusted by inflation to 2011. In addition, the 37% contingency items in the Rayson *et al*. report already include EPC charges, so these were added in at the EPC stage in the NETL calculation, as below. This gave the following capital inputs to the financial model, in $M:

Bare erection costs (BEC)	$1,813M (not incl. 37% contingency items)
Process contingency (PROC)	$ 422M (15%, 30% and 40% contingency items)
EPC Contractor Services (EPC)	$ 181M (10% of BEC items not containing EPC)
Project Contingency (PRC)	$ 392M (15% of BEC + PROC + EPC above)
Items already containing EPC	$ 196M (& 37% contingency in Rayson *et al.*)
Total Project Costs (TPC)	$3,004M (BEC + PROC + EPC + PRC)
Start up Costs (SUC)	$ $117M
Inventory Capital (IC)	$ $58M
Financing Cost (FC)	$ $81M (2.7% of TPC)
Other Owners Costs (OC)	$ $451M (15% of TPC)
Total Overnight Cost (TOC)	$3,711M (TPC + SUC + IC + FC + OC)
TOC in 2011 dollars	$4,044M

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[241] Rayson, M., M. Magill, R. Sault, G. Ryan and M. Swanson (2008). "Mineral Sequestration of CO_2 - Group 2, Phase 3", Discipline of Chemical Engineering, The University of Newcastle, NSW 2308. Report may be obtained by contacting the Discipline Secretary at the University of Newcastle.

Operating Costs, including credits and operating variables

Algae Growth with Anaerobic Fermentation (Campbell *et al.* (2008))

Operating Item	Cost or Credit	Unit
Algal-oil	\$0.50 to \$1.25	\$/litre, credit
Stockfeed	\$200	\$/tonne, credit
Natural gas price	\$5.74	\$/GJ in 2020 (real)
Electricity Price	\$75	\$/MWh (incl. margin) in 2020
Electricity consumption	0.27	MWh/tonne algae
Nutrient cost	\$1,144	\$/tonne
Nutrient consumption	0.0138	tonne/tonne algae
Flocculant cost	0.00243	tonne/tonne algae
Waste production	0.167	tonne/tonne algae
Waste disposal cost	\$105	\$/tonne
Fixed operating costs (labour, R&M)	9%	% of capital cost per year
Algae oil content	30%	% dry mass
Bio-oil density	0.8	kg/litre
Algae productivity	10 to 50	$g/m^2/day$
Algae carbon content	80%	% dry mass
CO_2 consumption	2.0	tonne/tonne algae
CO_2 collection efficiency	90%	% of input CO_2 consumed by algae

Mineral Carbonation (Rayson *et al.* (2008))

Operating Item	Cost or Credit	Unit
Iron and Chromium content	11%	% of serpentine feed rock
Price of Fe and Cr oxides	\$100	\$/tonne, credit
Natural gas price	\$5.74	\$/GJ in 2020 (real) assumed
Natural gas consumption	3.153	GJ/t CO2
Electricity Price	\$75	\$/MWh (incl. margin) in 2020 assumed

Electricity consumption	0.057	MWh/tonne CO_2
Water consumption	0.42	k litre/tonne CO_2
Water cost	$0.20	$/k litre
Mining cost	$4.50	$/tonne rock
Fixed operating costs (labour, R&M)	8%	% of capital cost per year
Net CO_2 efficiency	76%	Net CO_2 as carbonate (%)
CO_2 capture cost to provide “pure” CO_2	$50	$/t CO_2
CO_2 transport cost (power)	$2	$/tonne CO_2

Forestry, including capital costs (Hunt (2007)[242], Polglase *et al*. (2011)[243])[244]

Item	Hunt (2007)	Polglase *et al.* (2011)
Capital cost, plantings[245]	$3,220/ha	
Capital cost, land	-	$250/ha (low) $3,500/ha (high)
Establishment costs (once-of)	-	$3,000/ha
Maintenance costs (first 3 years)	$1,250/ha	
Opportunity costs (beef husbandry – annual)	$227/ha	

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[242] Hunt, C. (2008). "Economy and ecology of emerging markets and credits for bio-sequestered carbon on private land in tropical Australia." Ecological economics **66**(2-3): 309.

[243] Polglase, P., A. Reeson, C. Hawkins, K. Paul, A. Siggins, J. Turner, D. Crawford, T. Jovanovic, T. Hobbs, K. Opie and J. A. Carwardine, A. (2011). "Opportunities for carbon forestry in Australia: Economic assessment and constraints to implementation". CSIRO.

[244] In 2011 dollars.

[245] 3.25m tree spacing, 947 trees/ha, $3.40 per tree.

Probabilistic Calculations

In order to undertake the probabilistic calculations associated with the distributed "Price of CO_2 Required" and the Net Present Option Value (NPOV), assumptions must be made regarding the probabilistic distributions for the key variables. The following assumptions were used in the analyses:

Item	Type of Distribution	Description of probabilistic parameters
Capital costs	Log Normal	NETL assumption with a location of zero and a standard deviation of 0.297 times the mean for algae and mineral carbonation technologies, and a standard deviation of 0.134 for forestry.
Algae		
Algal-oil price ($/litre)	Triangular	For the sensitivity analysis: $0.25 (low)-$0.50 (centre)-$0.75 (high) $0.25 - $0.73 - $1.25 $0.75 - $1.00 - $1.25 $1.00 - $1.25 - $1.50
Algal productivity ($g/m_2/d$)	Log Normal	A location of zero and the following mean and standard deviation parameters for the sensitivity analysis: 20 + - 7 30 + - 10 40 + - 12 50 + - 12
Algal oil content	Normal	A mean of 30% and a standard deviation of 4%.
CO_2 consumption (tonnes per tonne of algae)	Triangular	A central value of 2.0, a lower limit of 1.9 and an upper limit of 2.5.
Mineral Carbonation		
By-product content of rock (%)	Normal	A mean of 11% and a standard deviation of 2%
Fe and Cr by-product value ($/t)	Normal	A mean of $100 and a standard deviation of $10
CO_2 capture cost ($/t CO_2)	Normal	A mean of $50 and a standard deviation of $5.
Gas consumption (GJ/t CO_2)	Normal	A mean of 3.15 and a standard deviation of

		0.5
Forestry		
Variable operating costs ($/ha/year)	Normal	A mean of $1,704 and a standard deviation of $170

Costs of Energy Inputs and CO_2 Price

The CO_2 and wholesale electricity prices in 2020 were taken from a recent Australian Treasury report[246] (2011). This gives a real CO_2 price in 2020 of $31/t CO_2, increasing exponentially to $133/t CO_2 real in 2050. For the NPOV calculations, the trajectory of the CO_2 price from 2020 to 2050 (and beyond for the 44 year forestry calculations) was also taken from the Treasury report as incrementing at 5% per year based on their analysis of future CO_2 price under a global CO_2 trading regime. The wholesale electricity price was assumed to increase linearly with time according to Treasury predictions using the relationship taken from the ATSE low-carbon energy report[247] (2010):

$$\text{Electricity Price} = 55 \ln(CO_2 \text{ Price}) - 135 \quad (\$/\text{MWh})$$

Application of this equation in 2020 gives a real wholesale electricity price of $54/MWh in 2020, increasing linearly to $134/MWh real in 2050. The price for electricity charged to the facilities as a cost was assumed as $75/MWh real in 2020, as 40% margin on the wholesale price for a large consumer. This price was escalated at the same rate as the wholesale price for the NPOV calculations.

The natural gas price in the calculations (a credit for the algae case and a cost for the mineral carbonation case) was assumed as $5.74/GJ real in 2020. This was assumed to escalate at 2% real per year from 2020 to 2050 for the NPOV calculations. This gives a real gas price of $10.40/GJ in 2050. The escalation rate of 2% is similar to the mean escalation rate estimated from the five future scenarios of the Australian Energy Market Operator[248] (2010).

Since the above prices are inherently uncertain, a "volatility" parameter was assumed to provide an increasing range of CO_2, electricity and gas prices at any year into the future for the NPOV calculations. As in the ATSE report, a "volatility" of 5% variance per year was assumed. That is, after 10 years the standard deviation of the distribution would be the square root of 5% times 10, or 7% of the mean CO_2 price. For a CO_2 price of ~$50/t CO_2 in 2030, this would mean a standard deviation of $3.50/t CO_2 then, and so on. This method gives probability distributions in the future with the approximate range of the scenario trajectories in CO_2 price *vs.* time provided by the first Garnaut

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[246] Australian Government Treasury: http://www.treasury.gov.au/carbonpricemodelling/content/report.asp

[247] Low-carbon Energy: Evaluation of New Energy Technology Choices for Electric Power generation in Australia, Australian Academy of Technological Sciences and Engineering, Nov. 2010. pp17, pp59. http://www.atse.org.au/resource-centre/ATSE-Reports/Energy/ pp 53-54.

[248] Australian Energy Market Operator (AEMO): http://www.aemo.com.au/planning/scenarios.html

report[249] (2008). The same method was also applied in this study to gas price trajectories. For the algae bio-oil case, the algal-oil prices were also assumed to increment each year at the same rate as natural gas for the NPOV calculation.

All probabilistic calculations were undertaken with Oracle “Crystal Ball”[250], a plug-in to Microsoft Excel.

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[249] “The Garnaut Climate Change Review, Final Report, Garnaut R, Cambridge University Press, 2008, ISBN 9780521744447.

[250] http://www.oracle.com/us/products/applications/crystalball/crystalball-066563.html