THE UNIVERSITY OF MELBOURNE

NEGATIVE EMISSION TECHNOLOGIES IN AUSTRALIA

Report on 2019 Roundtable Discussions

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SUMMARY

Meeting the 1.5°C Paris target requires deep and ongoing cuts in global emissions, reaching net zero emissions by 2050 or sooner. Indeed, many national and state governments have now established "net zero by 2050" as their long-term national emission target, but few have legislated a pathway to meet that 2050 target. Global progress has been slow: current emission trends will translate into 3°C or greater warming by 2100 if left unchecked. Rectifying these trends will need negative emission technologies (NETs), along with their related and underpinning technologies, to be deployed globally. Australia has a number of opportunities for large-scale land-based deployment of NETs with the potential to help meet national and international greenhouse obligations and build new low-carbon industries.

For NETs to deploy at scale, they must secure social and political acceptance, confirm global carbon storage potential, decrease their costs, and guarantee some degree of "certainty" of storage times. NETs are presently expensive and will need government support for their development and deployment. In the short term, the focus of some NETs may be in offsetting emissions that are difficult to mitigate such as those associated with agriculture or aviation. In the longer term, zero-emission industrial clusters could facilitate cost-effective deployment of NETs.

NETs based on carbon capture and storage (CCS) represent an important global opportunity. CCS is now an established technology with more than 50 industrial-scale projects underway or under construction and many millions of tonnes of CO_2 permanently stored every year. CCS is already an important mitigation option and underpins key NET opportunities. Afforestation and soil carbon sequestration are valuable global NET options, with added benefits in soil fertility. Bioenergy with CCS (BECCS) is technically viable now, but upscaling will be a challenge while avoiding competition with other land uses, notably food crops. Direct air capture with CCS (DACCS) is technically feasible but project costs are currently high. Mineral carbonation is a technically viable option and could be a valuable NET, particularly if project costs could be reduced and/or high demand, high value products developed. Enhanced weathering is technically feasible but of uncertain value as a NET.

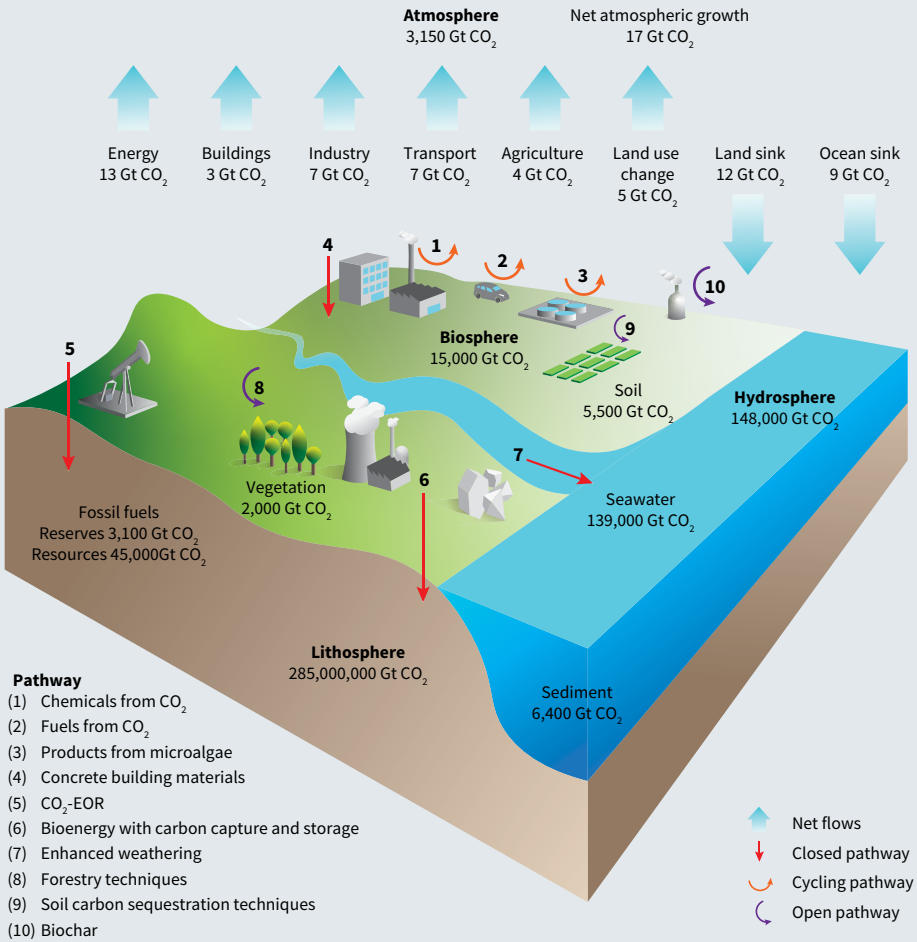
For Australia, decreasing emissions must be the priority. Strategies include increased efficiency, greater use of renewables and other low-carbon energy sources, and deployment of CCS. However, along with mitigation, Australia has the potential to apply NETs and their underpinning technologies. Its geological storage potential, strong CCS knowledge base and abundant renewable resources, provide a standout opportunity for CCS and CCS-based NETs, notably BECCS and DACCS. Australia's land area and agricultural

expertise provides the grounding for NETs based on large scale re/afforestation and enhanced soil carbon sequestration, with additional benefits arising from improved soil fertility. Given Australia's mining know-how and its mineral resources, mineral carbonation has significant potential for development as a NET.

In Australia, some NET opportunities will develop individually and opportunistically, but the greatest potential for cost effective NETs lies in building on existing expertise and assembling complementary technologies that are within, and benefiting from, industrial ecosystems (notably low-emission hubs with CCS as a core technology) and natural ecosystems (notably forest and soil-enrichment technologies). NETs must demonstrate and develop their mitigation and environmental potential for Australia in the context of national needs and priorities and international agreements. This will require government support for R&D and partnerships with industry.

NETs and their underpinning technologies can become an important part of a low-carbon and zero-emission future for Australia. They can contribute to meeting Australia's national emission policies and its greenhouse obligations, while providing benefits to the national economy through retaining and growing the national industrial base and creating new jobs in low-carbon industries and related innovative technologies.

Each year since 2005, the Global Carbon Project has produced and reported a global carbon budget that quantifies CO_2 emissions for the prior year, then apportions that carbon to the atmosphere, the ocean or the land (image after Global Carbon Project 2017). The annual carbon budget also provides a highly valuable resource within a climate policy framework, providing a definitive record of recent trends as well as quantitative updates on permissible emissions for given climate stabilization targets. With solid justification, one can describe the annual carbon budgets as products of high scientific quality with strong political relevance.



BACKGROUND TO THE ROUNDTABLE

Negative emission technologies (NETs), also known as carbon dioxide removal (CDR) technologies, were acknowledged in the first IPCC Assessment Report in 1992 as having the potential to decrease atmospheric CO_2 concentrations. Recently, NETs have received renewed and increasing attention. Reasons for this include the acceleration of overall global emissions and the realisation that, even with determined action, it will be very difficult indeed to achieve zero emissions in sectors such as refrigeration, mineral processing (including steelmaking and cement manufacture), air travel and agriculture. Modelling in IPCC reports shows that, in order to have a greater than 66% chance of meeting the 1.5°C target, the world must reach net zero emissions by 2055 or sooner [1].

As the US National Academy of Science points out in its 2018 study of negative emissions, "*the potential global uptake from current NETs is substantially lower than the negative emissions in most scenarios that would produce less than 2 degrees Celsius of warming. In order to play a large role in mitigating climate change, NETs will likely need to ramp up rapidly before mid-century to remove up to 20 billion tonnes of carbon dioxide (Gt CO_2/year) globally by century's end*" [2].

Most scenarios and current trends suggest significant need for additional NETs deployment by 2030 and increasing thereafter. "Middle-of-the-road" estimates require the world to achieve a net annual reduction of 8 Gt CO_2/year from the atmosphere towards the second half of the century [3]. To put this in perspective, the 2018 growth in atmospheric concentration of CO_2 was about 18 Gt CO_2 [4]. Therefore, to hold the global temperature rise to 1.5°C or less, each year we will not only have to stop emitting 18 Gt CO_2/year to the atmosphere, but in addition, we will need to extract a further 8 Gt CO_2/year from the atmosphere!

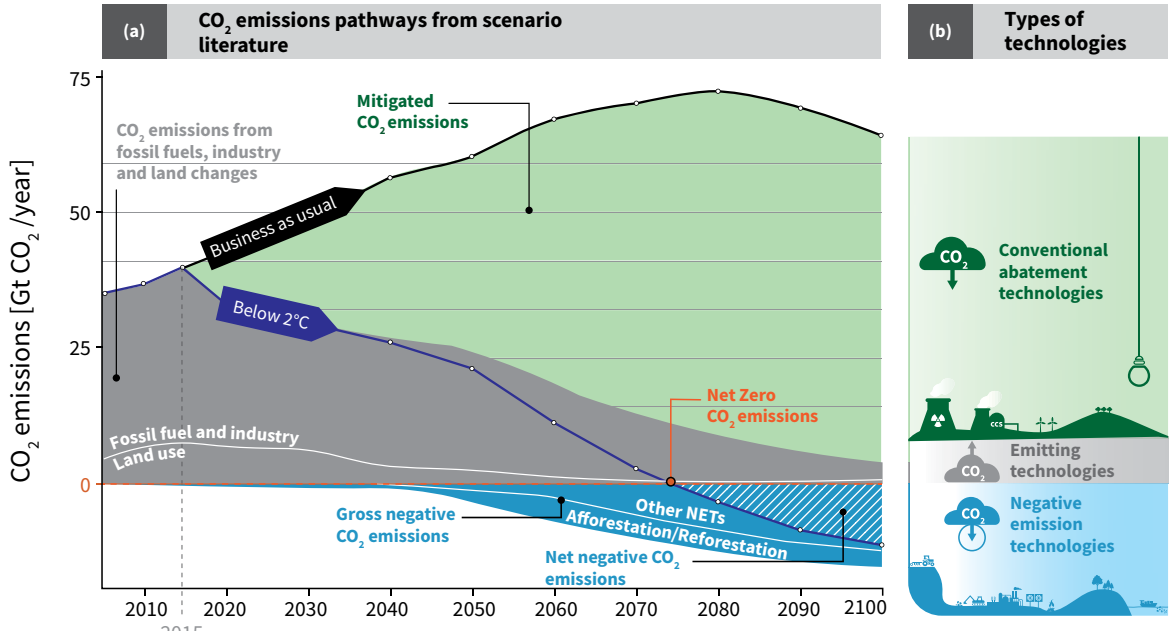
In order to explore the options for achieving such a global outcome and consider its relevance to Australia, both in terms of challenges and opportunities, a Roundtable on Negative Emission Technologies was co-hosted in June 2019 at the University of Melbourne by the Peter Cook Centre, the Melbourne Energy institute and the Australian-German College of Climate Change and Energy. It greatly benefited from the input of other universities and research organisations, NGOs, government departments and industry. A list of participants is provided on pp. 43-44 in this report. The meeting considered the latest available research on a range of land-based NETs. Ocean-based NETs are also important, but it was decided to limit the scope of the Roundtable to terrestrial NETs, with a particular focus on engineered NETs.

"Under emissions in line with current pledges under the Paris Agreement (known as Nationally Determined Contributions, or NDCs), global warming is expected to surpass 1.5°C above pre-industrial levels, even if these pledges are supplemented with very challenging increases in the scale and ambition of mitigation after 2030 (high confidence). This increased action would need to achieve net zero CO_2 emissions in less than 15 years. Even if this is achieved, temperatures would only be expected to remain below the 1.5°C threshold if the actual geophysical response ends up being towards the low end of the currently estimated uncertainty range. Transition challenges as well as identified trade-offs can be reduced if global emissions peak before 2030 and marked emissions reductions compared to today are already achieved by 2030." (IPCC 2018) [1].

This summary report gives major points or key observations arising from the Roundtable. However, it is important to point out that attendance/participation in the Roundtable does not mean endorsement of all elements in the report by all the organisations and individuals attending.

Some minor additional observations or references have been added to reflect developments that have occurred in the time since the Roundtable was held. Cost figures have been converted to Australian currency except where otherwise noted.

Presentations given at the meeting, along with more detailed observations, are available at the Peter Cook Centre website.



This diagram (after UNEP 2017 [5]) illustrates the potential role of negative emissions in climate change mitigation. It juxtaposes a pathway for emissions reduction (Panel A), with the types of technologies that emit CO_2, mitigate CO_2 and remove it from the atmosphere (Panel B) in a scenario with a 66% chance of keeping global warming below 2°C. Cumulative gross net negative emissions (compensating for earlier carbon budget overshoot) are represented by the blue area.

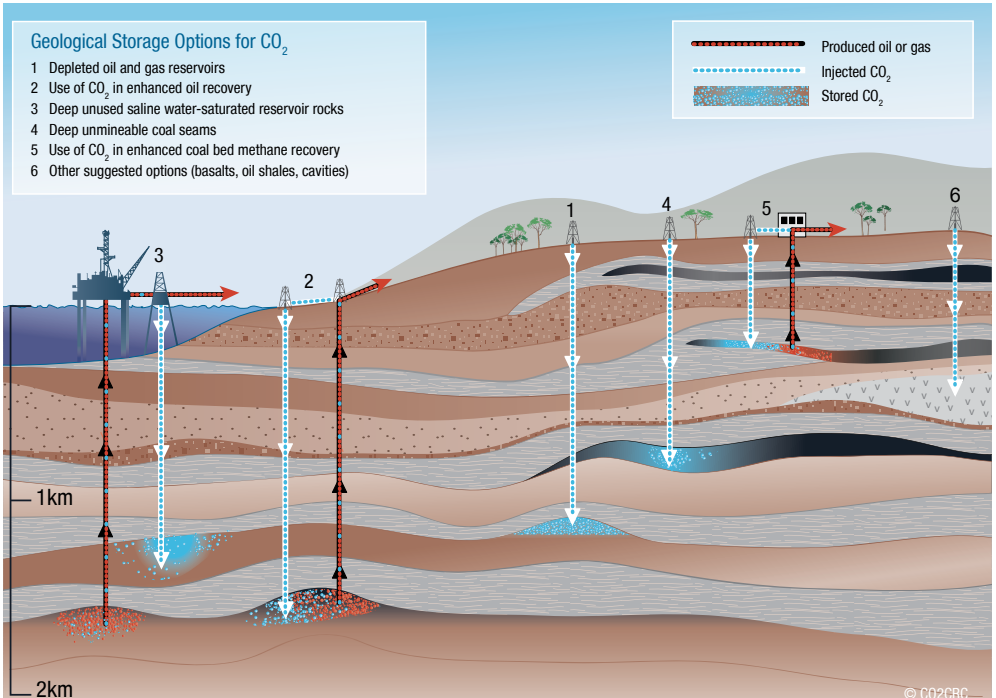
An estimated 10-20 Gt CO_2/year of gross anthropogenic emissions are from sources that will be very difficult or expensive to eliminate by emissions reductions alone. To achieve net zero by 2050 will require far greater mitigation of anthropogenic emissions over the next 30 years than is shown in this diagram, starting now and with earlier deployment of NETs [2, 5, 6].

WHAT ARE NEGATIVE EMISSION TECHNOLOGIES?

The purpose of a negative emission technology (NET) is to decrease the concentration of CO_2 in the atmosphere, by transferring that CO_2 from the atmosphere to a geological, biological or mineral medium, where it remains isolated from the atmosphere for an extended period of time ranging from a hundred years to many millions of years. In some cases, engineered NETs have been developed from zero-carbon technologies that displace the use of fossil fuels or abate their emissions.

As pointed out in the 2018 US NAS [2] report on NETs, "*a common misconception is that NETs would primarily be deployed to reduce atmospheric CO_2 levels only after emissions had been reduced to near zero. However, because emissions reductions become increasingly expensive as emissions drop, it will be less expensive to deploy mitigation and negative emission technologies concurrently. The central question is: which is least expensive and least disruptive in terms of land and other impacts, an emission reduction or an equivalent amount of negative emission? Building a broad portfolio of NETs also offers increased resilience to help manage risks of surprises from nature and mitigation actions. Thus, NETs are best viewed as a component of the mitigation portfolio, rather than a way to decrease atmospheric concentrations of CO_2 only after anthropogenic emissions have been eliminated*".

There are some CO_2 emission sources that are very difficult to mitigate and where NETs are the only option for attaining net zero emissions. However, in the first instance, avoiding CO_2 emissions or removing them from a large concentrated industrial source will almost always be cheaper than extracting CO_2 from a very dilute source such as the atmosphere. Equally important is the fact that removing atmospheric CO_2 causes the oceans to release some of their own CO_2, cancelling some of the NETs effort. Some of the finer details of these questions are outlined elsewhere in this Report.



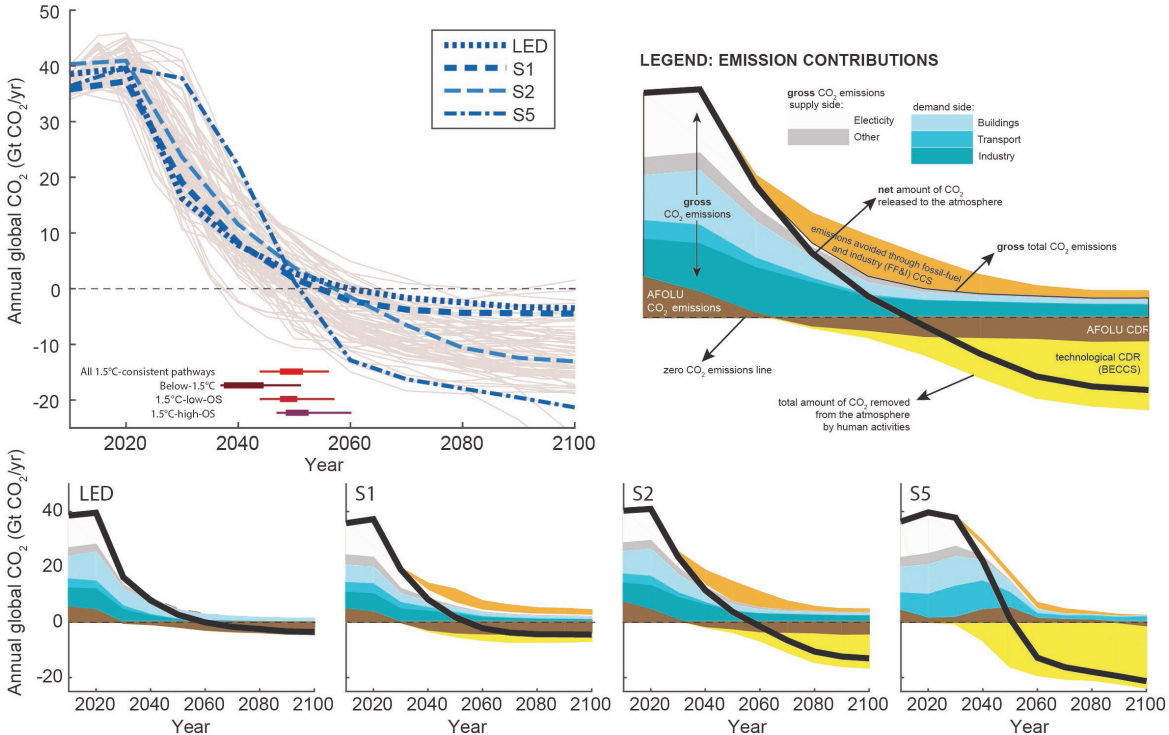
CCS is currently being applied at a number of sites around the world, including in Australia, to make deep cuts in large scale CO_2 emissions. CCS is also a bedrock technology for NETs such as BECCS and DACCS. Australia was an early mover in CCS, with CO2CRC commencing injection of CO_2 in 2008 at its advanced R&D facilities in the Otway Basin. Since that time, CO2CRC has successfully stored and monitored tens of thousands of tonnes of CO_2. It has also conducted a number of innovative field experiments that have served to confirm that geological storage is a safe and reliable way of permanently storing carbon (image: IPCC 2005) [7].

LAND-BASED NEGATIVE EMISSION TECHNOLOGIES COVERED IN THIS REPORT

This report covers land-based, as opposed to ocean-based, NETs:

- Changes in forest management and agricultural practices — these increase carbon sequestration in trees and/or enhance soil carbon storage.
- Bioenergy with carbon capture and storage (BECCS)—using cultivated crops, agricultural waste or organic-rich municipal or industrial waste to produce electricity, liquid fuels, and/or heat, with the by-product CO_2 then captured and geologically stored.
- Direct air capture with CCS (DACCS)—using chemically engineered and related processes that capture CO_2 from ambient air and geologically store it.
- Mineralization—reactive minerals such as peridotites and basalts form chemical bonds with CO_2 to produce stable and potentially useful carbonate minerals that permanently store CO_2.
- Enhanced weathering—a variant on mineralisation except that the mineralisation occurs not within a controlled industrial environment, but within the landscape, the concept being that the finely ground reactive rock is spread over wide areas and subject to weathering.

These technologies face a number of shared challenges that were discussed during the roundtable. We turn to these observations in the following section. Further on, we discuss the applicability of these technologies to the Australian context, as well as the benefit of concentrating most of them in low-carbon hubs driven by strong CCS infrastructure and capabilities.



Different mitigation strategies can achieve a pathway that limits global warming to 1.5°C. All pathways above use NETs, but the amount varies across pathways, as do the relative contributions of BECCS (yellow, bottom wedge) and removals in AFOLU (brown, second wedge from bottom) (image: IPCC 2018) [1].

SOME ROUNDTABLE OBSERVATIONS

Current emission trends suggest both deep cuts in emissions and future deployment of NETs are essential to meet the Paris 1.5°C target.

Despite the stated aspirations of individuals, communities and nations to decrease emissions, global emissions continue to rise. Even with radical action by governments and major technical breakthroughs, NETs will be an important and probably essential technology for the future. A 66% chance of limiting warming to 1.5°C equates to a 45% reduction in global emissions by 2030 compared to 2010 *and* net-zero global emissions by 2050 *and* global removal of 5 to 14 billion tonnes of carbon dioxide per annum (Gt CO_2/year) from the atmosphere from 2030 onwards [8].

Deep cuts in emissions must remain the priority now and into the future, as taking carbon out of the atmosphere is more difficult and more costly than avoiding the emissions in the first place.

Rapid reduction of the carbon content of the atmosphere is made difficult by the carbon cycle response from other carbon sinks, notably the ocean. The concentration of atmospheric CO_2 was 413.5 parts per million (ppm) in June 2019 compared to a pre-industrial 280 ppm. Concentrations of 350-450 ppm is consistent with a 1.5°C target [3]. However, removing, for example, 10 ppm excess CO_2 from the atmosphere will result in the ocean (a major CO_2 'sink') releasing 3-4 ppm of CO_2 back into the atmosphere over the following century to bring the ocean-atmosphere system back into equilibrium. Of course, this does not mean that it is futile for us to remove CO_2 from the atmosphere, but it does mean that the task is very challenging. In addition, removing carbon from the atmosphere relies on processes that can be relatively inefficient, slow-acting and/or energy intensive. Therefore, our emphasis first and foremost, must continue to be on reducing and ultimately eliminating emissions to the atmosphere.

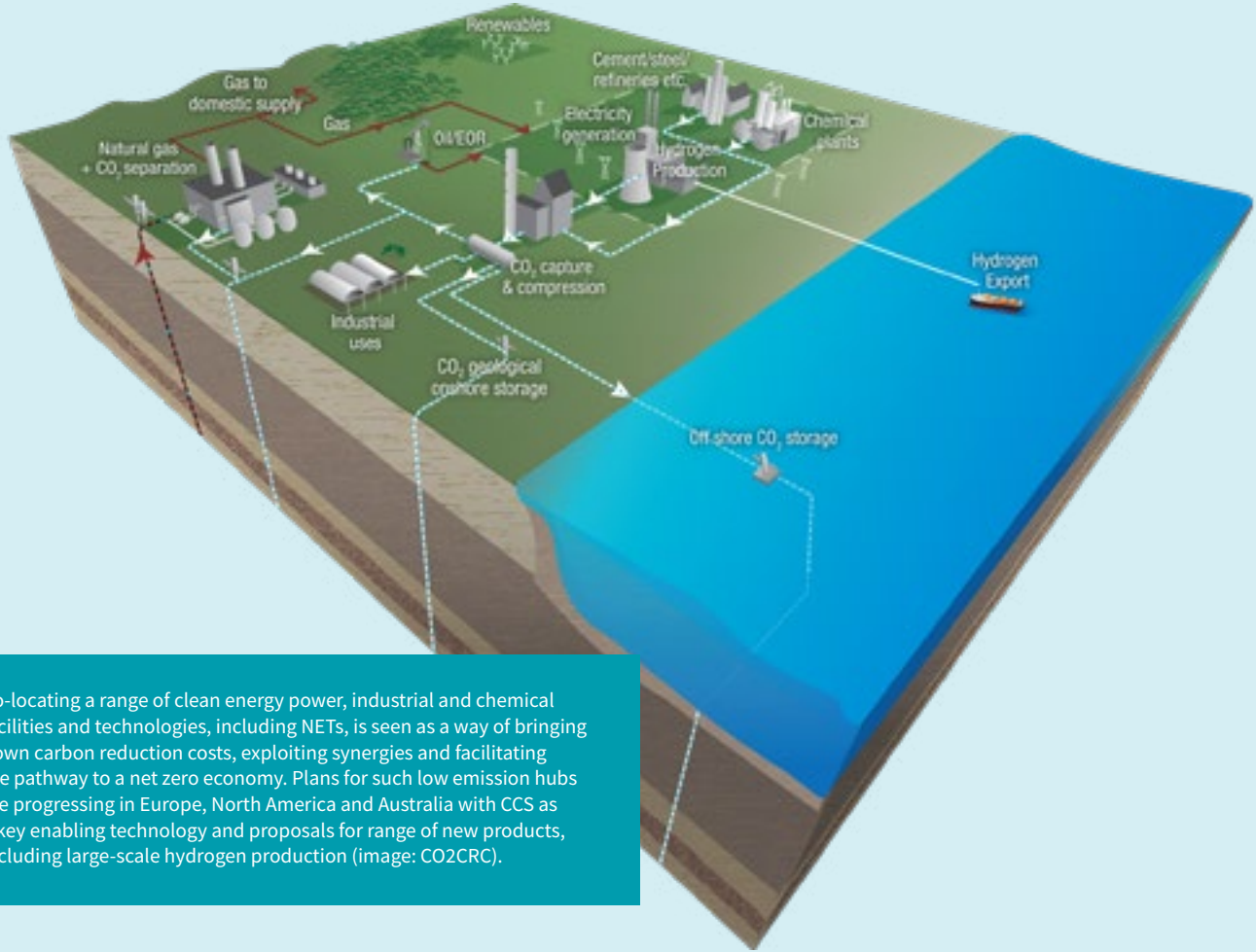
The Roundtable did not specifically consider a research agenda for NETs, but the 2019 report of the US National Academy of Science recommends “a substantial research initiative to advance negative emissions technologies (NETs) as soon as practicable. A substantial investment would (1) improve existing NETs (i.e., coastal blue carbon, afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils, and biomass energy with carbon capture and sequestration) to increase the capacity and to reduce their negative impacts and costs; (2) make rapid progress on direct air capture and carbon mineralization technologies, which are underexplored, but would have essentially unlimited capacity if the high costs and many unknowns could be overcome; and (3) advance NET-enabling research on biofuels and CO_2 sequestration that should be undertaken anyway as part of an emissions mitigation research portfolio” [2].

Social and political acceptance of NET-based actions will be essential if they are to play a role in mitigating climate change.

Recourse to NETs may not always be socially or ethically acceptable. Using NETs to compensate for increased air travel is illustrative of such considerations. Air travel emissions are difficult to mitigate, yet this activity is a relative luxury, enjoyed by a small portion of the world's population. Bioenergy with carbon capture and storage (BECCS), for example, could compensate for air travel emissions, but might also increase food prices if energy crops took up a substantial portion of arable land. Such vast deployment may be unlikely but is nonetheless assumed under some upper-boundary emission projections. In any case, NETs are comparatively expensive and if deployed at a large scale, will require significant public funds, which may affect social programs. Thus, the poor may suffer disproportionately from increased food prices or lower social welfare yet derive no benefits such as air travel. Social distribution of costs and benefits associated with NETs, and indeed with any mitigation option, must therefore be weighed carefully. To the extent that NETs approaches are implemented, they should aim to adhere to environmental and social safeguards in order to minimise unintended adverse consequences.

We must not only predict the natural carbon cycle response in quantifying the contribution of NETs, but also monitor and verify the certainty and time scale of their associated carbon storage.

Carbon storage times vary across various media. They range from decades in trees, centuries in timber and charcoal, thousands of years or more for mineral carbonation and millions of years in geological storage. Monitoring and verification are particularly important for shorter-term NETs, as they may require compensatory/additional CO_2 removal to achieve or maintain temperature targets. Long-term NETs involving geological or mineral storage also need to confirm long-term trapping of CO_2. Monitoring and verification can be more difficult when the lifecycle cuts across technologies, and when it concerns not just industrial-geological processes, but also biological processes. For instance, the amount of CO_2 geologically stored from a BECCS operation can be accurately measured and the storage time confidently predicted [9]. However, the details of how much carbon can be efficiently captured in the agricultural processes upstream is less well understood [10,11]. Carbon sequestration in soils has even larger uncertainties [2]. More research and better monitoring is required in this sector, particularly as it pertains to biological processes.



Co-locating a range of clean energy power, industrial and chemical facilities and technologies, including NETs, is seen as a way of bringing down carbon reduction costs, exploiting synergies and facilitating the pathway to a net zero economy. Plans for such low emission hubs are progressing in Europe, North America and Australia with CCS as a key enabling technology and proposals for range of new products, including large-scale hydrogen production (image: CO2CRC).

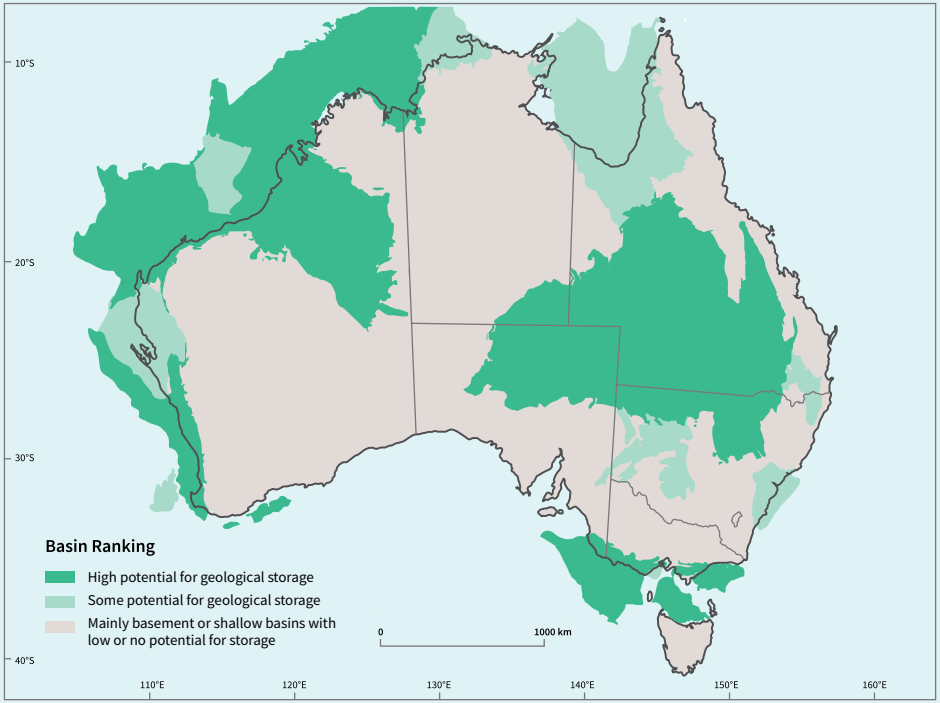
Currently, NETs seldom produce a valuable (saleable) product at scale to offset costs and their development and deployment will require support for some time to come.

To date, CO_2 sequestration has only been monetised through enhanced oil recovery (EOR) overseas or at a small scale in food production, or through government initiatives to place a price on carbon. Efforts are currently underway through, mineral carbonation, to develop valuable CO_2-based products such as building materials. These and other applications, broadly termed carbon capture, utilisation and storage (CCUS, or just CCU) have been proposed that might help to drive a "circular carbon economy" [12]; but presently, few can achieve truly negative emissions [13,14].

Given the challenges in meeting a 1.5°C target, few if any NETs are likely to be financially self-supporting through the sale of products, other than (perhaps controversially) the sale of oil from direct air capture of CO_2 with highly regulated EOR [15]. Financial, research and regulatory support, potentially including imposing costs and regulations on carbon emissions, will be needed to support NETs well into the future.

Net-zero industrial clusters based on low, zero and negative emission technologies that are targeted and adapted not only to meet local circumstances but in some cases to respond to international and even global needs, could be important instruments for limiting atmospheric concentrations of CO_2.

A number of low-carbon hubs have been suggested in Europe [16] and North America and similar opportunities exist in Australia. Establishing Australia as a low-carbon manufacturing cluster to serve the needs of the Asia-Pacific region, has bipartisan support [17]. For example, Victoria's Hydrogen Energy Supply Chain (HESC) initiative is an important motivator for CO_2 sequestration through the CarbonNet Project. A cluster based on CarbonNet would initially take advantage of Australian fossil fuel resources and CCS opportunities. It would also provide a pathway for future negative emission projects by broadening the portfolio of CO_2 sources and sinks. This could include a variety of technologies, including monetised carbon products. Once established, hubs can potentially provide the base for lower cost NET deployment.



Australia has many onshore and offshore sedimentary basins that are potentially suitable for large scale geological storage of CO_2. In 2019, Chevron commenced the world's largest CO_2 storage project in Western Australia, injecting 3-4 Mt CO_2/year for the next 20-30 years at Barrow Island as part of the Gorgon LNG Project. Other major storage opportunities are known in the offshore Gippsland Basin of Victoria, the Surat Basin of Queensland and the Cooper Basin of South Australia. These are currently based upon proposals to mitigate CO_2 emissions associated with fossil fuel extraction or hydrogen production, but nonetheless they may present opportunities to kickstart some future DACCS or BECCS projects, which can be preferentially sited in basins with low-cost storage opportunities and existing CO_2 infrastructure.

SOME ROUNDTABLE OBSERVATIONS

Amongst land-based NETs, CCS-related developments are attractive because of the abundance of geological storage sites globally and in Australia. Furthermore, CCS has been demonstrated as an operational mitigation technology that is deployable now [18]. However, costs and the lack of policy drivers currently limit uptake. These factors will need to be addressed by governments in collaboration with industry if CCS is to reach its potential, including for NETs.

According to the Global CCS Institute [18], there are 51 CCS facilities globally – 19 in operation, 4 under construction, and 28 in various stages of development with an estimated combined capture capacity of 96 Mt CO_2/year. CCS projects in commercial operation include for natural gas (Sleipner, Gorgon), coal (Boundary Dam, PetraNova), and biofuels (Decatur). Some rely on EOR to meet project costs, although the US Federal 45Q legislation and California's Low-Carbon Fuel Standard provide incentives for CO_2 storage that does not include EOR. Commercial, demonstration and pilot projects, provide a firm technological base for development of negative emission opportunities. Both bioenergy and direct air capture with CCS (BECCS and DACCS) will benefit from continued research, development and deployment of CCS. This will significantly reduce costs through innovation, new investment and developed experience. Related studies into utilisation of CO_2 (CCUS) are also important in order to provide a revenue stream over and above (or instead of) that available from a price on carbon.

Australia has abundant geological storage resources but only a small proportion of that resource has yet been fully characterised and permitted. A regulatory environment has been established offshore by the Commonwealth, and onshore by Victoria, Queensland, South Australia and Western Australia [19]. There are many opportunities for reliable long-term geological storage but not always near large-scale emission sources, which can mean costly transport of CO_2 from the source to the geological sink. An updated review of Australia's storage potential is needed [20]. CCS linked with EOR or perhaps enhanced gas recovery (EGR) along with CCS hubs, offer large-scale opportunities to Australia and could provide a launch pad for some NETs. The IEA has suggested that CO_2-EOR may offer a NET opportunity. This requires more consideration and independent validation. Outside the USA, there is currently a lack of support for CCS through legislation, regulation or financial instruments and until this is addressed, CCS deployment as a mitigation option or as a contributor to NETS, will be slow.

Afforestation is the term used for conversion of abandoned and degraded agricultural lands into forests. Reforestation is the planting of trees in deforested land. Both practices can contribute to negative emissions since the growth of additional plants sequesters atmospheric CO_2 and naturally sink it in their biomass and in the soil. Globally, large-scale afforestation could provide a accumulative removal of around 200 Gt C by the end of the century and Australia has the potential to be a significant contributor to that total. In Australia, reforestation and afforestation projects are subject to a permanence obligation. This means the sequestration must be maintained for the nominated permanence period (either 25 or 100 years) [18].

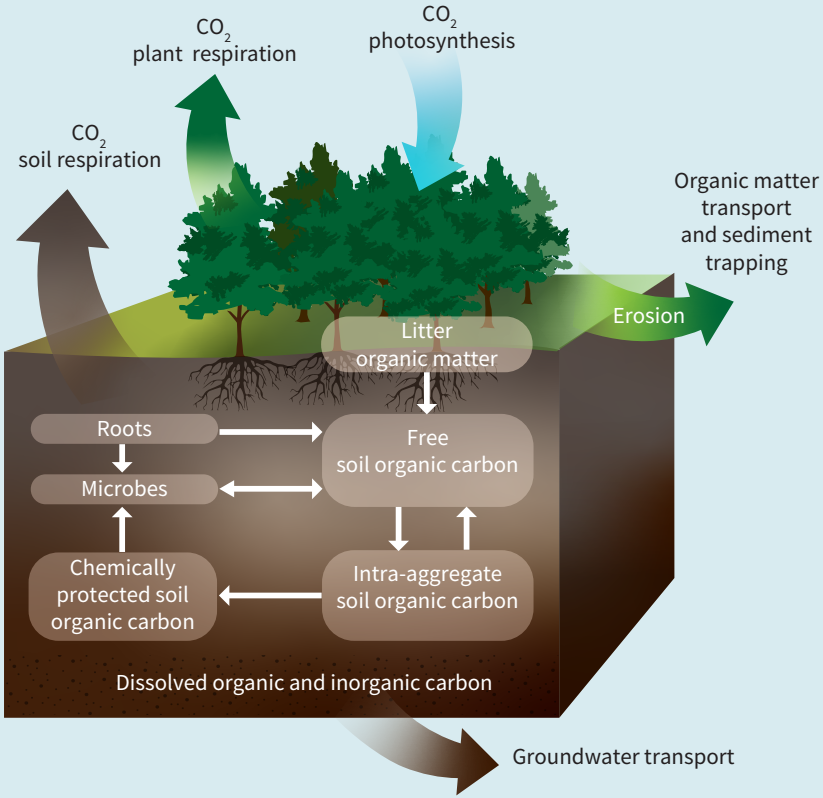
Afforestation

Afforestation is environmentally beneficial and a potentially cost-effective mitigation option for Australia, but its role as a NET is limited unless forests are managed, and growth maintained.

A "typical" tree is composed of approximately 50% carbon on a dry weight basis and planting trees for forestry is already a major carbon sink in Australia, although bushfires can be problematic. There are a number of companies selling carbon credits in Australia to offset a CO_2-producing activity such as air travel. One carbon credit usually represents one tonne of CO_2 stored in a forest for at least 100 years. This may well be difficult to achieve due to fire, disease, drought, etc. Consequently, afforestation is not always seen as a NET because it does not necessarily remove historical CO_2 from the atmosphere.

There are questions regarding the extent to which Australia can be afforested/reforested. In February 2019 the Prime Minister announced a target of planting one billion trees (about 400,000 ha of forest) by 2030. The inherent uncertainty of this for offset or NET measures is highlighted by the fact that during the 2019-2020 bushfire season, an estimated 18 million ha of forest burnt across Australian states (including the Northern Territory savannah fires) [21].

Nonetheless, if tree-planting is used above and beyond that needed to offset a concurrent emitting activity, then such afforestation could conform to most understandings of NETs. The issue that arises is that the life of the tree (and therefore the carbon storage time) is quite short, typically 100 years or less, at which stage all the sequestered CO_2 is returned to the atmosphere over a relatively short period of time. Nonetheless, afforestation could be regarded as an "early mover" NET. It should not necessarily be seen as a "cheap" NET, but it potentially provides a useful early short-term action to decrease historical CO_2 (depending on how the forest is managed) and it also offer a range of beneficial environmental outcomes. Afforestation should be part of Australia's NET portfolio.



The complexity of natural soil processes is shown here (after Reichle et al. 1999 DoE: Carbon Sequestration Research and Development) and serves to illustrate that one of the challenges of soil carbon as a NET, is determining the storage time, which can range from just a few years for some plant carbons to hundreds of years or longer in the case of biochar.

Soil carbon sequestration

Enhanced soil carbon sequestration has significant potential for Australia as a NET but the opportunity needs to be better understood, and soil management improved.

Soils are an important part of the carbon cycle with more carbon stored in soils than in plants. Soil processes influence carbon sequestration and transport. Well managed forests and farmlands can sequester large amounts of carbon. This can be further enhanced by adding biochar (charcoal) to the soil, a fertilisation process that humans have employed for hundreds of years. Biochar is produced by pyrolysis, which involves biomass being subjected to very high temperatures in the absence of oxygen. The process is also used by the chemical industry to produce a range of valuable by-products.

Massive amounts of carbon are sequestered in soils. Globally the technical potential for additional sequestration could be as much as 3.67-18.35 Gt CO_2/year (others claim some 29.3 Gt in total until 2050)[2]. However, understanding of soil carbon dynamics is limited and therefore estimated prices span a wide range, from $0 net cost to $146/t CO_2. For reference, a start-up company in the United States has commenced paying farmers US$5.70/t CO_2 for carbon sequestered in the soil [22]. Because of their age and the extent to which they have been weathered and leached, as well as being adversely impacted by historic agricultural activity, most Australian soils are low in carbon. Consequently, carbon sequestration in soils is likely to have added benefits, notably increased agricultural productivity. Regenerative agriculture, reforestation and land remediation all have the potential to increase carbon sequestration in soils, with added co-benefits for Australia. This NET opportunity is currently inhibited in Australia by lack of knowledge of soil carbon and uncertainty regarding sequestration times and soil permanence with exogenous carbon addition. Further scientific work is required to explore these uncertainties and to develop quick and reliable methods for the measurement of the soil carbon/atmosphere carbon flux. Nonetheless it appears that enhanced soil carbon could be an important NET for Australia. Australia has a number of soil carbon projects underway, with scope for many more.

Timber residues are a significant biomass resource, produced at each stage of timber and wood product processing, with 40-60 per cent of log biomass "lost" to residues. Using wood residues to produce bioenergy requires sustainable forest management to maintain environmental integrity. Organic matter typically makes up about two-thirds of solid municipal waste and is one of Australia's most under-utilised biomass resources. These resources coupled with Australia's geological storage potential represent a significant BECCS opportunity, estimated at 42 Mt CO_2/year in negative emissions and 25.4 TWh of power by 2050 [27].

Bioenergy with CCS

Bioenergy with CCS (BECCS) is technically viable and offers Australia a NET opportunity, but can involve trade-offs with other land uses, including for food crops. Forestry waste and municipal waste with a high organic content, are potential BECCS opportunities that Australia needs to consider.

Most emission reduction projections that assume delayed global action (i.e. the current trend) and temperature targets between 1.5-2°C, include BECCS [1,6]. This is because the CCS component is well understood and there is extensive experience in the use of biomass for energy production, including co-firing with or without coal [11]. At Decatur in Illinois, a BECCS (biofuels) project is currently storing approximately 0.7 Mt CO_2 /year [24,25]. A number of other projects incorporating biofuel with CCS, supported by 45Q tax credits are presently under consideration in the USA. Nonetheless, significant cost reductions and technology development are still needed for bioenergy with CCS [11,26]. The price estimates are of $75/t CO_2 for entry into the market, and this may be economically viable, but only if other baseload power is offline. The global potential, without serious competition with food crops, is optimistically estimated at around 10 Gt CO_2/year by 2040-2050 [8].

Use of municipal waste may be an important BECCS opportunity in major urban areas [27]. However, it needs to confront the potential release of toxic chemicals such as dioxin from chlorinated plastics in the waste. Nevertheless, energy production from municipal waste is already quite widely applied in Europe and coupling with CCS is being considered [28].

Australia has a wide range of biomass sources, including the dairy and meat industries, energy crops such as mallee trees, algae, waste from pulp and paper industry and crop residues. But bioenergy currently provides only 0.8% of Australia's energy production, sourced mainly from bagasse (sugar cane residue), wood waste from forest residues and landfill gas. Costs are presently high [27], but the potential exists to bring them down through improved transport, agricultural logistics and a new approach to waste management. Scope for growing energy crops (such as salt bush) in marginal land where food crops are not an option, warrants consideration.

BECCS represents a NET opportunity for Australia, with forest waste and municipal waste having the greatest potential in the short term, with energy crops a longer-term prospect.

A number of companies are working to commercialise DACCS. Their technologies are similar – drawing in the air using giant fans, separating out the CO_2 and expelling the air less the CO_2, but they employ different technologies to capture the CO_2. Global Thermostat uses dry amine-based chemical sorbents and porous, honeycomb ceramic "monoliths" to adsorb CO_2. Carbon Engineering removes the CO_2 as a carbonate salt, which is then processed to concentrate and purify the CO_2. Climeworks (shown) uses amine capture and a filter that expels the CO_2 when heated to 100°C. A key element in all these processes is driving down costs, through access to low cost or no cost residual/process heat from industrial processes or low-cost renewable-sourced electricity, modular construction, choice of siting to minimise transportation costs and link with renewable energy. The aim is to use the CO_2, but it could also be geologically stored. Australia has great potential for DACCS if costs can be drastically reduced (image: Climworks/Julia Dunlop).

Direct air capture with CCS

Direct air capture with CCS (DACCS) costs are presently high, but the technology has the potential advantage for Australia of being widely deployable in areas with low-cost renewable energy and suitable geological storage sites

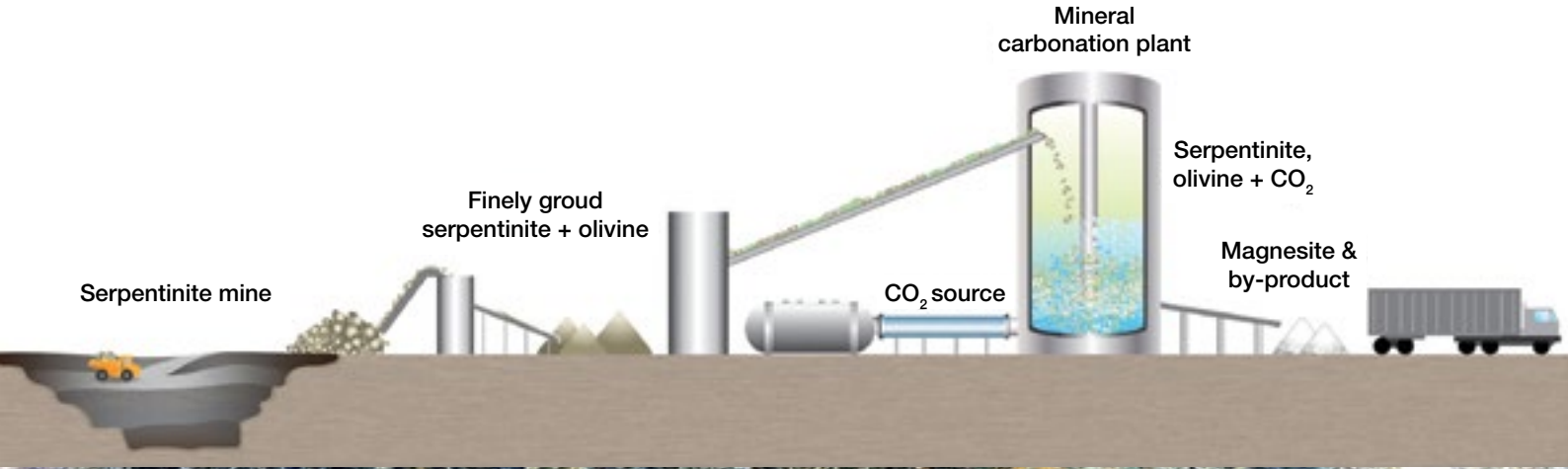
A recent study by Realmonte et al. concludes that deploying DACCS can significantly reduce mitigation costs but a key factor limiting DACCS deployment is the rate at which it can be scaled up [29]. They point out that average DACCS scale-up rates of 1.5 Gt CO_2/year would require considerable sorbent production and up to 300 EJ/year of energy input by 2100.

DACCS is presently deployed in pilot projects in Iceland, Switzerland and Canada [30]. Current cost estimates vary dramatically in the peer-reviewed literature: one study reports lowest cost estimates of \$1200/t CO_2 and little hope of deployment to tackle climate change [31]; while another claims \$80/t CO_2 are feasible by 2040 [32]. DACCS has energy requirements around four times those of normal CCS; but that energy could be provided by renewable sources and there may be no pipeline costs for transporting the CO_2 as the technology can be deployed in areas known to have good geological storage.

Opportunities are being investigated for using the DACCS-extracted CO_2 in food production and EOR. The Climeworks project in Europe is researching the production of renewable jet fuel from air, using a combination of direct air capture of CO_2, transformation of CO_2 and H_2 to syngas and transformation of syngas to synthetic hydrocarbons and then into jet fuel. Carbon Engineering in Canada is similarly investigating a DACCS-synfuel option. This sort of innovative research clearly has some way to go and will face many challenges in terms of upscaling but is an interesting example of how DACCS might be integrated into new net-zero industrial processes in the future. Given Australia's interest in developing a hydrogen economy, a DACCS-H_2 industry node might be an option for the future.

Under a concerted national and international push to lower carbon stocks and remove historic CO_2 from the atmosphere, Australia could deploy DACCS as a NET, given its high storage potential and abundance of renewable energy sources, notably wind and solar. There is a need to more quantitatively define geological storage resource at the national level to match those energy resources (Geoscience Australia is active in this area) and reduce uncertainty in DACCS costs.

DACCS may represent a future opportunity for Australia if developed and deployed alongside other mitigation options.



Sequestering CO_2 and producing a valuable product through mineral carbonation is an option being pursued by a number of companies, including in Australia by Mineral Carbonation International. The process is shown schematically above (after CO2CRC). Serpentinite is a fairly widespread rock in Australia, presently mined and crushed for use in steelmaking (image: Gabriel HM/Wikimedia). It is rich in Mg-rich phyllosilicate minerals such as olivine and readily reacts with CO_2 to produce carbonate minerals, which can potentially be turned into cement, pavers, plaster boards and other products for the domestic and international market.

Mineral carbonation

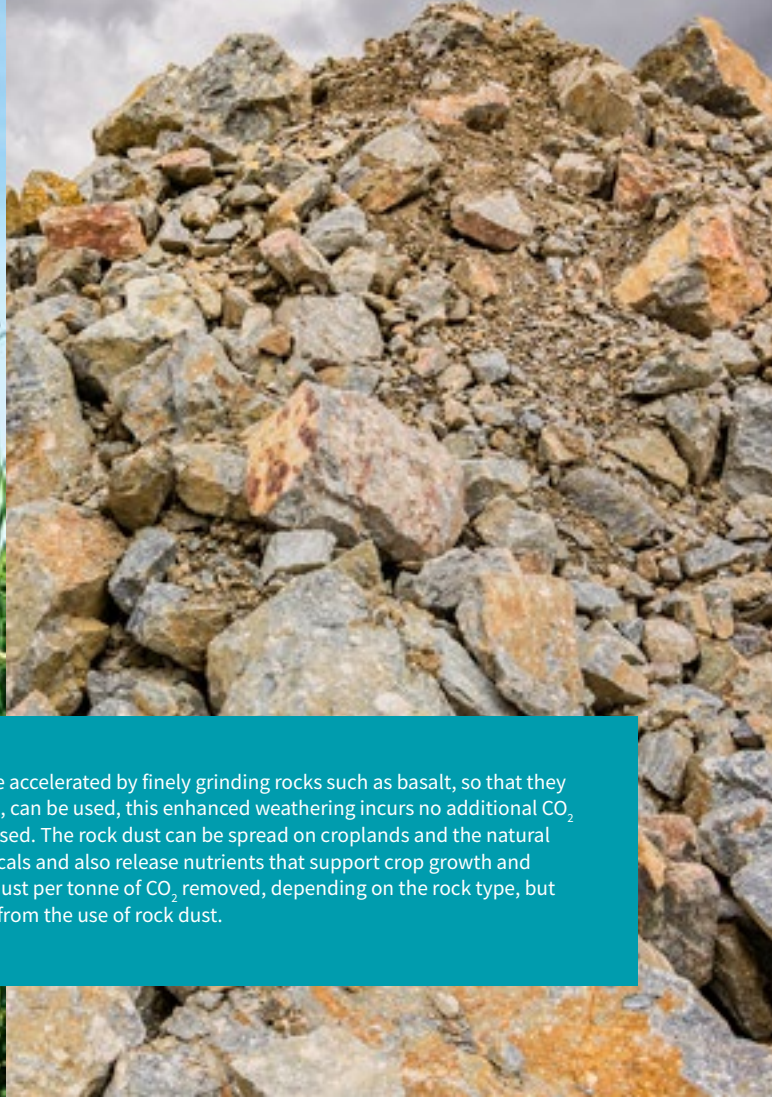
Mineral carbonation involving production of minerals/materials with a high proportion of CO_2 offers NET opportunities for Australia. The cost range and feasibility of this and similar technologies at scale are presently being investigated.

Mineral carbonation is a process that chemically binds CO_2 with calcium- or magnesium-containing minerals found in certain rock types, to form stable carbonate-rich materials. The material flux (crushing, transporting and disposing of rock) may have significant environmental impacts which require careful consideration. Cost estimates were in the order of $78-145/t CO_2 in the mid-2000s and reappraised at $94 in 2012 [33, 34]. If the chemical reactions can be accelerated and maintained with less heat, carbonation could become commercially competitive with other NET options [35]. It offers potential for the monetisation of carbon mitigation through the trapping of CO_2 in valuable products, but further consideration is required to match potential carbon-storing products to the needs of industry and consumers. The IPCC saw mineral carbonation as a useful but modest future contributor to global mitigation of CO_2 emissions.

In Australia, Mineral Carbonation International (MCi) is testing the commercial potential of mineral carbonation. The plant will bind CO_2 with crushed serpentinite rocks to create magnesium carbonate, which can be used to produce building and construction materials such as cement, paving stones and plasterboard. The global market for these products is potentially large. Demonstrations such as that undertaken by MCi are needed to test that operations of sufficient scale are feasible and can be undertaken at reasonable cost with the potential for further cost reduction.

As a country with a high level of mining activity and know-how, Australia is well placed to develop an industry based on mineral carbonation. Costs could be potentially offset by producing saleable mineral products but, with the exception of construction materials, sales are likely to be modest compared with the scale of the challenge of decreasing global CO_2 emissions or reducing levels of historic CO_2.

Mineral carbonation is a NET opportunity for Australia and should be part of its portfolio of technology options.



Removal of CO_2 from the atmosphere through natural rock weathering can be accelerated by finely grinding rocks such as basalt, so that they react faster. If reactive rock dust, a by-product of working quarries and mines, can be used, this enhanced weathering incurs no additional CO_2 emissions from mining and grinding, and its costs will be significantly decreased. The rock dust can be spread on croplands and the natural chemical reactions then capture and store the CO_2 in the reactive rock chemicals and also release nutrients that support crop growth and restore soils. A general 'rule of thumb' is that you need 4 to 5 tonnes of rock dust per tonne of CO_2 removed, depending on the rock type, but more research is needed, including into any adverse environmental impacts from the use of rock dust.

Enhanced weathering

Enhanced weathering might be a NET option for Australia alongside soil restoration measures but maintaining a high rate of CO_2 absorption is difficult and issues with large material fluxes and environmental and health issues could greatly limit its potential.

CO_2 in the atmosphere dissolves in rainwater forming carbonic acid, which, in contact with rocks, dissolves them [36]. The rate of reaction varies greatly with the rock type. Many quartz-rich rocks such as granite weather very slowly whereas magnesium-rich rocks such as serpentinites weather rapidly. Finely grinding the rock, results in more rapid weathering. The concept of enhanced weathering as a NET is that finely ground reactive rock would be spread over wide areas to enhance natural weathering and remove historical CO_2 from the atmosphere.

It has been estimated that a maximum of 5 Gt CO_2/year could be removed from the atmosphere by 2050 [8, 37]. Costs are estimated at \$73-293/t CO_2 [38] with the lower end reflecting use of fine waste products from mining and the high end, the considerable energy penalty for rock grinding.

Depending on the rock type, enhanced weathering may offer potential benefits in soil restoration [39], but it also faces major hurdles, most notably the massive scale of material grinding (an expensive and energy-intensive activity) and transport needed both to maintain the speed of chemical reaction and to achieve a sufficient amount of mitigation. Further, some finely ground reactive rocks, such as serpentinites may have components which constitute a health hazard, although this hazard could be minimised by using rocks such as basalt that are widespread, but do not generally contain hazardous minerals such as asbestos. The other issue is the time scale for effective weathering of rocks, even reactive rocks could well be many decades. Consequently, the removal of historical CO_2 from the atmosphere in the 21st century could be quite modest.

Enhanced weathering of suitable rocks could be a niche NET opportunity for Australia by combining it with mining operations. It is not presently seen as a NET priority for Australia, but warrants further investigation, to clarify the future opportunities and the challenges.

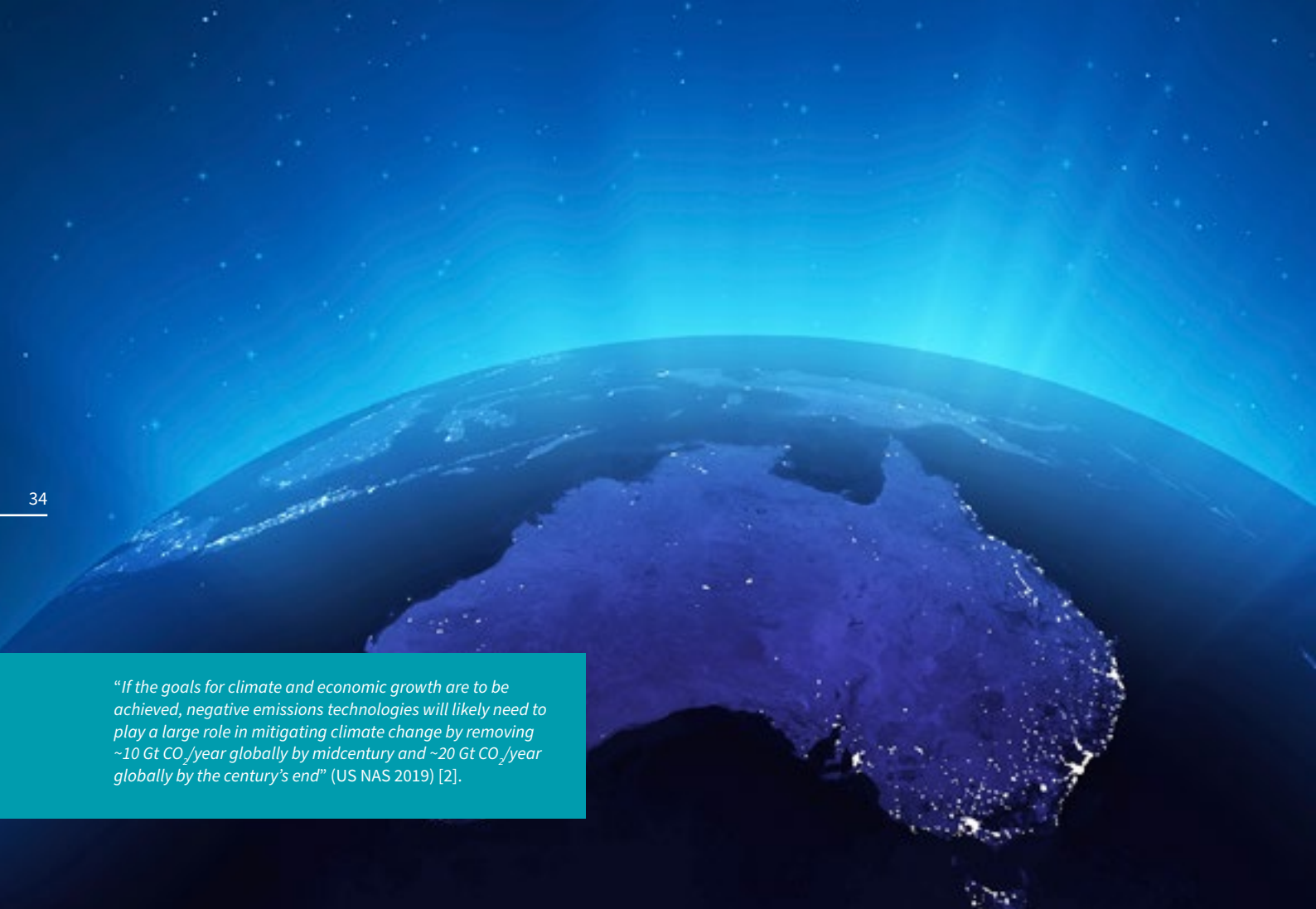
Large-scale zero-emission hubs based initially on CCS potential have been proposed for Australia. These include the CarbonNet Project and the related Hydrogen Energy Supply Chain (HESC) Project in Victoria and a proposal by Santos for use of the Cooper Basin and existing natural gas infrastructure in South Australia. The Surat Basin in Queensland is a potential site and there are opportunities in WA. A number of these proposals are based upon the use of fossil fuels, which is seen by many, not surprisingly perhaps, as inconsistent with NETs and a zero-emission economy. However, advocates point to the opportunity to move to zero emissions through the application of CCS, zero-emission hydrogen and zero-emission industrial processes, and to then provide the platform for development of DACCS, BECCS, CCUS, and other NET opportunities. Australia's industrial landscape will need to look very different in the future, which is both a challenge and an exceptional opportunity (image: CO2CRC).

Low-carbon hubs

NET opportunities for Australia may first develop locally and opportunistically. However, their greatest potential lies in being synergistically embedded within industrial and agricultural ecosystems. These correspond, respectively, to low-emission multi-industry hubs with CC(U)S, and afforestation *cum* soil-enrichment operations in agroforestry settings.

NETs are not a single class of technologies. They are a highly varied group of technologies with a wide range of costs, a diversity of time scales and varied potential in terms of the amount of negative emissions they can achieve. Initially they will likely develop in response to local opportunities: (DA)CCS in response to an EOR opportunity, or mineral carbonation because of a ready supply of crushed reactive rock. However, costs are presently too high to expect that NETs, in almost any configuration, will be widely deployed before 2030. Lack of support and/or lack of technological progress could push their availability further into the future. On the other hand, increasing concerns regarding climate change could bring it forward and accelerate technological advances.

Important opportunities for NETS lie in being part of a systems-based approach, with scope to attain economies of scale and especially with the opportunity to build on established technologies and capital investments. For example, the concept embedded in the CarbonNet proposal is of a hub initiated on the basis of geologically sequestering CO_2 for a hydrogen-from-fossil-fuels (HESC) project. But in time, that same infrastructure could be cost-effectively available to other sources of CO_2, including NET-captured CO_2. Other synergies may exist in the future with renewable technologies such as offshore wind generating hydrogen which is then able to use the established hydrogen infrastructure of HESC and CarbonNet. These synergies and opportunities will not happen overnight, but they can be part of a long-term vision for Australia to decrease and ultimately eliminate its emissions, whilst retaining and enhancing its economy, developing a low-carbon industrial base and creating new jobs.



"If the goals for climate and economic growth are to be achieved, negative emissions technologies will likely need to play a large role in mitigating climate change by removing ~10 Gt CO_2/year globally by midcentury and ~20 Gt CO_2/year globally by the century's end" (US NAS 2019) [2].

CONCLUSIONS

NETs are not an alternative to mitigation of existing and future emissions. Nonetheless, we should not wait until deep cuts in emissions have been made, or more dire predictions transpire regarding the impact of climate change, before turning to NETs. They should be undergoing extensive R&D and testing now, with the objective of ensuring they are available at a reasonable cost and sufficient scale when needed. Initially costs will be high but will come down as NETs are more widely deployed. Some NETs will prove to be impractical or too costly and it is important that we identify those as soon as possible and move on. Others may be particularly suitable for deployment under Australian conditions. We should also be looking for innovations that might provide useful products or other benefits in addition to removing existing and historical CO_2 from the atmosphere.

Developing and deploying NETs faces many challenges, but at the same time, some land-based NETs offer real opportunities for Australia, because of our endowment of natural resources including wind and solar, geological storage opportunities and the related CCS knowledge base, which offer potential opportunities for BECCS and DACCS. Our extensive land area offers the potential for re/afforestation and for enhancement of soil carbon. Our industrial and mining base provides scope for mineral carbonation and for developing useful products from CO_2. The oil and gas industry has the opportunity to identify and develop secure CO_2 storage opportunities in our onshore and offshore sedimentary basins for NETs deployment.

Some NETs will benefit from being able to draw on areas where Australia has a “competitive advantage”, but none of them are “low hanging fruit”. All of them need more work, more creativity, more collaboration including, and perhaps especially international collaboration. This will need more support from governments and industry, including financial, policy and regulatory initiatives. Developing a NET roadmap would be a useful step as part of the portfolio of measures required to meet our agreed emission targets and our national mitigation aspirations.

Land-based NETs and their associated technologies represent a real opportunity for Australia to develop new and creative low carbon industries and job opportunities and demonstrate its practical commitment to contributing to national and global greenhouse targets.

POSTSCRIPT

In early 2020, during the final stages of the writing of this report, the COVID-19 pandemic severely affected Australia and most other countries around the world. It was decided to delay the release of this report until later in 2020. Perhaps until a time when people could once again turn their minds from the immediate risks of a global pandemic to the more extended threat of global climate change.

Much has been written about the potential impact of climate change on health and the frequency of global pandemics, but can we also draw implications from the economic and socio-political impacts of the COVID pandemic to deployment of low carbon technologies?

The post-COVID budgets of countries, governments and companies will be severely constrained, which may potentially slow technology development and deployment. But many governments are looking to restart their economies through large scale infrastructure investment in cleaner energy, new greenhouse mitigation technologies (including NETs) and strategies, and large-scale low emission hubs.

A move to more home-based work and decreased transport and energy -related emissions will be beneficial to the global carbon budget. The COVID-19 crisis has highlighted how concerted action is possible; but also that even shutting down entire economic sectors has a limited effect on emissions merely returning the globe to 2006 levels [40]. But could a related sharp drop in petroleum prices encourage a move back to fossil fuels? Similarly, cheap oil will be a barrier to CO_2-enhanced oil recovery, which some may see as "a good thing", whereas others may argue it will remove a stimulus to the development of DACCS?

Most politicians have shown a willingness to accept models and scientific findings as a basis for implementing the precautionary principle when dealing with COVID-19, though there is no evidence that this same level of acceptance will extend to global warming! But the pandemic has demonstrated political party lines can change overnight, with a willingness by politicians to work together for the "greater good". So, could extreme manifestation of climate change perhaps result in governments speedily taking difficult decisions and people being willing to share the economic (and social) pain?

COVID-19 has demonstrated that whilst a global threat strengthens scientific collaboration, it does not necessarily result in a unitary global strategy, with national priorities taking precedence, perhaps for the very good reason that every country is different. This serve to illustrate that much of our approach to climate change may need to be built nationally but with an overarching global objective, which is of course exactly what the Paris Agreement aims to do through National Determined Contributions.

ACKNOWLEDGEMENTS

Financial support for the Roundtable and this Report was provided by the CarbonNet Project and the University of Melbourne's Peter Cook Centre for CCS Research, Melbourne Energy Institute and Climate and Energy College.

The Steering Committee played an active role in formulating the agenda for the Roundtable and included participants from the Federal Department of Environment and Energy, ANU, University of Tasmania, Common Capital and the University of Melbourne. Members of the Steering Committee provided valuable comment on drafts of this Report.

Roundtable participants, listed elsewhere in this Report, generously contributed their time and their ideas to the Roundtable.Especially valuable was the fact that their experience and insights came from a wide range of organisations including Federal and State Departments and Bodies, Australian and overseas Universities, CO2CRC, CSIRO and other research organisations, NGOs and Companies.

Bill Stathopoulos provided logistic support for the Roundtable and John Burgess kindly acted as a facilitator.

The Draft was circulated to participants for their input, but endorsement of this report and agreement to all its conclusions and recommendations was neither sought nor expected. The Co-ordinating Authors have done their best to capture the diversity of views expressed at the Roundtable and subsequently, but take responsibility for this Report

Figures and quotes used in this Report are from the various sources indicated in the text, Several are used with the permission of CO2CRC Ltd.

The skill of Roslyn McAlary in designing this Report is gratefully acknowledged.

Peter J Cook & Alfonso M Arranz
Co-ordinating Authors

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ROUNDTABLE PROGRAMME AND PARTICIPANTS

Programme

The Roundtable was an all-day event held at the University of Melbourne Woodward Conference Centre, 185 Pelham St, Carlton, Australia on 27 June 2019. It consisted of the following sessions where discussion was launched by short contributions from the listed speakers. The day finished with a summary session chaired by John Burgess from the University of Melbourne.

Publicly available presentations are hyperlinked below or you can find them at the Peter Cook Centre website.

Setting the scene: the need for negative emissions

Chair: Kristin Tilley, Commonwealth Department of the Environment and Energy

- Kristin Tilley, Commonwealth Department of the Environment and Energy
- Andrew Lenton, CSIRO
  - Carbon Cycle Fundamentals, the Role of Negative Emissions & simulating their response
- David Newth, CSIRO
  - Negative Emissions Technologies: An Economy Wide Prospective

Negative emissions technologies

Chair: Malcolm Garratt, University of Melbourne, Peter Cook Centre for CCS

- Henry Adams, Common Capital
  - Defining negative emission technologies
- Barry Hooper, Uno Technology
  - Carbon capture overview
- David Byers, CO2CRC
  - NETs… geological storage still matters
- Walter Gerardi, Jacobs Consulting
- Paul Webley, University of Melbourne, Chemical Engineering
  - Direct Air Capture
- Robin Batterham, University of Melbourne, Dept. of Chemical Engineering
  - Some thoughts on soil carbon
- Ralf Haese, University of Melbourne, Peter Cook Centre for CCS
  - Mineral Carbonation
- Marcus Dawe, Mineral Carbonation International
  - Mineral carbonation international
- Ian Filby, CarbonNet
  - CCS Hubs and Clusters: Enablers of Negative Emissions

ROUNDTABLE PROGRAMME AND PARTICIPANTS

Policy settings and regulation of NETs

Chair: Tony Wood, Grattan Institute

- Ross Garnaut, University of Melbourne
- Simon Every, Clean Energy Finance Corporation
- Clare Penrose, Victorian Department of Environment, Land, Water and Planning
  - Climate Change Policy in Victoria
- Matthew Riley, NSW Department of Planning, Industry & Environment
- Ian Havercroft, Global CCS Institute
  - Legal and regulatory considerations
- Fiona Haines, University of Melbourne, School of Social & Political Sciences
  - Negative emissions technology social and political concerns
- Monica Richter, World Wildlife Fund Australia
  - WWF's Position on Carbon Dioxide Removal

Transformation pathways and innovation requirements

Chair: Anita Talberg, University of Melbourne, Climate & Energy College

- Jan Minx, Mercator Research Institute on Global Commons and Climate Change
  - Negative emissions – transformation pathways and innovation requirements

Assessment of NET systems and their potential for deployment in Australia

Chair: John Burgess, University of Melbourne

- Matthew Stuchbery, Commonwealth Department of the Environment and Energy
- Andrew Heap, Geoscience Australia
  - Geological Storage of CO_2 – A National Perspective
- John Beever, GreenMag Group
  - Transformation of captured CO_2 into products which can be sold
- Barry Hooper, Uno Technology
  - Deploying low emissions technologies

Full list of attendees and affiliations

Most attendees participated in debates in all sessions; however, please note that attendance/participation does not mean endorsement of all elements in the report by the organisations or the individuals attending the Roundtable.

- Henry Adams, Common Capital, Canberra
- Alfonso M. Arranz, Monash University
- Robin Batterham, University of Melbourne, Dept. of Chemical Engineering
- John Beever, GreenMag Group
- Zoe Birnie, Monash University
- Mark Bonner, Minerals Council of Australia, Canberra
- Michael Brear, University of Melbourne, Melbourne Energy Institute
- John Burgess, University of Melbourne, Chemical Engineering
- David Byers, CO_2 CO2CRC Ltd, Melbourne
- Peter Cook, University of Melbourne, Peter Cook Centre for CCS Research
- Michelle Davey, University of Melbourne, Climate & Energy College
- Marcus Dawe, Mineral Carbonation International, Canberra
- Simon Every, Clean Energy Finance Corporation
- Ian Filby, CarbonNet, Melbourne
- Ross Garnaut, University of Melbourne, Faculty of Business and Economics
- Malcolm Garratt, University of Melbourne, Peter Cook Centre for CCS Research
- Walter Gerardi, Jacobs Consulting, Melbourne
- Ralf Haese, University of Melbourne, Peter Cook Centre for CCS Research
- Fiona Haines, University of Melbourne, School of Social & Political Sciences
- Joanne Halliday, Australian Climate Change Authority, Melbourne
- Ian Havercroft, Global CCS Institute, Melbourne
- Andrew Heap, Geoscience Australia, Canberra
- Barry Hooper, UNO Technology, Melbourne
- Will Howard, Commonwealth Department of the Environment and Energy, Canberra
- Andrew Lenton, CSIRO
- Daisy Lilley, Victorian Department of Environment, Land, Water and Planning
- Jeff McGee, University of Tasmania, Law Faculty

ROUNDTABLE PROGRAMME AND PARTICIPANTS

- Jan Minx, Mercator Research Institute on Global Commons and Climate Change, Berlin
- Kate Mumford, University of Melbourne, Dept. of Chemical Engineering
- Glenn Murray, CarbonNet, Melbourne
- David Newth, CSIRO
- Richard Owen, ExxonMobil, Melbourne
- Clare Penrose, Victorian Department of Environment, Land, Water and Planning
- Monica Richter, World Wildlife Fund Australia, Sydney
- Matthew Riley, NSW Department of Planning, Industry & Environment
- Mel Round, CSIRO
- Matthew Stuchbery, Commonwealth Department of the Environment and Energy
- Anita Talberg, University of Melbourne, Climate & Energy College
- Kristin Tilley, Commonwealth Department of the Environment and Energy
- Paul Webley, University of Melbourne, Chemical Engineering
- Michael Wheelahan, Proud Mary Consulting, Melbourne
- Tony Wood, Grattan Institute, Melbourne

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