Australian Academy of Science

GREENHOUSE GAS REMOVAL IN AUSTRALIA

A report on the novel negative emissions approaches for Australia roundtable

AUSTRALIAN ACADEMY OF SCIENCE
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ACKNOWLEDGEMENT OF COUNTRY

The Australian Academy of Science acknowledges and pays respects to the Ngunnawal people, the Traditional Owners of the lands on which the Academy office is located. The Academy also acknowledges and pays respects to the Traditional Owners and the Elders past, present and emerging of all the lands on which the Academy operates, and its Fellows live and work. They hold the memories, traditions, cultures and hopes of Aboriginal and Torres Strait Islander peoples of Australia.

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FOREWORD

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The Intergovernmental Panel on Climate Change has made clear that the world needs to both reduce emissions and remove greenhouse gases from the atmosphere if there is any hope of limiting global warming to 2°C, and more so for 1.5°C. Humanity cannot afford to underestimate the urgency and magnitude of this task.

Australia is highly vulnerable to climate change. It is in Australia's interest to limit global warming as much as possible. Coordination of global and domestic science talent, working together with the social sciences and humanities, is critical to understand the drivers of climate change and develop solutions to reduce emissions, remove greenhouse gases from the atmosphere and adapt to impacts on our lives and wellbeing.

Developing a robust portfolio of affordable and environmentally and socially acceptable greenhouse gas removal approaches will better place Australia, and the world, to respond to climate change and meet the Paris Agreement's goal to limit global warming to under 1.5°C. This requires investment and cooperation to accelerate development of a diverse set of solutions and explore innovative future opportunities.

> **Humanity cannot afford to underestimate the urgency and magnitude of this task.**

The Australian Academy of Science's independence and convening power made us an ideal host for a roundtable on novel negative emissions approaches for Australia. We are pleased to have been able to bring together a broad range of expertise for this purpose.

The roundtable was an opportunity to help shape the emerging negative emissions conversation in Australia and explore the science capability, research, collaboration and investment needed to support new breakthroughs in greenhouse gas removal. This roundtable and its accompanying report will help propel Australia into leadership of what will likely be a defining endeavour of the coming century.

I want to thank Academy Secretary for Science Policy Professor Ian Chubb AC FAA FTSE for leading the direction of the roundtable. I would also like to thank Dr John Finnigan FAA, Professor Deanna D'Alessandro and Professor Mark Howden for their assistance during the preparation of the roundtable, and Dr Andrew Lenton and Dr Pep Canadell for their presentations during the event. Finally, I would like to express our gratitude to all the participants in the roundtable for their contributions.

GLOSSARY

Adaptation: adjustments in human systems in response to the actual or expected climate and the effects of climate change, to moderate potential damage or benefit from opportunities.[1,2]

Blue carbon: the carbon stored by living organisms in marine and coastal ecosystems, and biomass and sediments.[1]

Carbon budget: the cumulative amount of global carbon dioxide (CO_2) that is estimated to limit global surface temperatures to a given temperature threshold.[1,3]

Carbon dioxide removal: the process of removing carbon dioxide from the atmosphere.[4]

CO_2: carbon dioxide

Climate change: change in the state of the climate that is directly or indirectly attributed to human activity.[5]

Co-benefits: positive outcomes that a policy or measure aimed at one objective might have on other objectives, thereby producing additional benefits for society or the environment.[1]

Direct air capture (DAC): chemical processes that capture carbon dioxide from ambient air.

Earth system science: an area of scientific research concerned with understanding the structure and function of the Earth as a complex, adaptive system.[6]

Enhanced weathering: a method to enhance carbon dioxide removal through dissolution of silicate and carbonate rocks by grinding them into small particles and applying them to soils, coasts or oceans.[1]

Greenhouse gases: gases in the atmosphere that absorb and emit radiation that causes the greenhouse effect.

Greenhouse gas removal: removal of a greenhouse gas from the atmosphere.

$GtCO_2$: one gigatonne (or one billion tonnes) of carbon dioxide.

Integrated assessment models (IAMs): models that integrate knowledge from two or more domains. They are used for applications such as assessing links between economic, social and technological development and changes in the climate system, or the costs associated with climate change impacts.[1]

IPCC: the Intergovernmental Panel on Climate Change.

Mitigation: human intervention to reduce emissions or enhance greenhouse gas sinks.[1]

Natural carbon sink: a natural mechanism or reservoir that removes or stores greenhouse gases, e.g., soil, ocean and plants.

NDCs: Nationally Determined Contributions.

Negative emissions: removal of greenhouse gases from the atmosphere by human activities, in addition to removal that would occur through natural carbon cycle processes.[1]

Net negative emissions: an outcome of human activities where more greenhouse gases are removed from the atmosphere than are emitted.[1]

Solar geoengineering: proposed approaches to reduce global temperature rise by reflecting solar radiation away from the Earth's surface.[7]

NOTE ON TERMINOLOGY

The negative emissions literature uses overlapping terms that can be applied inconsistently. Terms such as 'negative emissions', 'net negative emissions', 'negative emissions technologies', 'carbon dioxide (CO_2) removal', and 'greenhouse gas removal' are used by different authors and different related fields and differ geographically. They have specific meanings but often are not used consistently in the literature.

'Carbon dioxide removal' (CDR) refers to the process of removing CO_2 from the atmosphere. The term 'greenhouse gas removal' is a wider term that includes other, non-CO_2 gasses such as methane. Most methods currently discussed focus on CO_2, as removal of other greenhouse gases is at an earlier stage of research.[8] Methods that remove greenhouse gases from the atmosphere and store them, long-term or permanently, so that they do not re-enter the atmosphere, are described as 'negative emissions'.[4] 'Net negative emissions' is commonly used in an Earth system context when the total amount of emissions is smaller than the total amount of removals.

The roundtable discussed the use of different terms and issues associated with terminology. The participants acknowledged the need for a consistent terminological approach when engaging with stakeholders to enhance clarity, inform governance and accelerate adoption.

'Carbon dioxide removal' or 'greenhouse gas removal' were noted as more descriptive and easier to understand than 'negative emissions'. The group also highlighted the importance of terminology that reflects the longevity of storage and risk of reversal of carbon removals. An example is the Oxford Principles for Net Zero Aligned Carbon Offsetting, which distinguishes between short-lived storage, which has a high risk of reversal over decades, and long-lived storage, which has a lower risk of reversal.[9] It was suggested that this may be a more useful distinction than 'natural' and 'technological' approaches, which have been more common in the discourse.

Different terms may be useful in different contexts. For example, 'negative emissions' is useful in an Earth system context but is limited when discussing implementation and adoption. How greenhouse gas removal approaches are included and referred to in national greenhouse gas inventories may influence adoption of terminology.

Language and framing are critical to facilitate understanding and avoid polarisation in the negative emissions discussion.[10] For example, while negative emissions is different from solar geoengineering, the distinction can be poorly understood by non-experts. Clear terminology can help to avoid 'ideological bundling' of negative emissions with other issues, which can pre-emptively politicise the discussion and lead to polarisation and poor policy decisions.[10]

Being specific when referring to different greenhouse gas removal approaches was regarded as generally beneficial as it allows for consideration of potential risks and benefits in context and with nuance.

In this report, 'greenhouse gas removal' refers to human actions that remove greenhouse gases from the atmosphere and 'negative emissions' refers to the outcome, at a systems level, of removing greenhouse gases from the atmosphere.

The discussion around greenhouse gas removal in Australia is in its infancy. The Academy supports ongoing dialogues within the scientific community to develop clear and consistent language and shared terms to establish a collective voice and drive the agenda forward.

INTRODUCTION

Climate change has severe impacts on Earth and humanity, including heatwaves and extreme weather events, rising sea levels, ecosystem transformation and human wellbeing.

Countries including Australia have committed to limit global warming to well below 2°C—preferably to 1.5°C—above pre-industrial temperatures through the 2015 Paris Agreement.[11] However, Earth is likely to reach or exceed 1.5°C of warming in the early 2030s, and is on track for 2.8°C global warming by 2100 unless urgent action is taken to both reduce emissions **and** remove greenhouse gases from the atmosphere.[12,13] This level of warming is beyond what is considered manageable and could have potentially catastrophic impacts and risks for people, the economy and the environment.[14,15]

The Intergovernmental Panel on Climate Change (IPCC) reported that pathways that limit warming to 1.5°C, and most to below 2°C, involve rapid deployment of greenhouse gas removal to offset emissions from hard-to-abate sectors.[12,16] High CO_2 concentrations in the atmosphere also drive detrimental environmental impacts in addition to warming, such as ocean acidification. There are uncertainties about how land and ocean CO_2 sinks will function into the future given continuing ecological decline and further progression of climate change.

> **Planning to achieve negative emissions requires consideration of a range of future opportunities and options beyond currently favoured approaches, as part of a portfolio of solutions, including innovations from scientific breakthroughs.**

The magnitude of removal by existing technologies is currently insufficient to achieve the scale of greenhouse gas removal required to reach net zero emissions and limit global warming to 1.5°C and well below 2°C.[17] Planning to achieve negative emissions requires consideration of a range of future opportunities and options beyond currently favoured approaches, as part of a portfolio of solutions, including innovations from scientific breakthroughs.[18] This requires exploring innovative future opportunities and options to achieve the large-scale task at hand and understanding the co-benefits and trade-offs of different approaches. Co-benefits refer to positive environmental and socio-economic outcomes associated with greenhouse gas removal and storage activities.[19]

Australia has limited mechanisms to support the development and deployment of many negative emissions solutions, especially those outside the land sector and geological storage of CO_2.

Given that Australia, with its resources and research capabilities, has the potential for the development of greenhouse gas removal, the Australian Academy of Science hosted a roundtable to bring together experts to discuss:

- The novel solutions and science that would enable breakthroughs to meet the scale of the removal challenge.

- Australia's research strengths and comparative advantages for greenhouse gas removal.
- The research, cooperation and investment needs.

This report provides a high-level summary of the roundtable discussions and presentations and provides some guidance on opportunities and actions to support the development of greenhouse gas removal in Australia.

GREENHOUSE GAS REMOVAL AND NATURAL CARBON SINKS

The first session of the roundtable focused on the ecological impacts of greenhouse gas removal. To set the scene, Dr Pep Canadell (CSIRO) presented on the need for greenhouse gas removal and the complex behaviour of natural carbon sinks.

Limiting future climate change will require reaching net zero CO_2 emissions, staying within a finite carbon budget, and achieving strong and sustained reductions of other greenhouse gas emissions.

Greenhouse gas removal is needed for four key reasons:

- To offset emissions that are hard to abate either due to technological or financial constraints.
- To expand mitigation options and accelerate action. While countries have spent decades negotiating, greenhouse gases in the atmosphere have continued to increase. As such, the world needs more tools to limit future climate change than when negotiations began.
- To be able to reduce greenhouse gas concentrations in the likely case that we overshoot the Paris Agreement. At this point, it is likely that warming will surpass 2°C and removal approaches will be needed to meet Paris Agreement targets.[13,17]
- To further reduce greenhouse gas concentrations once we reach climate stabilisation. The ongoing impacts of climate change on the economy, society, agriculture and health, even at the levels agreed in the Paris Agreement, may not be acceptable.

It is important to distinguish between negative emissions (the outcome of removing greenhouse gases from the atmosphere) versus what is referred to as net negative emissions, the state at which we move beyond net zero emissions globally, i.e., more greenhouse gases are removed from the atmosphere than are emitted (Figure 1).

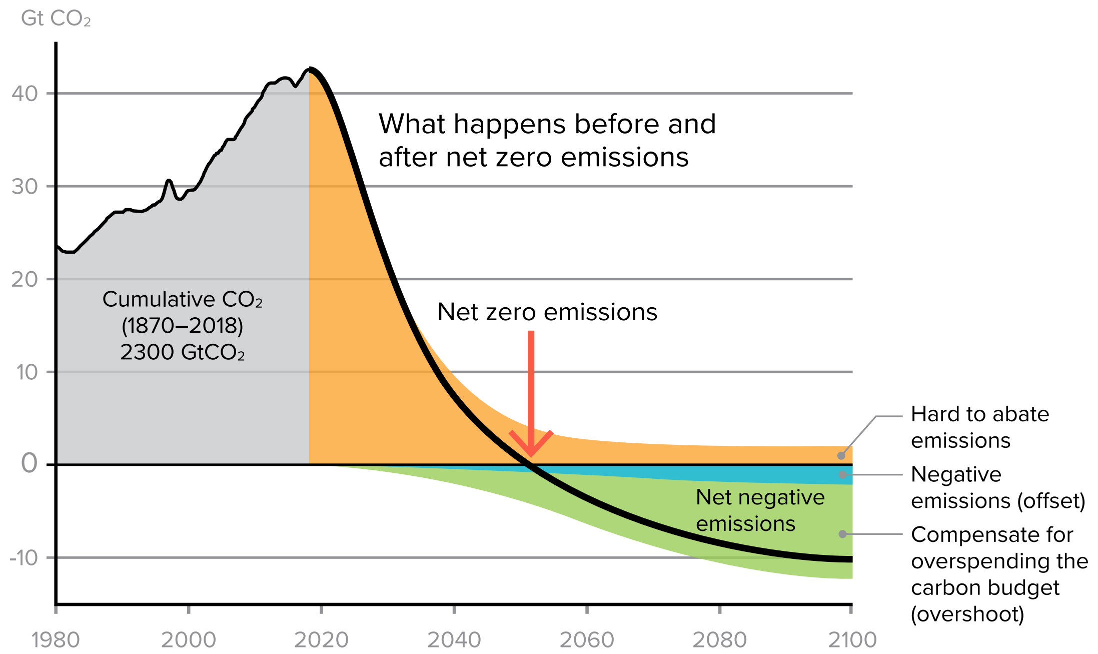

Figure 1: Gigatonnes of CO_2 ($GtCO_2$) emissions before and after global net zero emissions are achieved.
Credit: Adapted from Fuss et al. (2020).[20]

There is debate about the future behaviour of carbon sinks. One fundamental point is that the CO_2 removal by global land and ocean sinks is continuing to grow in response to increasing CO_2 concentrations in the atmosphere.[21] After we reach net negative emissions, it is expected that as CO_2 concentrations in the atmosphere fall, natural CO_2 sinks will also reduce.

Further, there are a growing number of ecosystem collapses where carbon stock changes occurred either from disruption and stress or due to massive climate change extremes (e.g., the Black Summer bushfires).[22]

Australia is highly vulnerable to climate change and therefore susceptible to changes in carbon sinks and stocks and potential ecosystem collapse. One of the most obvious impacts of climate change on Australia's natural sinks is forest fires, where the intervals between fires determine the capacity for forests to regenerate.[23]

In the case of blue carbon sinks, while carbon accumulation in biomass and sediments of mangroves, saltmarshes and seagrass has been characterised, the carbon budgets of kelp ecosystems are not well understood.[24] One component that is known well is the impact of the increasing frequency of marine heatwaves on seagrass and kelp. There are clear examples of marine heatwaves that have taken place over the last 10 years in Australia causing damage.[25,26,27,28]

ROUNDTABLE DISCUSSION

Following Dr Canadell's presentation, roundtable chair Professor Chennupati Jagadish led a discussion examining the imperative for emissions reduction and greenhouse gas removal, the impact of climate change on natural sinks, and the need to understand the carbon cycle.

MANAGING RISKS, NEGATIVE IMPACTS AND TRADE-OFFS

Participants explored a range of impacts, trade-offs and co-benefits related to the deployment of various greenhouse gas removal approaches. They emphasised that the implementation pathways selected will be critical to ensure positive impacts and co-benefits are maximised, negative impacts are reduced, and risks are appropriately managed. The governance of deployment and upscaling of greenhouse gas removal approval will be influential.

Participants observed that the large scales at which greenhouse gas removal approaches will need to be deployed will have impacts on ecological systems and other trade-offs. For example, large-scale afforestation may compete with agricultural land-use, disrupt food supply or cause changes to biodiversity. It will be essential that all risks of greenhouse gas removal approaches are considered and managed to avoid unintended consequences.

Different greenhouse gas removal approaches will have different ecosystem impacts. The way an approach is deployed will also change its impacts. For example, one participant noted that enhanced weathering may have significant ecosystem impacts depending on the way it is done. While enhanced weathering added to agricultural land can improve plant productivity, the heavy metals sometimes accompanying the process might cause problems both on-site and downstream.

Participants also highlighted that the ecological impacts of whatever greenhouse gas removal approaches are pursued will be happening in conjunction with the current state of environmental decline. There is a risk that greenhouse gas removal approaches will become an additional stressor on an already stressed environment. Assessments to inform the roll-out of greenhouse gas removal approaches will need to account for these cumulative impacts.

RECOGNISING CO-BENEFITS OF GREENHOUSE GAS REMOVAL

Participants noted the potential co-benefits associated with greenhouse gas removal approaches and suggested that approaches that bring co-benefits in the Australian context should be prioritised. In the context of this roundtable, the primary goal of these approaches is to reduce greenhouse gas concentrations in the atmosphere. However, participants recognised that there are multiple perspectives, and some groups may consider greenhouse gas removal a subsidiary benefit of some approaches, such as landscape regeneration.

Participants also emphasised that the quality of the co-benefits needs to be ensured, especially in relationship to claimed biodiversity co-benefits.

IMPACTS OF LAND CLEARING AND LAND RESTORATION ON NATURAL SINKS

Assessments are needed to determine what greenhouse gas removal potential there is in the landscape. A significant factor impacting this is the combination of land use and land restoration activities undertaken. Land clearing continues to take place in Australia. Recently, rates of regrowth and reforestation have been greater than land clearing and the net effect is estimated to be a sink.[29] This land sink comes from a combination of sources, for instance, allowing for the regrowth of dryland bush in western parts of NSW and Queensland by removing cattle. However, questions remain, including how vulnerable this sink will be into the future.

One participant noted that large, landscape-scale restoration and planting activities will require technology to grow the appropriate plants at scale and the ability to source and secure the appropriate seed socks. The seed supply challenge is particularly difficult in areas where landscape and vegetation are highly disturbed and fragmented, such as cleared farmland in southern Australia.

> **Mitigation and greenhouse gas removal go hand in hand. Greenhouse gas removal approaches do not permit a slowed effort to reduce emissions.**

Participants also highlighted important opportunities in relation to climate adaptation when considering management and restoration of landscapes. For example, by restoring parts of estuaries that will have limited agricultural productivity, there are opportunities to offer protection from flooding and limit storm surges, while also enhancing natural greenhouse gas sinks.

DYNAMIC CARBON STORE BEHAVIOUR IN A NET NEGATIVE WORLD

Participants emphasised the ongoing requirement to understand the fundamentals of the carbon cycle, particularly under a net negative emissions world.

As work progresses to create new carbon sinks and avoid the destruction of existing sinks, CO_2 concentrations in the atmosphere will slowly reduce. Natural CO_2 sinks largely respond to the CO_2 concentrations in the atmosphere. Based on the first principles of the dynamics of the carbon cycle, it is expected that this reduction in CO_2 concentrations will also lead to a reduction in the capacity of natural carbon sinks.[21,30] However, many of the details of how carbon sinks will behave over the next few hundred years are still uncertain and sinks may behave differently after the transition to net negative emissions.

For example, the ocean could potentially become a source of CO_2 in the next century. Further research is required to ensure understanding of this predicted behaviour is correct and to estimate appropriately the remaining carbon budgets, including overshoots. It is critical to understand these carbon cycle dynamics so that they can be modelled well within decarbonisation scenarios to guide planning and management.

REMAINING FOCUSSED ON MITIGATION

At the end of this session participants reiterated that whatever combination of greenhouse gas removal approaches are used, rapid emission reduction remains essential to achieve any level of temperature stabilisation. Mitigation and greenhouse gas removal go hand in hand. Greenhouse gas removal approaches do not permit a slowed effort to reduce emissions.

NOVEL GREENHOUSE GAS REMOVAL APPROACHES

The roundtable's second session focused on novel greenhouse gas removal approaches. Dr Andrew Lenton (CSIRO) opened the session with an overview of novel approaches to atmospheric CDR and permanent CO_2 storage, both of which are required at an affordable scale.

Dr Lenton outlined that there are chemical and biological approaches to atmospheric CDR. Direct air capture (DAC) technologies use physicochemical processes for direct removal of CO_2 from the atmosphere. There are a wide range of approaches in development including solid and liquid sorbents and metal organic frameworks. Interesting case studies include CSIRO's Airthena, MIT's electro-swing process and the ocean approach of Hawaii-based start-up Heimdal.[31,32,33] Because some of these technologies are energy-intensive, it will be critical to lower energy costs and increase the scalability to remove the levels of CO_2 required.

Biological removal approaches include using photosynthesis in novel ways (e.g., American technology company Hypergiant's bioreactor) and bioengineering and synthetic biology approaches to manipulate systems to increase carbon uptake in plants.[34] Approaches that attempt to manipulate biological systems must manage other risks, for example, ensuring they do not strip the environment or ocean of nutrients that fuel the natural biochemical cycle or provide ecosystem services.

> **Achieving negative emissions will require integrating atmospheric carbon removal, permanent storage and utilisation technologies. These holistic solutions require significant effort and creativity.**

There are two main types of CO_2 storage with large potentials: geological storage and ocean storage. Geological storage opportunities for Australia may include using mafic and ultramafic rocks. These rocks may have potential for carbon sequestration via *in situ* and *ex situ* mineral carbonation, including through mine waste management and critical mineral recovery. Approaches include using rocks that react with CO_2 to form new rocks, injecting CO_2 into basalt, and mineral carbonation.

Oceans also have large CO_2 storage potential, but critical questions around how to use the oceans to achieve permanent carbon storage while minimising harms and maximising co-benefits need to be addressed. Ocean alkalinity enhancement is an example of an ocean carbon storage approach that both counters ocean acidification and promotes increased take-up of CO_2 by the ocean. Proposed methods for achieving increased alkalinity include using specially designed dissolvable substances made from waste material and harnessing electrochemical processes. Other avenues include biomass in the ocean and deep ocean storage. Potential impacts on ecosystems are of prime importance when considering any of these approaches.

> **A portfolio of solutions suited to Australia's unique environment and natural assets is needed. If done correctly, this portfolio of greenhouse gas removal approaches will both create new industries and reshape existing ones.**

There are also options to use captured CO_2, for example, to create high value products such as cement or polymers. However, utilisation is only relevant to achieving negative emissions if it is associated with permanent storage or ongoing utilisation within a circular economy.

Achieving negative emissions will require integrating atmospheric carbon removal, permanent storage and utilisation technologies. These holistic solutions require significant effort and creativity. Verification and monitoring of these technologies is also essential. Knowledge and insights from diverse disciplines can help develop solutions that are not only technically feasible but which, for example, have social license and environmental co-benefits.

A portfolio of solutions suited to Australia's unique environment and natural assets is needed. If done correctly, this portfolio of greenhouse gas removal approaches will both create new industries and reshape existing ones.

ROUNDTABLE DISCUSSION

After Dr Lenton's presentation, participants discussed a range of emerging approaches to greenhouse gas removal, storage and uses, and avenues for further investigation, summarised in this section. Individual approaches were not discussed in detail, and the approaches mentioned here are not exhaustive.

GREENHOUSE GAS REMOVAL APPROACHES IDENTIFIED IN THE DISCUSSION

Carbon harvesting technology

Participants raised carbon harvesting technologies as a CDR approach, which separates CO_2 into elemental carbon and oxygen. This process is energy intensive, but this could be overcome by the development of innovative approaches. The example provided in the discussion involves electrolysis of CO_2 to produce CO and oxygen, followed by a low temperature reaction which yields elemental carbon and oxygen.[35] The carbon can then be added to soil or used in other applications. Researchers at Australian universities are investigating these technologies.

Offshore ocean-based solutions

While it is assumed that Australia has vast land resources, it is not a given that greenhouse gas removal and storage activities will have the acceptance of Traditional Owners, agricultural producers, environmentalists and local communities. Participants noted that offshore ocean-based solutions such as offshore DAC may be an important avenue of research and development for Australia. As with land-based approaches, ocean-based solutions also have significant social and environmental risks that will need to be considered.[36]

Soil carbon

Participants noted the growing interest in soil carbon. They agreed that soil carbon storage should continue to be used as part of the portfolio of approaches to achieve greenhouse gas removal. But there is much uncertainty and participants noted its potentially limited capacity and vulnerability to ongoing climate changes. Soil carbon is an approach that is needed, in tandem with other nature-based solutions, while we are developing novel technological solutions.

Research is needed to enhance understanding of soil carbon, including:

- Development of new, comprehensive spatial-temporal datasets to gauge how soil can contribute and with what certainty.
- Assessments of the size, distribution and vulnerability of soil inorganic carbon storage, which is significant under Australian semi-arid and arid climates. Soil inorganic carbon is mostly unexplored, but it has potential implications for carbon storage.
- How ‘newer’ practices such as regenerative methods and biochar additions could improve the potential for soil carbon in cropping regions.
- Further research into soil carbon in rangelands. Estimates suggest that this is where the potential for soil carbon lies, with approximately one third of Australia’s total 0–30cm carbon stock held in rangelands, but there are challenges to achieving and measuring this that need to be addressed.[37,38]

Methane removal approaches

In addition to atmospheric CDR, participants highlighted emerging chemical and biological approaches for removal of methane from the atmosphere. Methane has a shorter lifetime in the atmosphere but is more potent than CO_2 at warming.[39] Chemical approaches to methane removal include the use of:

- Zeolites (an inexpensive group of minerals known for their high absorbency, which are currently used to make cat litter).[8,40]
- Photocatalysts (a material that absorbs light and provides this energy to catalyse a chemical reaction).[8,41]
- Iron-salt aerosols (iron-containing particles that enhance natural methane sinks by mimicking natural reactions caused by mineral dust particles).[8]

There are also emerging biological methane removal approaches using methanotrophs (methane-consuming bacteria).[42]

Table 1: Novel approaches to greenhouse gas removal and storage noted by participants during the roundtable and the pre-roundtable survey. Note that this is not a comprehensive list of all approaches.

Atmospheric greenhouse gas removal

Chemical approaches

- Direct air capture (DAC)
  - Metal-organic frameworks (e.g., CSIRO's Airthena)[31]
  - Solid and liquid sorbents (e.g., amines, amino acid salts and lime-based)
  - Trains that capture CO_2 while travelling between mine sites, to be stored subsequently at mine sites
  - DAC used to accelerate biomass production (e.g., bamboo) with a view to use in cross laminated timber as a large-scale replacement/augmentation for steel structures in buildings
- Electrochemical approaches (e.g., MIT's electro-swing process)
- Ocean alkalinity enhancement
  - Hawaii-based start-up Heimdal's seawater approach[33]
  - Canada-based start-up Planetary Technology's approach, which uses mine tailings, water and renewable energy to extract valuable metals, and produce hydrogen and material that can be used[43]
  - Addition of alkalinity-enhancing substance generated from mine tailings and other waste
  - Electrochemical approaches
- Carbon harvesting technologies
- Zeolites, photocatalysts and iron air salts for methane removal

Biological approaches

- Capture CO_2 via photosynthetic organisms (e.g., bioreactors), using bioengineering and synthetic biology to manipulate biological systems to take up more CO_2
- Methane removal by methane-consuming bacteria
- Use of microalgae to capture carbon followed by protein extraction (for human consumption) and biochar production from the remaining biomass for sequestration to soil
- Ocean farming (e.g., kelp, seagrass) for CO_2 capture
- Soil carbon 'farming' and innovative (regenerative) soil land management methods
- Inorganic soil carbon

Other

- Integrating carbon capture into current structural materials and systems (e.g., building materials can perform a dual role as carbon capture surfaces or retrofitting HVAC systems to provide capture function)

Carbon storage

Geological storage

- Mineral carbonation (*in situ* and *ex situ*)
- Storing CO_2 in certain types of mine tailings
- Geosequestration
  - Basalt
  - Depleted oil and gas reservoirs
  - Deep saline aquifers
- Enhanced mineralisation (also known as enhanced weathering)

Soil storage

- Biochar production from residual biomass in agriculture and forestry for sequestration in soil
- Sediment carbon in mangroves, saltmarshes and seagrass[44]
- Carbon 'farming' and innovative soil management methods that help to preserve the more stable (long-lasting) forms of soil organic carbon

Ocean storage

- Biomass in the ocean (e.g., seaweed that sinks to the deep ocean)
- Blue carbon
- Deep ocean storage

Storage in high value products

- Building materials (e.g., cement production) and polymers

BUILDING ON INNOVATIONS IN POINT SOURCE CO2 CAPTURE

Thermochemical processes originally developed for CO_2 capture from point sources such as coal-fired power plants (e.g., amine-based CO_2 capture and chemical looping) can be adapted for DAC.[45,46] For example, the soda-lime process that absorbs CO_2 could be used to remove large quantities of CO_2 from the atmosphere.[45,46]

A picture of the VAMCO chemical-looping technology developed by Laureate Professor Behdad Moghtaderi and his team at the University of Newcastle for capture of CO_2 or methane.

TIMESCALE OF STORAGE

The longevity of storage is essential for achieving negative emissions. Participants highlighted the importance of robust measurement, reporting and verification of storage. The timescale for storage varies between different approaches and is still uncertain for some. Some approaches like soil and carbon storage in woody vegetation (terrestrial trees or mangroves) provide storage in the scale of decades to centuries, while other approaches such as mineral carbonation or DAC with geological storage can provide storage on geological timescales with estimates exceeding 100,000 years.[47,48] Participants emphasised the importance of improving understanding of the timescale of different storage approaches and its uncertainties and risks. A key component of this is understanding what storage is at risk of being reversed, for example, the release of CO_2 from trees due to forest fires.

THE ROLE OF UTILISATION APPROACHES

A point of contention that emerged in this session was the role of utilisation approaches in negative emissions. The discussion emphasised the need to be clear about the difference between avoided or reduced emissions and permanent emissions removal and storage. Utilisation approaches can only be considered negative emissions if associated with permanent or long-term carbon storage. For example, captured CO_2 can be used in the production of aviation fuel to reduce emissions during the production process but this use does not permanently lock away CO_2. Though an interesting and valuable technology as part of a wider decarbonisation strategy, it is not in the scope of negative emissions as defined for the roundtable and this report.

> **… there will be no 'silver bullet'.**

On a related note, another participant observed that it is important to consider the circular economy when designing CO_2 utilisation approaches, with a focus on the entire system rather than a single product.

THE NEED FOR A PORTFOLIO OF SOLUTIONS

Participants concluded the session by reiterating that a portfolio of solutions is required to achieve negative emissions—there will be no 'silver bullet'. At this stage, all potential solutions should be investigated to develop a strategy for Australia.

AUSTRALIA'S RESEARCH STRENGTHS AND COMPARATIVE ADVANTAGES

In this session, participants discussed Australia's comparative advantages that present opportunities for greenhouse gas removal. These advantages include:

- A large land area that could present locations for testing and development of different greenhouse gas removal approaches. Australia also has potential for underground storage of carbon.[49] Further research and community engagement is needed to understand locations appropriate for use.
- World leading renewable energy potential. Noting that greenhouse gas removal approaches can have high renewable energy demands, Australia could be uniquely able to meet these demands.
- Large ocean resources and marine research capabilities place Australia in a position to investigate safe marine greenhouse gas removal.
- Australia's advanced and interdisciplinary research capabilities.

> **Australia should be proactive about developing new technologies to reach net zero targets and negative emissions.**

Development of greenhouse gas removal is intertwined with renewable energy. Roundtable participants noted Australia's research capability and potential for renewable energy. However, Australia lacks large-scale commercialisation and manufacturing capability. Supply of critical minerals was also discussed as an important consideration for renewables and energy storage, and a potential comparative advantage for Australia.

Participants observed that Australia has been active in promoting land-based solutions for greenhouse gas removal, which government support has been directed towards through programs such as the Emissions Reduction Fund. While Australia has land and ocean areas with potential for carbon sequestration, further research is needed to understand feasible storage capacity. Further, restoring and expanding carbon sinks requires consideration of co-benefits, interests of communities living in the regions and economic viability.

Nature-based solutions can only account for part of the greenhouse gas removal required and accelerated development of technological approaches is needed. Australia should be proactive about developing new technologies to reach net zero targets and negative emissions, which will require investment and global collaboration. Participants mentioned that there are several small-scale initiatives and start-ups that exist in Australia developing promising technologies, and negative emissions could expand into a new industry for Australia.

Innovation is potentially risky. However, processes to manage risk are embedded in research and development practices and learning from unsuccessful attempts is a key part of innovation. Acknowledging failures, and sharing and learning from them, particularly between industry and research, is important to help accelerate development of new technologies for greenhouse gas removal.

> **Acknowledging failures, and sharing and learning from them, particularly between industry and research, is important to help accelerate development of new technologies for greenhouse gas removal.**

Data and knowledge sharing were identified as important to support technology development for greenhouse gas removal. Australia's approach to making data publicly available is a strength for attracting international investment. For example, Geoscience Australia invests in gathering and sharing pre-competitive geological information that provides insights for geological carbon storage.[50,51,52] Development of greenhouse gas removal capability in Australia would benefit from arrangements for industry to share data.

Other strengths that were noted in the discussion included strong international links with the US and Europe, which are making significant investments in negative emissions technologies and existing research partnerships in Asia. Participants also observed that Australia has a sophisticated legal system to support development and manage trade-offs. Australia's existing research landscape and institutional arrangements can also be leveraged to support the innovation system and build up greenhouse gas removal capability quickly, including organisations like the Australian Research Council, the Australian Renewable Energy Agency (ARENA) and the Clean Energy Finance Corporation.

SCIENCE CAPABILITIES, RESEARCH, INVESTMENT AND OPPORTUNITIES FOR COLLABORATION

In this session, roundtable participants considered Australia's greenhouse gas removal research capabilities and needs. Participants also discussed how to create an ecosystem that will support research, innovation and implementation of greenhouse gas removal.

Table 2: Knowledge gaps and challenges identified by participants before and during the roundtable.

Knowledge gaps and challenges	Examples
Public engagement	• Growing public awareness • Earning trust in research and the social license to operate • Ensuring First Nations representation in decision-making • Avoiding polarisation and politicisation
Implementation	• Identifying implementation pathways that appropriately balance risks and benefits
Government support	• Creating effective market incentives • Introducing necessary regulatory framework to manage trade-offs • Ensuring sufficient infrastructural support and supply chains
Technology efficiency and scalability	• Advancing innovations through technology readiness levels • Overcoming the energy penalties of capture • Ensuring large-scale proof of concepts
Monitoring, reporting and verification	• Implementing monitoring, reporting and verification across entire supply chain and across the entire life cycle
Permanence of removals	• Ensuring permanence of storage
Collaboration	• Developing and implementing mechanisms to foster collaboration and strategic coordination
Investment decisions	• Developing guidance on short-term and long-term greenhouse gas removal investment opportunities • Conducting multidisciplinary assessments to support investment decisions in emerging greenhouse gas removal
Earth system science and modelling	• Improving understanding of the impacts of climate change on the behaviour of natural sinks • Improving understanding of the impact of deploying greenhouse gas removal approaches at scale
Research capabilities	• Developing a pipeline of new researchers

FOSTERING STRATEGIC COLLABORATION AND COORDINATION

Given the urgent need for greenhouse gas removal, collaboration rather than competition is required. Throughout this session participants observed the current lack of coordination for the research, development and deployment of greenhouse gas removal in Australia.

Given the urgent need for greenhouse gas removal, collaboration rather than competition is required.

Collaborative work will likely require funding and the appropriate mechanisms to bring groups together and collectively pool resources. Participants mentioned several examples of other areas of science that have used funding mechanisms to build community and capability. For example, the synthetic biology community of researchers was built up through a CSIRO Future Science Platform which led to a new Centre of Excellence.[53,54] Through this, there was a significant investment in building capability including postdoctoral research and PhDs to develop the community.[53,55]

Interdisciplinary collaborations were highlighted as important to the development of greenhouse gas removal approaches. Interdisciplinary projects and programs can be challenging to operate effectively in practice. It is essential that, in addition to recognition for work that accounts for various knowledges and expertise, work is also undertaken to ensure they function.

While generally agreeing on the importance of collaborative efforts and building networks, some participants noted that there is a risk of being too prescriptive. A diversity of approaches is required, since coalescing around only one or two technologies would be counterproductive.

DEVELOPING A POLICY AND REGULATORY ECOSYSTEM TO SUPPORT GREENHOUSE GAS REMOVAL INNOVATION

Technology development is a long journey, from fundamental research to scaling up and commercialisation. In Australia, there are limited opportunities for spin-offs and many researchers take their innovations overseas. Given the urgency of this issue, government support mechanisms are needed to accelerate the progression from fundamental research to commercialisation.

Australia has some existing programs to support research and translation, for example, ARENA programs, CRCs and ARC Fellowships. However, participants suggested that a new overarching framework could provide direction and dedicated funding to accelerate greenhouse gas removal. Participants made a range of suggestions for new programs or adjustments to existing programs, including:

- A small business innovation research program (like in the US) to nurture technologies developed in the research sector until they are ready for the marketplace.
- Test beds in Australia for greenhouse gas removal technology that are brought together with common monitoring and evaluation frameworks. These test beds could provide a mechanism to test and share knowledge. Commercial in-confidence aspects may present barriers to accessing information and bringing emerging ideas into test beds.

- An extension of ARENA with new funding to support novel greenhouse gas removal projects.
- A new CRC on greenhouse gas removal.

Additionally, in this emerging field, building human capital (particularly the pipeline of young researchers) is critical. Participants commented that Australia needs to be investing in graduates and postgraduates. One participant observed that even if they do not stay in research, these trained people will bring valuable knowledge and skills into industry, start-ups and other areas needed to develop greenhouse gas removal.

DISTINGUISHING EMISSIONS REDUCTIONS AND REMOVALS IN DOMESTIC AND INTERNATIONAL REGULATION

Participants suggested that regulatory reform is required to recognise the need to both reduce and remove emissions and avoid the risk that greenhouse gas removal may disincentivise emissions reduction. The current regulatory framework does not distinguish between emissions reductions and emissions removals. At the international level, the Paris Agreement does not require countries to distinguish between emissions reductions and negative emissions in their Nationally Determined Contributions. Domestically, the *Climate Change Act 2022* does not distinguish between reductions and removals. A regulatory framework which makes this distinction could encourage greenhouse gas removal development and deployment, including by establishing a price signal to incentivise negative emissions.

Further, distinction between high-quality and low-quality offsets will be needed to move the agenda forward. In Australia, there has been some government investment in nature-based solutions. Support is also needed, however, for technological solutions that are currently expensive but will provide high-quality carbon offsets.

CREATING THE INTERNATIONAL FRAMEWORK FOR OCEAN-BASED GREENHOUSE GAS REMOVAL

Participants noted that based on past experience, greenhouse gas removal approaches with ocean components will face unique challenges gaining acceptance and support in terms of international regulation, with several international treaties governing the use of the world's oceans. Ocean-based solutions require tracking and verification work to build the confidence that is already established for many land options. They will also need to adhere to international laws, such as the London Convention and Protocol and the United Nations Convention on the Laws of the Sea. Currently, international policy frameworks for ocean-based solutions require development.[56]

UNDERTAKING EARLY PUBLIC ENGAGEMENT AND BUILDING TRUST

Participants noted that while public engagement is often done at the end of the research process, it is essential to engage with communities, stakeholders and policymakers early. The development of integrated solutions that consider trade-offs and co-benefits need to be supported by early public engagement. It is essential that this is done responsibly, with concern for the communities involved. It is not only environmental outcomes that need to be considered, but also other aspects such as impacts on communities and livelihoods.

Greenhouse gas removal and storage intersects with Indigenous lands and waters so engaging with Traditional Owners about their Country is essential. Further, it is important that greenhouse gas removal projects do not continue or worsen existing social inequalities or threaten biodiversity and culturally significant plants and animals. Central to this is free, prior, and informed consent, acknowledging the rights of Aboriginal and Torres Strait Islander communities, understanding the values of communities, and effectively communicating the benefits and risks of projects.

RECOGNISING THAT SOCIAL RESEARCH IS KEY TO GREENHOUSE GAS REMOVAL DEPLOYMENT

The range of social considerations related to greenhouse gas removal is vast as each approach varies in terms of its risks, technology readiness and implications. Social research is a critical component of achieving negative emissions at scale. It will be important to identify what social research currently exists and how to connect it with the technical research to build multidisciplinary research teams.

For example, one participant noted that emerging research on the drivers of public trust in emergent and potentially disruptive areas of science and technology development may provide useful guidance for novel greenhouse gas removal approaches. The research undertaken by CSIRO identifies that public trust in the research and innovation sector is largely driven by perceptions of responsible innovation, especially science practices supporting responsiveness to society and the perceived effectiveness of risk management practices of the institutions undertaking such research.[57]

> **… people do not expect there to be no risks with new areas of science and technology development but rather that the benefits must be clear, the risk management arrangements must be strong, and a level of trust must exist …**

Further, approximately three-quarters of public expectations about socially responsible outcomes being delivered from these emergent and potentially disruptive areas of science and technology development can be explained by perceived benefits of those technologies, the level of public trust in the research and innovation sector, and the perceived risk management effectiveness of the institutions.[57] This suggests that people do not expect there to be no risks with new areas of science and technology development but rather that the benefits must be clear, the risk management arrangements must be strong, and a level of trust must exist in those stakeholders driving these new areas of research and innovation.

EARTH SYSTEM SCIENCE AND MODELLING ARE CRITICAL UNDERPINNINGS FOR GREENHOUSE GAS REMOVAL

Participants strongly emphasised that Earth system science and modelling research and capabilities need to be supported with long-term funding. They are critical underpinnings to the development and deployment of both natural and engineered greenhouse gas removal approaches. Research is needed to not only understand the ongoing impact of climate change on the natural environment but the success of greenhouse gas removal interventions and how greenhouse gas removal may impact Earth systems.

Continued work is also needed to understand how climate change will affect the options available for nature-based greenhouse gas removal. For example, blue carbon approaches may be impacted by sea-level rise but currently there is no Australia-wide spatially explicit model of the effects of sea-level rise on the land-ocean interface and related emission sources and sinks.

The development and deployment of technological solutions also needs to be supported by a deep understanding of Earth system dynamics. Further, work needs to be done to better account for technological greenhouse gas removal approaches in modelling. Novel technology can be difficult to implement into models because of insufficient information about factors such as uptake, implementation, and commercial-in-confidence projects.

PUTTING GREENHOUSE GAS REMOVAL ON THE NATIONAL AGENDA

Participants noted that one significant hurdle for people working on research and development in this space is that fundamental science and research and development for greenhouse gas removal and negative emissions is not prominent on the national agenda. While Australia has some research and development capabilities supporting greenhouse gas removal, we are falling behind the rest of the world.

A related issue participants observed is the need to improve understanding of negative emissions in policy and political quarters. This understanding will be critical to form the foundation of a functional and informed debate about the relevant governance, institutional arrangements, research and incentives. Further, the importance of a clear narrative to communicate the need for greenhouse gas removal was also highlighted as important by participants.

GUIDING INVESTMENT DECISIONS

Participants stressed that investment in any emerging and potential greenhouse gas removal approaches should be based on a sound multidisciplinary assessment.

A suggestion that arose in this session was for the scientific community to collaboratively develop a matrix of short-term and long-term opportunities to provide guidance to industry and government. This matrix would highlight which greenhouse gas removal projects are already or soon to be viable versus those which require further research and investment.

Guidance could also be provided on which approaches offer other benefits in addition to negative emissions, such as improved livelihoods, biodiversity, and soil and water quality. This will require a significant scientific effort and a systems approach. Approaches bringing co-benefits in the Australian context should be prioritised.

Participants noted the opportunity of value-add technologies that come with additional outputs given some negative emissions approaches by themselves may not be economically viable. These technologies could be more attractive for industry investment. While government can play an important role in providing incentives, participants suggested that scaling up and having a sizeable impact will be achieved by industry.

OPPORTUNITIES, CONCLUSIONS AND NEXT STEPS

In the final session of the roundtable, participants identified key opportunities for the development of negative emissions in Australia based on the earlier discussions.

Reducing greenhouse gas emissions as much and as fast as possible is the highest priority. In parallel, we need rapid and large-scale removal of greenhouse gases from the atmosphere, combined with long-term storage. There is no 'silver bullet'—we will need to explore all potential options for greenhouse gas removal to develop a mix of different approaches that suit the specific social, economic and political context.

> **The urgent need for greenhouse gas removal is both a challenge and an opportunity.**

Participants began by reemphasising the urgent need for greenhouse gas removal approaches that can be used at scale. Participants also emphasised that without swift action Australia risks falling behind our peer nations that are making progress in this space.

Of the range of different greenhouse gas removal options available, some are ready now (e.g., nature-based solutions), while some (discussed in Section 2) are early-stage technologies that require investment and development to scale up but could be part of a new industry for Australia. Enhancing understanding of potential greenhouse gas removal approaches and whether they are ready to implement in the short, medium and long-term will support investment and policy decision making.

The urgent need for greenhouse gas removal is both a challenge and an opportunity. The development and deployment of novel greenhouse gas removal approaches will require new industries as well as the transformation of existing ones. Building greenhouse gas removal capacity presents a range of opportunities including for job creation in regional Australia.

Participants highlighted the need for mechanisms to create the innovation environment for greenhouse gas removal solutions and support successful technologies to scale up. Early-stage technologies are expensive, and it can take decades for new revolutionary technologies to reach fruition. We need to accelerate this to develop greenhouse gas removal solutions at scale as soon as possible.

This effort will require national commitment and focus, with the right frameworks to nurture and develop these technologies. Participants raised the need to consider whether current research governance structures are fit for purpose and to explore ways to best organise scientific research and development, translation and community engagement. One participant suggested that a national institute on greenhouse gas removal could be part of this framework.

Raising the visibility of new technologies among industry and attracting investment will have a large impact on development. There are small groups and start-ups working on greenhouse gas removal solutions in Australia, but they may never receive the funding needed to scale up. We need to foster an innovation system to carry greenhouse gas removal solutions through the pipeline, from science research through to development and deployment.

Participants also reiterated the value and importance of learning from failures to prevent the duplication of effort and waste of resources.

Further interdisciplinary research into the co-benefits, trade-offs, governance and social acceptance of greenhouse gas removal is required to fill knowledge gaps and give policymakers a more complete picture.

OPPORTUNITIES FOR DEVELOPMENT OF NEGATIVE EMISSIONS IN AUSTRALIA

The roundtable identified the following opportunities across research, policy and society to promote development of greenhouse gas removal in Australia:

- Fostering interdisciplinary basic research and collaborative networks to develop negative emissions approaches as part of a robust and diverse negative emissions portfolio.
- Improving holistic assessment of the benefits, risks and limitations of removal of CO_2 (and other greenhouse gases), storage and use approaches to inform decision making.
- Improving data and knowledge sharing across research, government and industry to avoid duplication of efforts and learn from past experiences.
- Fostering the innovation and regulatory environment to accelerate the development of novel negative emissions approaches and attract private sector investment.
- Investing in human capital, especially young researchers, to develop negative emissions capabilities.
- Engaging early with policymakers and communities, especially First Nations peoples, to co-design appropriate approaches to negative emissions portfolios. Building community confidence in benefits and risk management is also required to support greenhouse gas removal activities.
- Establishing a collective voice and a common language to facilitate clear and productive discussion.
- Further research is needed in areas including the societal aspects of negative emissions development and implementation, comprehensive understanding of climate change impacts and adaptation on greenhouse gas removal capability, removal of other greenhouse gases (e.g., methane), and circular economy carbon use.

Across all of these, mechanisms for high-level, strategic coordination and connection between knowledge generation and policy development are vital.

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METHODOLOGY

SELECTION OF PARTICIPANTS

Eighteen experts were selected to bring together a representative group of expertise on greenhouse gas removal, climate change and innovation policy. Experts were identified from nominations by the Learned Academies, state and territory chief scientists and the Academy's National Committees for Science. Selection of participants was made by an advisory group.

PRE-EVENT SURVEY AND ISSUES PAPER

A survey was distributed to participants to gather information about novel negative emissions technologies and natural sinks. The questions were:

1. In 2100, which mechanism(s) do you think will pull down the most carbon?
2. What fields of research are relevant to understanding negative emissions or novel negative emissions approaches?
3. Are there novel ways to capture carbon? Please provide up to three examples.
4. Are there novel ways to store carbon, what is the timescale for storage and what safeguards need to be in place? Please provide up to three examples.
5. Are there novel ways to use carbon? Please provide up to three examples.
6. Can these novel approaches complement existing emerging technologies?
7. What are Australia's negative emissions research strengths or comparative advantages?
8. Is there an area of negative emissions where you see Australia as a potential world leader?
9. Are there knowledge gaps or challenges in negative emissions?
10. What are the ecological impacts of high levels of carbon dioxide drawdown on natural sinks?
11. What are potential flow-on impacts of high levels of carbon dioxide drawdown by natural sinks?
12. Would additional carbon dioxide removal approaches depend on well-functioning natural sinks?
13. How would additional carbon dioxide removal approaches interact with natural sinks?

Responses to the survey informed an issues paper shared with participants before the roundtable.

ROUNDTABLE

The roundtable was held online via Zoom Webinar. The event was broken into six sessions (Appendix 2). The roundtable did not seek to reach consensus on research priorities, but discussed novel solutions, issues and opportunities to develop greenhouse gas removal in Australia.

STATEMENT

A statement (Appendix 1) was released after the roundtable, sharing the key points and opportunities from the roundtable.

POST-EVENT SURVEY

A survey was distributed to participants after the roundtable to capture feedback on the topics discussed and the organisation of the event. The questions were:

1. Which comments or opportunities from the roundtable did you particularly agree with?
2. Which comments or opportunities did you particularly disagree with?
3. Was there an issue that wasn't discussed today that should have been?
4. Do you have any feedback for the organisers?

FINAL REPORT

Input from participants gathered at each stage of the process is collated and summarised in this report. A draft of the report was circulated to participants for feedback.

APPENDIX 1: ROUNDTABLE STATEMENT

STATEMENT: ROUNDTABLE ON NOVEL NEGATIVE EMISSIONS APPROACHES FOR AUSTRALIA

The concentration of greenhouse gases (GHGs) in Earth's atmosphere must be reduced if there is any hope of limiting the global average temperature increase to close to the 1.5°C lower limit stipulated in the Paris Agreement.

In Australia, much of the discussion has focused on achieving 'net zero' by 2050. This will require removal of GHGs from the atmosphere to offset difficult to abate sectors like steel or concrete production. Removals will have to increase further if we are to limit global warming to 1.5°C.

Reducing GHG emissions as much and as fast as possible is the highest priority. In parallel, we need rapid and large-scale removal of GHGs from the atmosphere, combined with long-term storage.

Of the present methods used for removal of GHGs (primarily CO_2) and their long-term storage or utilisation, none are at the scale required.

How do we develop the capacity to drawdown GHGs at a globally effective scale while reducing emissions to close to zero? Do we have the knowledge and science capability?

A roundtable on novel negative emissions approaches for Australia was organised on Friday 16 September 2022 by the Australian Academy of Science.

Methods that remove GHGs from the atmosphere, and store (for thousands to millions of years) or use them (at sufficient scale and as part of a circular economy) are described as achieving 'negative emissions'.[4]

The aim of the roundtable was to discuss the science that would enable breakthroughs to meet the scale of the removal challenge, the research needed, the cooperation and investment required to deliver the means to the essential end—a liveable and more sustainable planet.

Professor Chennupati Jagadish, President of the Australian Academy of Science, chaired the online invitation-only roundtable. Participants joined from across Australia and comprised of experts in GHG removal, storage and use, climate and environmental science, climate policy and governance and innovation policy.

Participants identified a range of novel approaches across capture, storage, utilisation and monitoring. These are new areas of research that could prove fruitful, but are currently not a core part of the negative emissions discussion. Some of the approaches discussed included directly splitting carbon dioxide into elemental carbon, ocean alkalinity enhancement, and using zeolite to capture methane. Novelty also included using existing technologies in new ways.

Critical principles that new approaches should meet were also identified. Their impact should be measurable, scalable, affordable and permanent. They should provide social, economic and environmental co-benefits, and limit externalities and future risk. A wide range of options should be explored as part of a portfolio of solutions. New approaches should be adopted where they best suit specific social, environmental, economic and political contexts.

The roundtable identified the following opportunities:

1. **Research: coherence and focus in Australia's research effort**
    - Establish a means to foster interdisciplinary research and collaborative networks.
    - Invest in human capital, especially young researchers.
    - Improve data and knowledge sharing between research, government and industry.
    - Examine the societal aspects of negative emissions development and implementation.
    - Develop a comprehensive understanding of climate change impacts and adaptation on GHG removal capability.
    - Establish a collective voice and a common terminology to facilitate clear and productive discussion.
2. **Society**
    - Engage early and continuously with policymakers and communities, especially First Nations peoples, to co-design appropriate approaches to negative emissions portfolios.
    - Build community confidence in the benefits and risk management to support GHG removal.
    - Build the social licence for negative emissions activities.
3. **Policy**
    - Improve holistic assessment of the benefits, risks and limitations of removal of CO_2 (and other GHGs), storage and uses to inform policy development.
    - Create the innovation and regulatory environment to accelerate the development of new approaches, and to attract private sector investment.
    - Build vital strategic coordination and connection between knowledge generation and policy development.

The Australian Academy of Science will produce a full report on the outcomes of the roundtable, to be released later this year. The report will offer guidance to the Australian research community, private sector, and governments on opportunities for development of negative emissions in Australia.

AUSTRALIA'S RESEARCH STRENGTHS AND COMPARATIVE ADVANTAGES IN NEGATIVE EMISSIONS

Australia has strengths and comparative advantages that could make it an international leader in negative emissions. Roundtable participants identified that Australia has the following comparative advantages:

- World leading renewable energy potential and a wealth of critical minerals. GHG removal approaches can have high renewable energy demands.

- An abundance of land and ocean for testing and deployment of GHG removal and storage approaches, however further research is needed to understand the amount of available space.

Australia could also leverage the following strengths for development of negative emissions:

- A sophisticated legal and political system and institutional landscape with the capability to incentivise development and deployment, and to manage trade-offs.
- Experience sharing data publicly to attract investment, for example collecting and sharing pre-competitive geological information.
- World leading researchers with strong linkages with the international research community.

WHAT IS GREENHOUSE GAS REMOVAL?

Participants discussed the issue of terminology. The field has many overlapping terms that are used inconsistently. While a single clear solution was out of the scope of the roundtable, participants raised the need for a consistent terminological approach when engaging with stakeholders to enhance clarity and accelerate adoption.

Carbon dioxide removal (CDR) refers to the process of removing carbon dioxide from the atmosphere.[4] The term 'greenhouse gas removal' is a term more commonly used in the UK and Europe and includes other greenhouse gases such as methane.

APPENDIX 2: ROUNDTABLE AGENDA

Time	Agenda item	Presenter
10.00	Welcome **Acknowledgement of Country and Welcome address**	Professor Chennupati Jagadish
10.15	Session 1 **Ecological impacts of CDR** Presentation—Dr Pep Canadell	Professor Chennupati Jagadish Dr Pep Canadell
10.45	Session 2 **Novel negative emissions approaches** Presentation—Dr Andrew Lenton	Professor Chennupati Jagadish Dr Andrew Lenton
11.35 – 11.45	Break (10 min)	
11.45	Session 3 **Australia's research strengths and comparative advantages for negative emissions solutions**	Professor Chennupati Jagadish
12.15	Session 4 **Science capabilities, research, investment and opportunities for cooperation to deliver breakthroughs in negative emissions**	Professor Chennupati Jagadish
13.00 – 13.30	Lunch break (30 min)	
13.30	Session 5 **Common terminology** Introduction—Professor Deanna D'Alessandro	Professor Chennupati Jagadish Professor Deanna D'Alessandro
13.45	Session 6 **Novel negative emissions opportunities for Australia** Discuss key takeaways and opportunities identified in the discussion for the statement summarising the outcomes of the roundtable	Professor Chennupati Jagadish
14.25	Conclusion and next steps	Professor Chennupati Jagadish
14.30	Roundtable concludes	

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