CLIMATE CHANGE AUTHORITY

2024 ISSUES PAPER

TARGETS, PATHWAYS and PROGRESS

The Climate Change Authority recognises the First Nations people of this land and their ongoing connection to Culture and Country. We acknowledge First Nations people as the Traditional Owners, Custodians and Lore Keepers of the world's oldest living cultures, and pay our respects to their Elders.

Accessibility

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IMPORTANT NOTICE – PLEASE READ

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About this paper

Later this year the Climate Change Authority will provide a series of reports to the Australian Government on Australia's emissions reduction targets and the transition to a net zero economy.

In August, the authority will submit its review of the *potential technology transition and emission pathways* that best support Australia's transition to net zero emissions by 2050 – for electricity and energy, transport, industry and waste, agriculture and land, resources, and the built environment. This review will inform the development of the government's Net Zero by 2050 Plan and provide valuable information for the authority's advice on Australia's 2035 emissions reduction targets.

The authority expects to provide its advice on Australia's *2035 emissions reduction targets* in October. This is to inform the government's decision on targets to be included in Australia's next Nationally Determined Contribution (NDC) under the Paris Agreement.

The authority will also provide later this year its advice on Australia's progress towards its 2030 emissions reduction targets, in the form of the 2024 Annual Progress Report, to inform the Minister's annual climate change statement.

Figure 1 below sets out the sequencing of the authority's consultation program in 2024.

This issues paper presents our approach, direction, and latest thinking on our work for your consideration and feedback.

Figure 1: Climate Change Authority consultation program for 2024

We want to hear from you

We are grateful to the individuals and organisations who contribute their time and expertise to the authority's work, including those who provided submissions and participated in consultation in 2023. Your input in response to our 2023 *Issues Paper: Setting, tracking and achieving Australia's emissions reduction targets* and *Economic Modelling Consultation* will continue to inform our analysis and advice on sectoral pathways and emissions reduction targets.

The authority's work is progressing at pace. This issues paper presents our current thinking and invites you to provide your feedback and input.

We welcome submissions responding to specific questions and those responding to the broader issues we seek to address. We also welcome responses that draw on or point to submissions to other consultation processes, highlight research and data we may not be aware of, and those that share personal perspectives and experiences with climate change.

You can make a submission via our *Consultation Hub* until 17:00 AEST, 14 May 2024.

Summary

The *Targets, Pathways and Progress* paper sets out the authority's initial considerations in making recommendations to the government on 2035 emissions reductions targets that are ambitious and achievable.

This includes the global context for Australia's climate action, economic and wellbeing considerations, and the authority's initial analysis of emissions reductions technologies that will likely determine Australia's success—together with the decisions and actions of governments, businesses, investors, communities and individuals.

In signing the Paris Agreement, Australia committed to doing its part to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. The authority considers that an ambitious, science-aligned target for Australia should focus on the 1.5°C degree goal.

An ambitious target is also one that contributes to growing international momentum. In developing its advice on Australia's 2035 targets, the authority is considering ambition in other countries. This is because Australia can both be impacted by and can influence other countries' targets.

Australia has an export-based economy, so decisions taken by others in our export markets will reverberate along global supply chains right back to jobs and growth in the Australian economy. If other countries set strong targets, green economy exports can be expected to prosper, while emissions-intensive export industries may falter. If Australia's targets are much stronger than our competitors, companies could be expected to move offshore in the absence of new measures to address carbon leakage, with adverse impacts on the Australian economy and the global environment.

The evidence the authority has considered so far suggests a 2035 target in the range of 65-75% below 2005 levels would be ambitious, and could be achievable and sustainable if additional action is taken by governments, business, investors and households to achieve it. However, attempting to go much faster could risk significant levels of economic and social disruption and put progress at risk.

In its Sectoral Pathways Review**,** the authority will identify the technologies, including operational changes, in each sector that best support Australia's orderly transition to net zero. Planning the pathways and sharing the benefits and burdens will be essential to achieving an orderly transition.

As part of its review, the authority is examining the barriers that might stand in the way of realising the potential contribution of different technologies and what can be done to overcome those barriers. The authority will also consider the interdependencies between sectors.

To assist the formulation of its final advice and recommendations, the authority is seeking views and actionable suggestions in response to the following questions.

Questions

1. How should the authority take account of climate science and Australia's international obligations in considering possible emissions reductions targets for 2035?
2. How should the authority weight the goals of ambition and achievability in considering possible emissions reductions targets for 2035?
3. How can Australia further support other countries to decarbonise and develop sustainably?
4. What technologies are important for each sector's pathway to net zero and why?
5. How can governments use mandates, rules, and standards to accelerate Australia's decarbonisation? Is more planning by governments needed? If so, how should this be coordinated and how can this be done while making the transition inclusive, adaptive, and innovative?
6. How can governments stimulate private finance needed for the net zero transition – are there innovative instruments that could be deployed or new business models that governments could support? Is there a bigger role for governments to play in coordinating the investment needed to transition the economy?
7. How can governments better support markets, including carbon markets, to deliver emissions reduction outcomes?
8. What further actions can be taken by governments (e.g. through public funding), the private sector and households to accelerate emissions reductions, including in relation to the deployment of technologies and access to new opportunities in the transition to net zero? What barriers stand in the way and how could they be overcome?
9. How should governments decide upon the appropriate allocation of resources towards reducing emissions, removing carbon from the atmosphere, and adapting to climate change impacts?
10. How can governments, businesses and people, including First Nations people, help ensure the benefits and burdens of the net zero transition are equitably shared?
11. How can governments better ensure First Nations people are empowered to play a leading role in the development and implementation of climate change policies and actions, including as they relate to the ongoing curation of the Indigenous estate?
12. How can Australian governments support the wellbeing of workers, communities and regions as the nation decarbonises, including in relation to cost of living, workforce and industry transition and access to low emissions technologies and services?
13. How can governments help Australians prepare for and respond to the impacts of climate change?
14. What else should the authority be considering in its advice to government?

Introduction

Global temperature records are tumbling, with 2023 the warmest year on record in a series of warming decades, each warmer than the last (WMO 2023). These climate trends are also reflected in Australia, with trends of declining rainfall in southeastern and southwestern Australia, an increase in extreme fire weather and longer fire seasons, higher sea surface temperatures, rising sea levels and increasing ocean acidification. More frequent, short-duration heavy rainfall events are also occurring (Bureau of Meteorology and CSIRO 2022).

This is what approaching 1.5°C of global warming looks like—consider what a 2.9°C rise in global average temperature could mean. That is the future we can expect by the end of the century based on countries' current Paris Agreement pledges, according to the United Nations Environment Programme (UNEP 2023). A temperature rise of this magnitude – 2.9°C – would present severe risks to Australia's economic, social and environmental life (Australian Academy of Science 2021; Lawrence et al. 2022), not only because of the direct impacts on Australia but also the impacts on the global community of which we are a part.

The clear and unambiguous link between greenhouse gas emissions and warming means strong global action is critical to reduce emissions and limit warming. The same global action to reduce emissions can also ensure a cleaner and fairer future. Think new jobs in green industries and flow-on benefits to regional communities. Think energy efficiency improvements contributing to lower energy bills. Think cleaner air, as experienced in places when there were fewer cars on the road during the COVID lockdowns.

Australia stands to prosper in a world with lower emissions. This sun-drenched, windswept land has the potential to generate large amounts of renewable energy. An abundance of clean energy and critical minerals, combined with a skilled, highly educated workforce, innovative companies and strong institutions, will give Australia advantages in the global low-emissions economy and offset the loss of jobs and international competitiveness associated with a progressive decline in fossil fuel exports. Australia could become a hub for low- and zero-emissions manufacturing and processing, and there may be long-term potential for Australia to offer sequestration of carbon emissions captured overseas, further supporting global decarbonisation efforts (CCA 2023a).

But it's not going to be easy. Australia needs to carefully manage the inevitable transformation of highly emissions-intensive industries, a transition already underway in some areas such as coal-fired power generation. There are difficult decisions to be made about the allocation of resources like land and water, and there will be barriers to overcome on the way. Overcoming the 'green premium' (i.e., the additional cost of choosing a clean technology over one that emits more greenhouse gases), the skills gap, supply chain constraints and gaining a social licence to operate will not always be easy.

Planning the pathways and sharing the benefits and burdens will be essential to achieving an orderly transition.

In what follows, you can read about how the Climate Change Authority is preparing to recommend targets that are ambitious, achievable, and would be advantageous to Australia and Australians.

Setting targets under the Paris Agreement

Australia is one of the 194 nation states, plus the European Union, that are Parties to the Paris Agreement—the legally binding international treaty on climate change. Parties to the Paris Agreement are required to submit NDCs, which outline their individual commitments to combat climate change, including targets for reducing greenhouse gas emissions, along with details on the policies, measures, and strategies they will implement to achieve these targets.

The Paris Agreement requires that each Party's successive NDC represents a progression beyond the Party's then current NDC and reflects its highest possible ambition.

In the current cycle of the Paris Agreement, Parties are required to submit new NDCs to the United Nations by early 2025.

The *Climate Change Act 2022* sets out the authority's role in providing advice to the Minister on the greenhouse gas emissions reduction targets the authority considers should be included in a new NDC. The Act requires that the authority provide advice on:

- the social, employment and economic benefits of any new or adjusted greenhouse gas emissions reduction targets and associated policies, including for rural and regional Australia; and
- the physical impacts of climate change on Australia, including on rural and regional Australia.

The authority's advice must also include an explanation of how the greenhouse gas emissions reductions targets have taken into account the matters set out in Article 2 of the Paris Agreement. Article 2 sets out the aims of the Paris Agreement with respect to strengthening the global response to climate change, in the context of sustainable development and efforts to eradicate poverty, including by:

- holding the increase in the global average temperature to well below 2°C above pre-industrial levels; and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels;
- increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production; and
- making finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development.

Article 2 also provides that the Paris Agreement will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances.

Ambition and achievability

In approaching the task of advising on emissions reduction targets and sectoral pathways, the authority is considering both ambition and achievability. Setting achievable targets while maintaining a high level of ambition is crucial for driving meaningful progress towards deep and sustained emissions reductions over time.

As noted above, the Paris Agreement calls for countries' NDCs to reflect 'their highest possible ambition' (UNFCCC 2015). This recognises the urgency and criticality of an effective global response to climate change, and the inherent uncertainty surrounding the question of whether a given level of global action will avert its worst impacts (Australian Academy of Science 2021).

Ambitious goals catalyse transformative action – consider President Kennedy's 1961 declaration that the United States would land an astronaut on the moon by the end of that decade. The Apollo program not only achieved that objective but led to advances with broader applications in several fields including science, engineering, computing and materials science (Jet Propulsion Laboratory 2016). Accelerating action to reduce emissions can create virtuous cycles of learning and improvement, leading to rapidly falling costs, as has been experienced in relation to the deployment of renewable energy technologies (Way et al. 2022).

Overly conservative targets or approaches that are limited to incremental change may fail to adequately address the systemic changes required for success, and may perpetuate a sense of inertia—delaying the implementation of more ambitious measures that could lead to greater long-term benefits.

However, setting overly ambitious targets without realistic pathways to achieving them can undermine the credibility of policy efforts, creating scepticism and eroding trust in the efficacy of climate change policy initiatives. Failure to meet overly ambitious targets runs the risk of disillusionment and defeatism, hindering future efforts to mobilise support for and to implement climate action.

The authority acknowledges that people will hold different views on what amounts to 'ambitious' and 'achievable' targets. In developing its advice on emissions reduction targets and pathways that are ambitious and achievable, the authority is carefully considering scientific evidence, technological feasibility, economic implications and social acceptance. In its final advice, the authority will be aiming to push the boundaries of what is currently deemed possible while providing a clear roadmap for implementation.

The authority will recommend a target that is **ambitious**

An ambitious target is one that aligns with limiting warming to 1.5°C

In signing the Paris Agreement, Australia committed to doing its part to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels. The authority considers that an ambitious target for Australia should focus on the 1.5°C goal.

Limiting global warming to 1.5°C is in Australia's best interests. Australia is already feeling the effects of a changing climate. For example, heat waves have contributed to many hospitalisations and deaths in Australia (Varghese et al. 2020; AIHW 2023) and are projected to continue to become more frequent and intense under further warming. The differences between 1.5°C and 2°C of warming are also likely to be significant for preserving biodiversity (Smith et al. 2018; Hoegh-Guldberg et al. 2019; Warren et al. 2018). Rising temperatures also present significant economic challenges, with impacts in areas such as labour productivity, agricultural crop yields, tourism, and the costs of increasingly frequent and severe natural disasters. The extent of economic disruption will increase significantly with greater temperature increases (Treasury 2023a).

However, Australia can't achieve 1.5 degrees alone. Internationally, through the first global stocktake in 2023, Parties to the Paris Agreement – including Australia – recognised 'the need for deep, rapid and sustained reductions in greenhouse gas emissions in line with 1.5°C pathways' (UNFCCC 2023). This reflects the scientific understanding that more significant climate change impacts are likely even as we move beyond 1.5°C of global average temperature increase towards a 2°C outcome.

Box 1 – Is 1.5°C still alive?

In the latter half of 2023, close to half the days were observed to have mean global surface air temperature in excess of 1.5°C above the pre-industrial (1850-1900) baseline (Copernicus 2024). But the climate is more than a single day, month or even year.

Global average temperatures go up and down naturally. When looking at climate change, scientists typically average data over several decades to account for year-to-year variability. For example, the IPCC defines the 1.5°C threshold as the midpoint of the first 20-year period during which surface air temperatures reach 1.5°C of global warming on average (IPCC 2021).

If the 1.5°C threshold is breached, reducing emissions as much as possible, as fast as possible, will be just as important as it is now. And removing emissions already in the atmosphere and responding to the impacts of climate change will be even more so.

Every increment matters. Exceeding 1.5°C would bring greater risks and impacts, and exceeding 1.6°C would add to those.

An ambitious target is one that is science-aligned

Since 2010, Australia's emissions have declined by 11 Mt CO_2-e per year, on average. This needs to increase to 16 Mt CO_2-e per year on average if Australia is to meet its 2030 target. If Australia achieves the 2030 target and emissions continue to decline at the same rate for another five years, emissions would be 56% below 2005 levels in 2035 (Figure 2).

The Intergovernmental Panel on Climate Change (IPCC 2022) found that limiting global warming to 1.5°C (50% probability) with no or limited overshoot[1] would require deep, rapid and sustained reductions, including:

- global greenhouse gas emissions reductions of 43% from the 2019 level by 2030
- global greenhouse gas emissions reductions of 60% from the 2019 level by 2035
- reaching net zero carbon dioxide emissions around 2050.

What does this mean in the Australian context? Australia has chosen 2005 as the base year when setting targets in its NDCs, as many other countries have done. In Australia, achieving emissions reductions of 60% from the 2019 level by 2035 translates to a target of 67% below 2005 levels.

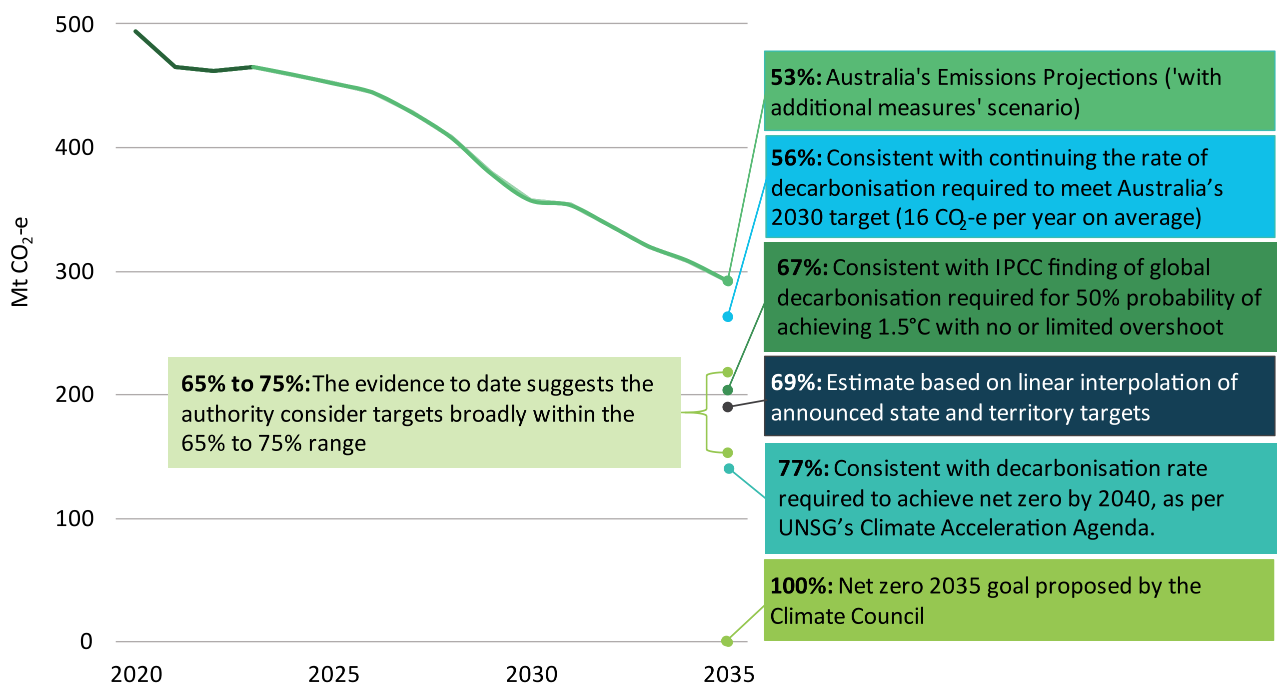
The United Nations Secretary General's Climate Acceleration Agenda (UN 2023) suggests developed countries should, among other things, reduce emissions to net zero by 2040. For Australia to achieve net zero by 2040, it would need to realise average yearly emissions reductions from now until then of 27 Mt CO_2-e per year. Based on a straight-line trajectory from current emissions, this would imply emissions reductions for Australia of 77% on 2005 levels in 2035.

Some studies suggest that Australia should adopt an even more ambitious target, based on various approaches for calculating countries' emissions budgets as a share of the global budget. For example, Meinshausen and Nicholls (2023) found that a 1.5°C-consistent pathway for Australia requires at least a 67% reduction relative to 2005 levels by 2030 and net zero by 2038 based on an approach to calculating Australia's fair share of the remaining emissions budget. In another example, the Climate Council (2021) took account of carbon cycle feedbacks and recommended achieving net zero by 2035, based on an emissions budget for a 67% probability of holding warming below 1.8°C.

The authority's preliminary view is that while Australia should strive to reduce emissions as quickly as possible, going too fast would risk significant levels of economic and social disruption. The authority will continue to provide advice on how Australia can decarbonise in an orderly and sustainable way, in accordance with its statutory principles and functions.

[1] 'Overshoot scenarios' are those in which specific warming levels are exceeded before returning to the given level. Some scenarios simulated for the 1.5°C global warming level entail overshoot. These scenarios need to take account of the physical impacts of overshooting and uncertainties around the efficacy of removals as a means to return from overshooting.

Figure 2: Considering possible 2035 emissions reduction targets



Sources: Historical data (dark green line) and emissions projections (light green line) are from the 2023 Emissions Projections (DCCEEW 2023a). Percentage reductions on 2005 levels in 2035 are based on CCA analysis. Climate Council 2035 goal from Seize the decade: How we empower Australian communities and cut climate pollution 75% by 2030 (Climate Council 2023a)

An ambitious target is one that contributes to growing international momentum

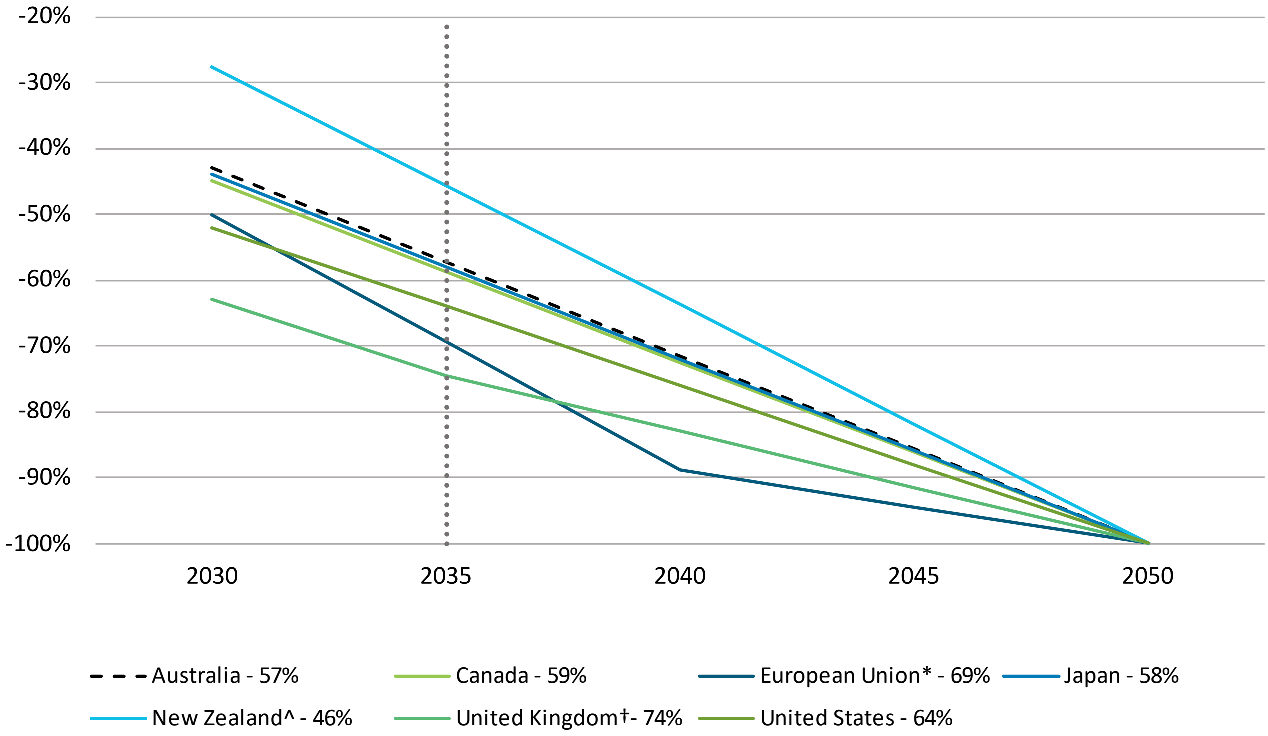
In developing its advice on Australia's 2035 targets, the authority is considering ambition in other countries. This is because Australia can both be impacted by and can influence other countries' targets. Australia has an export-based economy, so decisions taken by others in our export markets will reverberate along global supply chains right back to jobs and growth in the Australian economy. If other countries set strong targets, green economy exports can be expected to prosper, while emissions-intensive export industries may falter. If Australia's targets are too much stronger than our competitors, companies could be expected to move offshore, with adverse impacts on the Australian economy and the global environment.

By committing to a target aligned with the likely ambition of other developed countries, Australia can contribute to growing international momentum. The Paris Agreement is designed to create a race-to-the-top by obliging countries to successively pledge more ambitious targets at least every five years, taking account of a global stocktake of countries' collective progress towards meeting the global goals.

Although Parties to the Paris Agreement must submit a new NDC by early 2025, few have yet done so. For the purposes of developing its advice, the authority is using countries' 2030 and net zero targets, which allow a straight-line approximation of currently committed trajectories. Proposals for interim targets put forward by relevant advisory bodies have been used for the European Union and United Kingdom. Figure 3 shows how a sample of countries' trajectories compare with Australia's current targets and where they would be in 2035.

The authority will continue to monitor developments in international climate change policy and emissions reduction target setting, including to consider the implications for Australia of either an accelerating or a weakening of international ambition.

Figure 3: An approximation of countries' 2035 emissions reductions relative to 2005 levels, based on straight line trajectories from 2030 targets to net zero in 2050



Note: *Emissions reductions are relative to 2005 levels. While it is unlikely countries would set a straight-line trajectory to 2050, this provides a proxy for what the relative ambition for each country might be in 2035 ahead of formal commitments being made and assuming 2030 targets are met.*

**The European Commission has proposed a 90% net GHG emissions reduction compared to 1990 levels as the recommended target for 2040. Endorsement of a target will occur later in 2024.*
^New Zealand's NDC to reduce net greenhouse gas emissions to 50% below gross 2005 levels by 2030 differs from many other national targets which are net emissions reductions below net baseline levels. Rebased to net 2005 levels, New Zealand's target is a reduction of 28% by 2030. Source: CCA Analysis, 2024 adapted from DCCEEW 2023a; European Union, 2024; UNFCCC, n.d.a; UNFCCC, n.d.b.
†The United Kingdom legislated the sixth carbon budget (CB6) in June 2021, limiting the volume of greenhouse gases emitted from 2033 to 2037. CB6 reduces emissions by approximately 78% by 2035 compared to 1990 levels. The UK has not put this forward as its 2035 NDC.

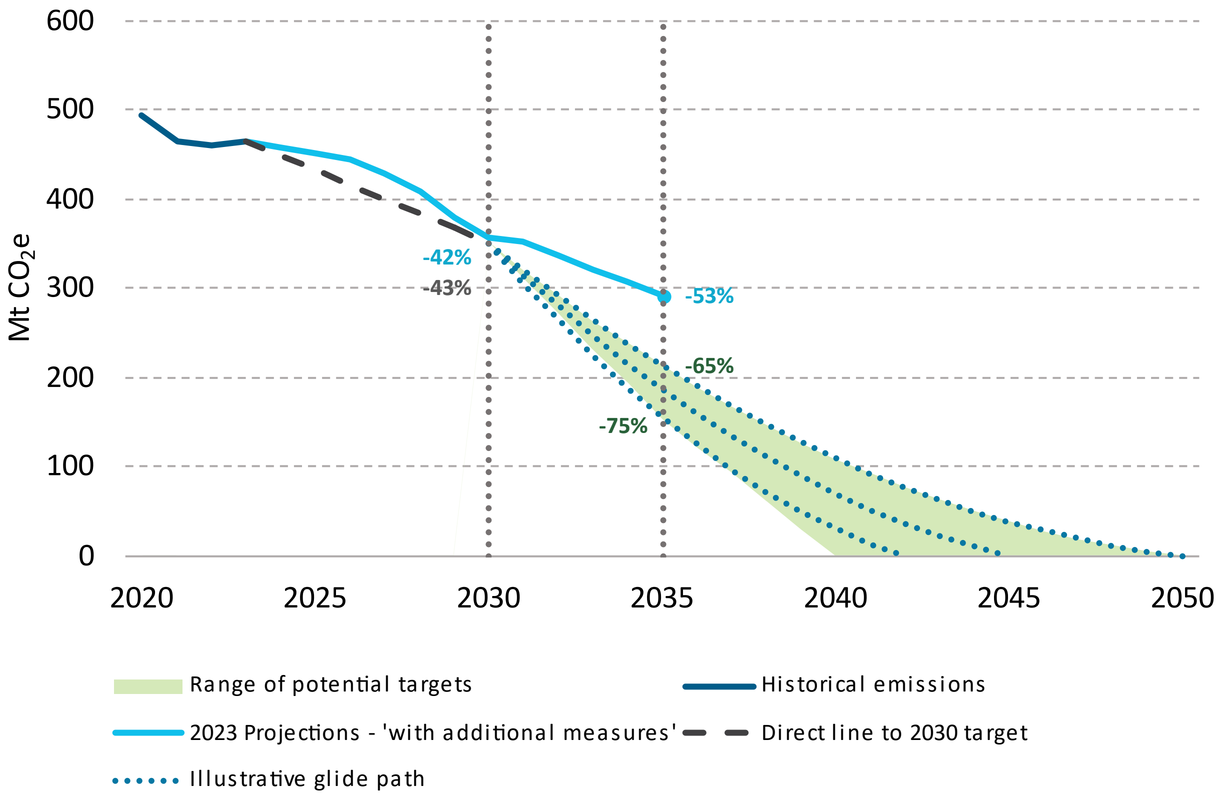
An ambitious target is one with strong roots to grow from

Despite some global and domestic momentum in recent years, the scale of technological and behavioural changes required indicate that achieving a target more ambitious than a 75% reduction by 2035, as well as net zero before 2040, would require significant and costly economic and social upheaval.

At the heart of the challenge, emissions-intensive sectors cannot just 'flick a switch' to decarbonise. There are not yet *readily available* low- or zero-emissions alternatives for products like steel, cement and fertilisers, whether for reasons of cost, technical challenges or other reasons. Emissions reduction options for some sectors are limited and their decarbonisation pathways require development of new technologies and behavioural changes over the coming decades. Alignment of technology availability with the multi-decade investment cycles common across these emission-intensive sectors will be important to reduce the risk of offshoring production, closure of facilities, or locking in emissions. An orderly transition requires nationally led planning, coordination, and commitment, with the broad buy-in and support of those affected by the change.

Achieving a target in the range of 65-75% below 2005 levels would require a significant acceleration in efforts to reduce emissions in Australia. Figure 4 illustrates the scale of the step-up from Australia's projected trajectory to 2035 and a target in the 65-75% range. This figure presents illustrative 'glide paths', representing Australia's possible emissions pathways to net zero, which are under investigation by the authority for its Sectoral Pathways Review.

Figure 4: Australia's emission: 2023 Projections and glide paths to net zero



Note: *Source: 2023 Projections (DCCEEW (2023a) and CCA analysis)*

To achieve emissions reductions of 65-75% below 2005 levels by 2035, Australia would need to reduce emissions by 27-39 Mt CO_2-e each year, on average, from 2031 to 2035. These figures assume Australia achieves its existing 2030 target of a 43% reduction in emissions below 2005 levels. This 27-39 Mt CO_2-e/year rate of reduction is a significant increase from the average yearly reduction of 16 Mt CO_2-e currently required to meet Australia's 2030 target.

To give a sense of the scale of such a task, Australia's five highest emitting industrial facilities in 2021-22[2] emitted 32 Mt CO_2-e in aggregate (CER 2023) and Victorian brown coal generators emitted 37 Mt CO_2-e in total in 2022-23 (CER 2024a). Australia does not need to address all the emissions in any given sector at once. Progress will need to be made by reducing emissions across all the sectors of the economy, recognising that the scale and pace of emissions reductions will vary.

Achieving an ambitious target in this range could be possible if additional action is taken by governments, business, investors and households. It would require accelerating deployment of the necessary and available technologies, discussed further in the following pages. This would in turn require increased levels of strategic planning, coordinated decision-making and policy interventions by governments, as well as consumers, business and investors all playing their part.

The authority is interested in people's views on the extent and forms of government intervention (e.g., regulatory, fiscal, market-based and informational) needed to support the achievement of

[2] Four LNG projects and one steelmaking facility.

Australia's targets. With the right mix of policies in place, Australia could ratchet up its emissions reduction ambition over time on the pathway to net zero emissions.

In preparing its final advice, the authority will undertake further analysis, incorporating the economy-wide and sectoral modelling it has commissioned (see Appendix 1) and the responses to this paper, and draw on the results of the extensive consultation currently underway.

An ambitious NDC is one that supports emissions reductions beyond domestic borders

Under the Paris Agreement, countries measure, report and commit to reducing the greenhouse gas emissions that occur within their own borders. In this way, countries take responsibility for their own environmental impact while promoting equitable and sustainable development globally. The authority's recommendations for Australia's next NDC will be consistent with this approach.

The authority will recommend a domestic emissions reduction target as the centrepiece of Australia's NDC. The authority will also advise how Australia's other activities contribute to the goals of the Paris Agreement. Examples already underway include support for global financial flows through mechanisms like the recently announced $2 billion Southeast Asia Investment Financing Facility, to support clean energy and infrastructure projects in this region (PM&C 2024), and bilateral agreements such as the $30 million partnership with Singapore to accelerate the development and deployment of low emissions fuels (DCCEEW 2023c). The potential for a significant change in Australia's role as an exporter is perhaps most important.

Australia's contributions to global emissions as an exporter are likely to change dramatically as the world decarbonises. This is because demand for Australia's clean energy, critical minerals, green products and sequestration potential are likely to increase at the same time demand for fossil fuels declines. The cost and pace of global decarbonisation is likely to benefit from Australian exports of clean energy and minerals, and chemicals and other products made with clean energy, given that our large clean energy resource base, endowment of minerals and small population makes us particularly well suited to the export role.

At present, the emissions overseas from use of Australia's coal and gas exports are more than double the amount generated by Australia's entire economy (Table 1). However, the International Energy Agency's modelling of a 1.5°C-aligned energy system in its net zero scenario shows demand for fossil fuels needs to drop quickly (IEA 2023a). It finds 'no new long-lead time upstream oil and gas projects are needed in the NZE Scenario, neither are new coal mines, mine extensions or new unabated coal plants. Nonetheless, continued investment is required in existing oil and gas assets and already approved projects.' The IEA observes that if 'current energy sector assets were to be operated until the end of their normal technical and economic lifetimes, and in the same manner in which they have been operated, they would generate further cumulative emissions…far more than the remaining CO_2 budget to remain below 1.5ºC' (IEA 2023a).

Table 1: Australia's domestic emissions and exported coal and gas emissions

	Mt CO_2-e (2022)	% of global emissions (2022)
Australia's net domestic emissions	461.5	0.86
Emissions from combustion of Australia's exported LNG and black coal	1106.6	2.06

Sources: *CCA analysis based on DISR 2023; DCCEEW 2022a; DCCEEW 2022b DCCEEW 2023d; Crippa et al. 2023.*

A central takeaway from the authority's 2023 consultation was a call for a phase out of fossil fuels, including exports. Australia's fossil fuel industry is currently a significant part of the country's economy (see Table 2) and has provided energy security for and supported the development of trading partners. Transitioning to clean energy exports, and exports of low emissions intensity products produced using clean energy, can support our trading partners' emissions reduction efforts and help ensure Australia continues to prosper as global demand for high emissions products declines. Consultation respondents noted that Australia is well placed to benefit from green exports and should work proactively with trade partners to develop clean energy supply chains.

Table 2: Australia's coal and gas exports

	Metallurgical coal	Thermal coal	LNG
Global export rank (2023)	1	2	2^
Amount exported (2022-2023) (Mt)	156	182	82
Export nominal value (2022-2023) (A$ billion)	61.9	65.6	92.2

Source*: DISR 2024, tables 5.1, 5.2, 6.1, 6.2, 7.1. ^Note: Australia and Qatar both exported 20% of global LNG exports in 2023.*

Through initiatives such as the National Hydrogen Strategy, the Critical Minerals Strategy, and the National Reconstruction Fund, the Australian Government is supporting Australian industry to take advantage of growing global demand for products needed for the net zero transition, such as critical minerals, green metals and renewable energy. By exporting low emissions products, Australia can contribute to the goals of the Paris Agreement by supporting other countries to decarbonise. Such contributions are not counted towards Australia's emissions reduction targets and could, in fact, lead to higher domestic emissions. For example, increased mining of critical minerals would contribute to a reduction in global emissions but would likely add to Australia's emissions due to the emissions that continue to be associated with such mining activity.

For Australia to continue to prosper in a decarbonising world, it will need to work with trade partners to develop and supply clean energy, critical minerals and low and zero emissions products. An orderly, global phase out of fossil fuel supply chains will require international coordination and active management of supply chain closures or refurbishments, and support from mechanisms such as carbon border adjustments. And governments in Australia will need to consider that the domestic and export net zero transitions are tightly coupled in that they will share supply chains and production systems, and potentially compete for resources (such as public funds, access to electricity supply and land access).

The authority acknowledges the work currently underway to prepare Australia for these challenges, including establishment of the Net Zero Economy Authority and the Carbon Leakage Review. Although beyond the scope of its work program in 2024, the authority observes the ongoing need for analysis and advice and stands ready to contribute further in 2025.

Emissions from international aviation and shipping are not counted in national greenhouse gas inventories, so do not contribute to national targets. Those emissions fall under the auspices of the International Civil Aviation Organisation and International Maritime Organisation. Some countries are taking greater account of their international transport emissions alongside their domestic targets. While these emissions do not factor into Australia's target setting directly, the actions that need to be taken in Australia towards reducing these emissions will add to the demand for resources, such as land and feedstock required to produce alternative liquid fuels.

The authority will recommend a target that is **achievable**

An achievable target is one that every sector can contribute to meeting

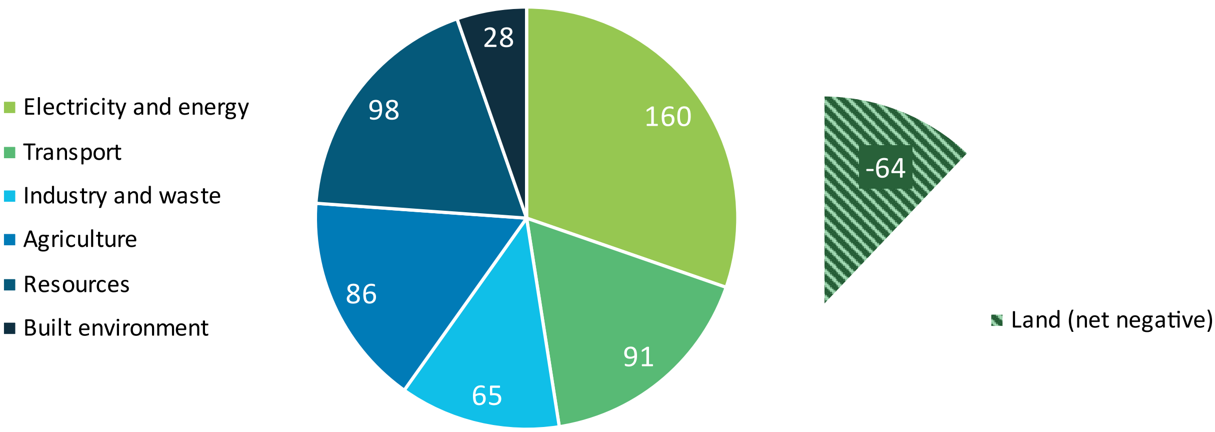
Each sector can support Australia's transition in various and significant ways that must work together for Australia to achieve net zero. For example, the transport sector will rely on the electricity sector to deliver clean energy to charge electric vehicles.

While some sectors have very hard-to-abate emissions and may be unable to achieve net zero, the land sector already achieves net negative emissions by removing carbon from the atmosphere. For Australia to achieve net zero emissions economy-wide, any residual emissions remaining in a sector will need to be offset by the removal of carbon from the atmosphere – likely in another sector – or accessing international carbon markets under the Paris Agreement, discussed further below.

For the most efficient and sustainable transition across all sectors, Australia will need to work towards a circular economy. The authority's analysis of the circular economy will consider how Australia can reduce the need for virgin resource extraction and production from both the supply and demand perspectives. It is closely related to supply chain considerations and development of closed-loop systems.

The below figure outlines how Australia's emissions were distributed among sectors in 2020-21.

Figure 5: Sectoral share of Australia's emissions (Mt CO_2-e), 2020-21



Note: *This chart reflects the authority's interim analysis of 2021 emissions data from the Paris Agreement inventory (DCCEEW 2023e). All emissions in Australia's Paris Agreement inventory (2020-21) are attributed to sector from which they are directly emitted (scope 1). See Appendix 2.*

The authority's Sectoral Pathways Review will identify the technologies, including operational changes, in each sector that best support Australia's transition to net zero based on their readiness, emissions reduction potential and costs.[3]

As part of its review, the authority is examining the barriers that might stand in the way of realising the potential contribution of different technologies and what can be done to overcome those barriers. The authority will also consider the interdependencies between sectors.

[3] More detail on the Australian Parliament's referral of the Sectoral Pathways Review and the authority's approach are available in Appendix 1.

Some of the authority's initial analysis is presented below, with additional details provided in Appendix 3.

The referral for the authority's Sectoral Pathways Review identified six sectors to be analysed. Emissions numbers in this paper include a preliminary allocation of Australia's emissions to those sectors. These allocations will be refined ahead of the finalisation of the authority's Sectoral Pathways Review report.

Electricity and energy

In 2022-23, the electricity sector's economic contribution amounted to a gross value add of $24 billion (rounded and seasonally adjusted) which amounts to 1% of Australia's GDP in 2022-23 (ABS 2023, ABS 2024a). In 2023, the sector accounted for approximately 0.6% of total employment, employing approximately 84,000 people in electricity and gas supply, including 22,000 women (ABS 2024b)[4] and 1,000 First Nations people (ABS 2022).

In 2021, the electricity and energy sector emissions amounted to 160 Mt CO_2-e or 34% of Australia's total emissions. The government's projections indicate that emissions for the electricity sector[5] (which comprises the largest component of the electricity and energy sector) will decline to 81 Mt CO_2-e in 2030 and to 37 Mt CO_2-e in 2035 under a baseline scenario, and to 60 Mt CO_2-e in 2030 and to 32 Mt CO_2-e in 2035 under a scenario with additional policy measures (DCCEEW 2023a).

The challenge ahead lies in deploying the available technologies over the coming decade at the scale and pace required to support the achievement of Australia's current and future emissions reduction targets. Renewable electricity generation will be required to meet new demand in other sectors, such as transport and industry, where electrification can underpin further reductions in emissions, and in emerging industries such as hydrogen and critical minerals.

Technologies

Australia cannot transition without decarbonising and expanding electricity generation to meet other sectors' increasing demand for clean energy. Fortunately, the necessary technologies are available to get most of the way to a fully decarbonised electricity supply—such as wind and solar electricity, battery storage, and pumped hydro—and have proven their ability to achieve significant emissions reductions and cost competitiveness (Appendix 3). Renewables across Australia contributed 30.9% of total electricity generation in 2021-22 (DCCEEW 2023f, table 13), and more recent trends in Australia's largest electricity grid indicates this is continuing to grow, with renewables contributing 42.9% of generation in the NEM in the final quarter of 2023 (AEMO 2024, table 3).

Fully realising the potential of wind and solar depends on investment in supporting infrastructure in the form of transmission and distribution networks and the flexible, dispatchable generation needed to back up a high penetration of renewables. This will include batteries and pumped hydro, complemented with longer duration solutions such as gas-fired power stations and potentially hydrogen in the longer term.

Barriers and enablers

The barriers to accelerated rollout of the necessary technologies include:

- workforce constraints, with the build of new infrastructure projected to create demand for around 48,000 skilled workers by 2025, which will grow to 70,000 by 2044-45 under AEMO's step change scenario (AEMO 2023a)

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[4] Workforce numbers based on annualised four-monthly averages and rounded to '000s.

[5] As defined under Australia's Paris Agreement inventory, please note this is different to the 'electricity and energy' sector defined under this report.

- supply chain constraints, which may harbour temporary but significant risks of higher equipment costs or equipment shortages (AEMO 2023a)
- social licence concerns from communities hosting generation and transmission infrastructure. Social licence will be critical in enabling rollout of these activities and depends on earning and maintaining the trust and acceptance of those groups and communities most affected by impacts (AEMO 2023a)
- grid connection delays and delays through planning and approvals processes for renewable energy projects, with noted variation in approval timeframes across jurisdictions (CCA 2023b).

Certain technologies needed for firming renewable generation face challenges, such as higher upfront costs of longer duration storage options (including 4 to 8 hour batteries or pumped hydro storage). In relation to peaking gas, challenges exist in relation to addressing associated emissions, the availability and cost of natural gas, and financing of gas-fired power stations required to operate for only brief periods.

In addition, as the share of distributed variable wind and solar energy in the electricity system increases, new challenges emerge for maintaining system security—that is, the capacity of the system to continue operating safely should a major, unexpected event happen such as the disconnection of a large generator or transmission link. Traditionally, system security services have been provided by coal- and gas-fired power stations, the large spinning turbines of which create significant inertia in the system and hence resistance to disturbances. Electricity market bodies and transmission network service providers will need to ensure that there are sufficient system security services available as the system transforms to very high levels of renewables.

Australia has existing enablers that place it well to continue decarbonisation of the sector. These include Australia's wind and solar resources (Graham and Havas 2023, p305) and projected declines in capital costs for solar and wind generation technology (CSIRO 2023a).

However, Australia needs to address the above barriers if the electricity and energy sector is going to decarbonise at an even faster pace than has been achieved historically. This includes finding new ways of working collaboratively and respectfully with rural and regional communities; reform, reprioritisation and coordination of planning and approvals processes; capacity and resource building in grid connection services to avoid delays; and for the government to consider policy and funding options for less mature or more expensive firming technologies (such as peaking hydrogen turbines or pumped hydro storage).

Built environment

The authority defines the built environment sector to be composed of residential and commercial buildings as well as physical infrastructure. The sector is a significant part of Australia's economy with the construction industry accounting for 10.8% of GDP (Master Builders Australia 2024) and employing approximately 1,325,000 people, including 175,000 women (ABS 2024b) and approximately 26,000 First Nations people (ABS 2022).

The built environment contributed 28 Mt CO_2-e scope 1 emissions (6%) and an estimated 79 Mt CO_2-e scope 2 emissions to Australia's 2021 emissions (DCCEEW 2023e). Just over half of the scope 1 emissions come from onsite combustion of gas and almost a third from refrigerant gas leaks (DCCEEW 2023e). The built environment has the largest electricity consumption of any sector (ASBEC 2021) and has significant opportunities to improve energy productivity and contribute to grid stability.

Technologies

With millions of individual building owners and millions of buildings, appliances and other assets to upgrade, the built environment faces unique transition challenges. The technologies needed to deliver significant emissions reductions in the built environment are generally available, and in many cases can deliver net financial savings over time, but they may entail high upfront costs for individuals and businesses. The net zero transition in the built environment involves not only relatively simple substitutions (e.g. electric heat pumps for space and water heating) but also the transformation of complex systems (e.g. active participation of building operators in electricity demand management (GBCA 2023). Transforming these systems with low and zero emissions technologies will deliver necessary emissions reductions and can also deliver significant co-benefits to individuals (e.g. more resilient housing), to businesses (e.g. lower energy costs) and systems (e.g. benefits for electricity system operation from grid-integrated buildings).

Priorities for this sector include electrification, energy efficiency, and grid integration. Electrification of homes and commercial buildings involves replacing technologies, processes or products which use fossil fuels with electric equivalents underpinned with renewables. For example, replacing gas water heaters with heat pumps. Actions such as these could abate about 199 Mt CO_2-e to 2050 (ASBEC 2022). Electrification across the sector could save consumers an estimated $50 billion in operating costs to 2050 (ASBEC 2022).

Energy efficiency technologies and activities may involve using current appliances better or upgrading to higher efficiency appliances. Thermal efficiency reduces energy use by reducing the amount of heating or cooling needed to keep a building comfortable, such as by installing insulation. By 2030, through energy efficiency alone existing commercial buildings could cost-effectively reduce their total energy consumption by an average of 34%, saving 340 MJ/m² per building and 40 Petajoules of energy across Australia (Common Capital 2020). These technologies are currently available.

Integrating buildings into the electricity grid and optimising energy consumption can provide critical grid security services as renewable energy penetration increases (GBCA 2023). Load shifting one third of sector demand by three hours per day could reduce Australia's emissions by 0.6% annually (GBCA 2023). Digitalisation could underpin 1 GW of flexible demand capacity (CSIRO 2023b).

Barriers and enablers

Through consultation, the authority has identified a number of barriers to decarbonisation. These include high upfront costs (e.g. electrification and thermal efficiency upgrades, especially to commercial buildings), the absence of a national plan for phasing out gas in buildings, split incentives for owners and tenants in upgrading buildings, future workforce limitations for installation and maintenance of key technologies, challenges and expense of retrofitting existing buildings, challenges with decarbonising refrigerants, and difficulties in implementing digitalisation to improve energy efficiency.

Potential enablers the authority has identified include regulation and mandates (e.g. strengthening building codes), the widespread commercial availability of these technologies, low cost and financial incentives (including subsidies and low-interest loans, as well as payback periods leading to future energy savings and financial benefits), improving information and data (such as cost comparisons) and advances in digitalisation and connectivity (e.g. grid integrated buildings).

Industry and waste

Australia's industry and waste sector generated around 7.1% of gross value add in 2022-23 (ABS 2023, ABS 2024a), produced $14 billion in export revenue in 2022-23 for alumina and aluminium (DISR 2024), and $58 billion for manufactured goods in 2023 (ABS 2024c).

The sector accounts for approximately 8.1% of total employment, employing more than 1,100,000 people, including more than 340,000 women and 14,000 First Nations people (ABS 2024b; ABS 2022).

The sector was responsible for 65 Mt CO_2-e in 2021, which is 14% of national scope 1 emissions (CCA unpublished).

Technologies

A portfolio of solutions is required to decarbonise the industry and waste sector, which comprises many activities with varying process, energy and feedstock requirements. The authority is focusing on technologies to decarbonise the highest emitting subsectors, responsible for over 75% of the sector's emissions:

- Electrification of digestion and electric or hydrogen calcination can reduce up to 98% of alumina refining emissions (ARENA 2022).
- Direct reduction of iron using hydrogen with an electric arc furnace can reduce 95% of emissions from steel production (AIETI 2021).
- Material substitution, electric or hydrogen kilns, and Carbon Capture Utilisation and Storage (CCUS) can reduce emissions from cement by over 80% (IEA 2023b).
- The use of renewable hydrogen as a feedstock or electrified steam methane reforming (SMR) with carbon capture and storage, with an electrified Haber-Bosch process, have the potential to significantly reduce emissions associated with ammonia production. (AIETI 2021, IRENA 2022).
- Based on outcomes in Germany, diversion of organic waste from landfills to composting applications, in conjunction with other existing emissions technologies, can reduce landfill methane emissions by over 90% (German Environment Agency 2023).

Barriers and enablers

Low technology maturity, high costs and nascent markets for low emissions products are the key barriers to uptake of these technologies.

- Technology readiness – Many of the technology solutions to decarbonise the industry sector are not yet mature. Prospective technologies include those to decarbonise high temperature processes, such as alumina calcination and clinker production, and direct reduction of iron using hydrogen. Depending on the readiness of each solution, targeted support is required to advance technology, noting Australia will be a technology leader for some emissions reduction activities and a technology taker for many others.
- Cost – Significant investments are needed to replace or retrofit large industrial assets, power energy intensive processes, and replace high emitting feedstocks. Continued technology advancement will contribute to lower costs, while widespread deployment of renewable energy and investment in shared infrastructure will support access to clean electricity, hydrogen and CCS. It is important investment decisions do not lock in emissions, result in stranded assets or add to the cost of decarbonisation.
- Market – Markets for low emissions products are still developing, lacking depth in demand and supply. Governments can boost demand through their own procurement activity and incentivising shifts in consumer preferences, and encourage supply through support for technology innovation, production and through regulatory and funding measures.
- Electricity and hydrogen – Development and access to key enabling infrastructure such as renewable electricity and hydrogen.

Resources

Australia's resources sector contributes to approximately 13.4% of GDP and accounts for more than two-thirds of Australia's total merchandise exports (DISR 2024).

The sector accounts for approximately 2.1% of total employment, employing more than 299,000 people, including 62,000 women (ABS 2024b) and 9,000 First Nations people (ABS 2022).

The sector was responsible for 98 Mt CO_2-e in 2021, which is 21% of national scope 1 emissions (CCA unpublished).

Technologies

Within the broader resources sector, the authority has focused on the mining, gas processing and liquefied natural gas (LNG) subsectors based on their relatively large emissions footprint, which accounts for approximately 99%[6] of the sector's emissions (CCA unpublished). Key emissions reduction technologies for these subsectors include:

- fuel switching from diesel (for mining haulage and equipment) and natural gas (for the extraction and production of domestic gas and LNG) to lower carbon alternatives, such as renewable electricity or hydrogen
- pre-mining drainage and ventilation air methane (VAM) abatement technologies for fugitive emissions from coal mining
- reservoir CCS and a suite of fugitive abatement measures to reduce venting, flaring and leaks from domestic gas and LNG production.

Barriers and enablers

Barriers to deploying technologies across the resources sector typically include high upfront costs associated with capital expenditure and possible production downtime. Asset replacement cycles are a consideration across subsectors with large, capital intensive assets including haulage fleets in mining and compressors in the gas processing and LNG subsectors. The lack of maturity of some potential technology solutions in terms of meeting safety or operational performance standards is a barrier, such as with coal mine air methane emissions reductions technologies and battery or fuel cell electric haulage in mining.

Enablers to support the deployment of these technologies include:

- targeted efforts to accelerate research and development and demonstration of more prospective technologies
- alignment of financial incentives and business models to support investment into decarbonisation opportunities
- development and access to key enabling infrastructure such as renewable electricity and hydrogen
- policy certainty and supportive regulatory settings (e.g. restrictions on venting and flaring, equipment standards and streamlined environmental approvals).

Transport

The transport sector includes road transportation (cars, light commercial vehicles, heavy duty trucks and buses, motorcycles) and off-road transportation (domestic aviation, domestic shipping, rail). Transport, postal and warehousing amounted to a gross value add of $104 billion (rounded and seasonally adjusted) which amounts to 4.3% of Australia's GDP in 2022-23 (ABS 2023, ABS 2024a). Transport accounts for approximately 4.5% of total employment, employing approximately 634,000 people in 2023, of which 147,000 are women (ABS 2024b) and 9,000 are First Nations people (ABS 2022). This includes aviation which employed around 90,000 prior to COVID-19, contributing $20 billion to the economy (DITRDCA 2023b).

[6] This number includes some emissions from oil extraction and processing operations.

Transport contributed 91 Mt CO_2-e (20%) to Australia's 2021 emissions. Road transport is the largest source of transport emissions (87%) but has relatively mature emissions reductions technology for light vehicles, in the form of electric batteries to replace internal combustion engines. Heavy vehicles and some light vehicles will require a mix of solutions. Non-road transport (rail and domestic aviation and shipping) forms a smaller source of emissions (12%) but emissions reductions opportunities are limited by low energy density, cost and supply outlook challenges associated with the available decarbonisation technologies (see table in Appendix 3).

Technologies

Transitioning the light vehicle fleet to battery electric vehicles offers the most immediate and significant opportunity for reducing transport sector emissions, provided the electrification is sourced from renewables. The use of hydrogen fuel cell vehicles for long haul heavy transport is less developed but also prospective. Hydrogen may also contribute to reducing emissions from non-road transport, although it is likely that other emerging, low emissions alternative liquid fuels like ammonia, methanol and sustainable aviation fuel will need to play a role.[7]

Barriers and enablers

For all technologies, the major barriers are the higher upfront purchase cost or fuel price premiums, and the need for supporting recharging or refuelling infrastructure. Enablers include increasing renewable electricity generation in the grid and co-benefits such as reduced air and noise pollution, and reduced dependency on international fuel supply.

- Battery electric technology barriers include concerns about product life, driving range and recharge time, which can be addressed by ongoing battery research and development. There may be some light vehicles that undertake tasks that battery technology is not suited for and for which alternative solutions may be required.
- Light vehicles have an asset life of 10 to 15 years, meaning net zero emissions by 2050 implies sales must reach 100% zero emissions vehicles by 2035-2040 to account for fleet turnover (AEMO 2023b). Heavy vehicles and rail have longer asset lives and low rates of turnover, requiring even longer lead times for full adoption of technologies by 2050.
- Reforms to width and mass limits will be necessary to enable the greater uptake of low and zero emission trucks in Australia.
- Hydrogen, methanol and ammonia have additional barriers in the form of their cost premiums, reduced energy density compared to conventional fuels, and the long asset lives of associated subsectors (see table in Appendix 3). There is also a need to develop hydrogen storage options. SAF has sustainability and lifecycle emissions concerns but can be enabled by certification schemes. SAF also faces a considerable green premium (the additional cost of SAF relative to conventional jet fuel).
- Mode shifting to active and public transport can be impeded by consumer preferences, safety concerns, weather conditions and fitness of travellers, but can be enabled by well-planned cities and service improvements. Co-benefits include improved health, reduced congestion and increased road safety.

Agriculture and land

The agriculture and land sector is a vital contributor to Australia's economy and food security. Agriculture accounted for 2.4% of Australia's GDP in 2021-22 and farm incomes have been at record highs in recent years (ABARES 2023a). Agriculture accounts for approximately 2.2% of total

[7] Sustainable aviation fuels are derived from a range of feedstocks such as biomass, waste products, natural oils and fats, other carbon sources and hydrogen.

employment, employing 272,500 people, including 90,300 women (ABS 2024b) and approximately 4,300 First Nations people (ABARES 2023b).

This sector provides Australia's food and fibre production, ecosystem health and services, biological carbon storage, natural aesthetic values and cultural values. Agriculture accounts for 55% of Australia's land use (ABARES 2023a) and the Indigenous Estate covers 57% of Australia (ABARES 2020). Balancing demands on Australia's landscapes to maximise positive environmental, social and economic outcomes is key to ensuring a sustainable and equitable transition to net zero emissions.

Agriculture contributed 86 Mt CO_2-e (19%) to Australia's 2021 emissions and land contributed a 67 Mt CO_2-e (14%) sink.

Technologies

There are limited existing solutions to reduce agricultural emissions. The land sector is currently a net sink with significant sequestration potential (CSIRO 2022). Decarbonising the agriculture and land sector will require a suite of technologies and practice changes, including:

- Feed supplements such as *Asparagopsis* and 3-NOP are a prospective emissions reduction technology, but studies have shown variable results and further research is recommended into health, safety and environmental impacts (Wasson et al. 2022). A further challenge arises with a significant proportion of Australia's beef herd raised in northern production areas, where livestock range over an area too large to access controlled feeding.
    - Other technologies such as early life programming, methane vaccines and existing practices such as improved herd management, genetics and pasture improvement will be required to reduce emissions from ruminant animals.
- Nitrification inhibitors from fertilisers can more than halve the emissions from fertiliser use (Grace et al. 2023; Meng, et al, 2021).
- Improving manure management practices can significantly reduce methane and nitrous oxide from decomposition of manure.
- Substitution of fossil fuels with renewable fuels or renewable electricity could also play an important role, however transition costs are currently high and limiting uptake (EY 2021).
- Sequestering carbon in vegetation and soils through avoided land clearing, plantation forestry, revegetation and reforestation provide an opportunity to address climate change and nature repair concurrently.

Barriers and enablers

Costs are a key barrier to adoption of emissions reduction activities in the sector, for example, suitability of land for plantations generally competes directly with highly valuable agriculture land, with the economic benefits from agriculture outstripping economic benefits from plantation forestry. Logistical implementation barriers also exist for multiple technologies, for example, establishment of new plantation forestry activities may be limited by access to suitable land areas and availability of labour, skills and knowledge.

Key enablers include:

- Reduced costs – this may be achieved through targeted policies or mechanisms, and better provision of information for farmers to adopt new ways of working.
- Funding for research and development – this can overcome implementation barriers for technologies such as feed supplements, by quantifying benefits and trade-offs.
- The Australian Carbon Credit Unit scheme – this continues to be an important policy for incentivising the uptake of emissions reduction activities in the sector.
- Other financial incentives or support through public and private finance – this may be needed to achieve emissions reductions in the near term.

First Nations people are custodians of more than half of Australia's land area and play a vital role in ensuring Australia's land is managed sustainably now and into the future. They play a critical role in helping Australia mitigate and adapt to climate change, including through savanna fire management practices across much of northern Australia. Participation of First Nations and non-First Nations land managers in decision-making about land use can help ensure the transition is managed in a way that is both sustainable and equitable. See Appendix 3 for further information.

Land management can support a sustainable transition to net zero emissions and provide social and environmental benefits, including via farming practices that increase the storage of carbon in soils and vegetation, such as low- or no-till cropping. The scope and interest in nature repair and nature positive initiatives are likely to continue to grow in importance for farmers and land managers.

An achievable target is one with residual emissions counterbalanced by removals

It is not yet possible for all necessary economic activities to achieve absolute zero emissions: despite best efforts, some will generate *residual* emissions. Some activities remove carbon from the atmosphere, known as negative emissions or carbon dioxide removal (CDR) activities. Once removed from the atmosphere, carbon can be stored for a limited period in biological form such as forests, or stored durably in geological formations or in long-lived products and used to counterbalance residual emissions.

The authority's Sectoral Pathways Review will investigate the likely sources of residual emissions and the likely amount of carbon removals (negative emissions) available to counterbalance them.

CDR includes conventional land sector removals in biological sinks (e.g. vegetation and soil), most of which occurs in the land sector, and novel engineered removals (e.g. direct air capture (DAC), pyrolysis and mineral carbonation) in geological formations, minerals, char and products. Point capture of emissions, a component of carbon capture and storage, and of carbon capture and utilisation (CCU), is not a carbon removal technology – it captures carbon at the source and prevents emissions entering the atmosphere. However, CDR and CCS use similar technologies and face similar barriers.

The authority is considering land sector and engineered removals, as well as point source capture technologies. The most prospective technologies identified are avoided deforestation, plantation forestry, permanent plantings, point-source carbon capture, DAC powered by renewable energy, biochar and mineral carbonation.

The current global rate of carbon dioxide removal needs to increase several times over to keep the world under warming limits. Modelling by the IPCC found around six billion tonnes of removals per year is needed by 2050 – equivalent to around 10% of global emissions in 2019 (IPCC 2022). Most scenarios that limit warming to 1.5°C require rates of removals that lead to net negative emissions beyond 2050.

Sector pathways and plans can help inform a framework for anticipating future sequestration demand by clarifying the extent to which emissions reductions are expected to be possible.

In addition to whole-of-economy net emissions reduction targets, the authority is considering recommending three complementary types of targets:

- gross emissions reduction targets
- land sector removals targets
- engineered removals targets.

Additional target types enhance transparency about the relative contribution and weight of effort between emissions reductions and removals. Separate targets signal that while Australia is prioritising emissions reductions, public and private finance is needed now to start scaling up removals.

Removals targets are emerging in climate policy discussions and countries' long-term strategies. By incorporating separate targets in its NDC, Australia has an opportunity to restore confidence in its use of land sector abatement and demonstrate its leadership in the growing field of carbon removals, a potential future export industry. Many countries that have limited geological and biological sequestration capacities, such as Singapore, Japan and the Republic of Korea, will likely look to countries like Australia to meet their carbon storage needs.

Developing removals targets is challenging given uncertainties around Australia's *realisable* sequestration potential – that is, what can be achieved under real world conditions. Realisable sequestration incorporates factors such as competition for land, water and energy, as well as other inputs such as feedstocks, infrastructure, capital, and future innovations in sequestration and removal technologies. The authority's 2023 carbon sequestration insights paper (CCA 2023a), informed by a technical report by the CSIRO, explored the role for carbon sequestration in contributing to and accelerating decarbonisation in Australia. The authority found that more work is required to map and understand just how much of Australia's sequestration potential can be realised. The authority has recommended the government develop a sophisticated modelling capability to enable estimation of Australia's sequestration potential (CCA 2023b).

For its Sectoral Pathways Review, the authority proposes a long-term removal target range could be based on:

- Australia's realisable removals potential
- Australia's contribution to estimates of what is needed globally
- the estimated domestic need, according to residual emissions in sectors, under the premise that sectors prioritise emissions reductions.

Near-term removal targets could be derived from the long-term target to inform the authority's 2035 Targets Advice.

An achievable target is one Australia can meet at home

The authority holds the view that in the near-term Australia should focus on domestic emissions reductions, supported by domestic removals, to meet its targets. Nonetheless, the authority's analysis will consider whether there could be a role for international carbon offsets in helping Australia meet its targets and/or increase its ambition.

The authority has previously recommended the government develop a national carbon market strategy setting out how Australia will use domestic and international carbon markets in its transition to net zero emissions (see Review of International Offsets [CCA 2022]), Review of the Carbon Credits (Carbon Farming Initiative) Act 2011 [CCA 2023c] and Annual Progress Report [CCA 2023b]).

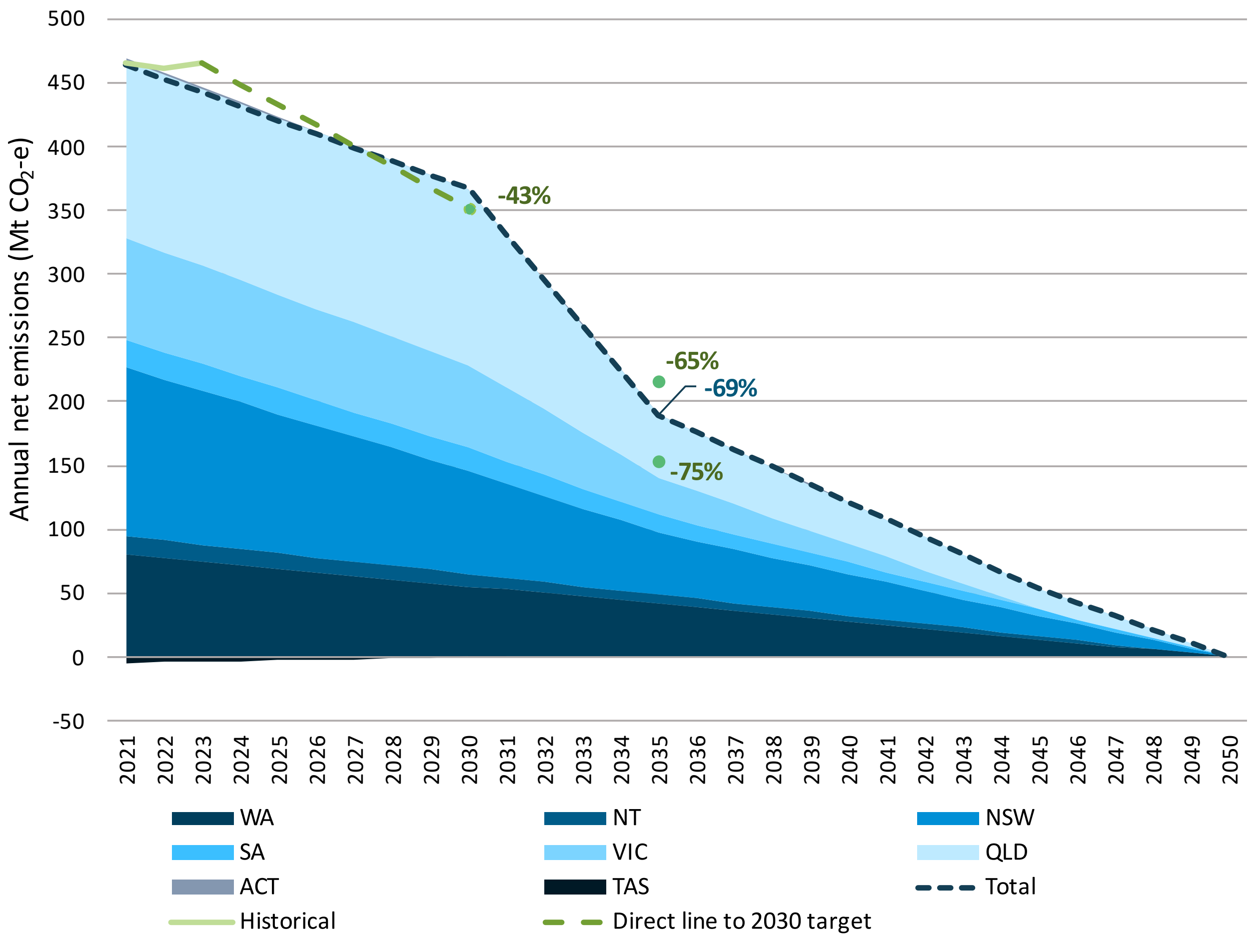
In response to the authority's 2023 issues paper, there were mixed views on the use of international units towards meeting Australia's targets. There was general support that any international units must be of high integrity and align with Australia's national objectives. Although international carbon markets under the Paris Agreement are at the early stages of development, the authority recognises that in the future, deep, well-designed international carbon markets could help to differentially price offsets based on integrity, support sustainable development, and reduce the overall cost of achieving global mitigation goals (CCA 2020; CCA 202; CCA 2023b).

An achievable target is one that all jurisdictions contribute to meeting

Most Australian states and territories have committed to ambitious emissions reductions targets. New South Wales, Victoria, Queensland and Tasmania, which are cumulatively responsible for three -quarters of domestic greenhouse gas emissions (DCCEEW 2023g), have announced state emissions reductions targets of at least 70% by 2035.[8] Some states and territories will move faster than others but all have committed to net zero by 2050 or earlier.

The authority has calculated the aggregate impact of these subnational targets, finding them to be equivalent to a national 2035 target of 69% on 2005 levels (Figure 6). This falls within the range of targets the authority is currently considering.

Figure 6: State and territory target trajectories



Note: *Climate Change Authority analysis of DCCEEW (2023g). Each state and territory's emissions are assumed to fall linearly from 2021 towards their targets.*

[8] Existing State/Territory 2035 Targets: NSW (70%); VIC (75-80%); QLD (75%); TAS (net zero already achieved); WA, SA, NT & ACT (yet to establish a 2035 target).

The authority will recommend a target that is **advantageous** to Australia and Australians.

An advantageous target is one that supports Australia to realise the opportunities of the global transition to net zero emissions.

As a resource-rich trading nation, Australia has potential to produce and export clean energy and to become a low and zero emissions manufacturing and processing hub. Reducing emissions associated with the production of Australian exports is necessary for achieving Australia's targets, but also for remaining competitive in a global economy that is increasingly prioritising low and zero emissions products and services.

Australia has comparative advantages it can leverage to capitalise on increased global demand for low carbon products, creating new economic opportunities. For instance, CSIRO projected that Australia would have the third cheapest average renewable industrial electricity in 2050, behind only China and India (CSIRO 2023c). Australia also has large reserves of minerals which will be vital for the global net zero transition, including critical minerals, and are projected to grow in demand (Austrade 2024).

Several industries can take advantage of Australia's cheap renewable energy to produce energy intensive products, including green steel, critical minerals, green hydrogen and ammonia (Climate Council 2023b). Studies of the potential economic benefits of these new green industries include:

- The Australian Industry Energy Transitions Initiative forecast that rapid decarbonisation of the industrial sector can allow regions to capitalise on increasing global demand for low-carbon products and energy exports, generating over a million jobs (AIETI 2023).
- A Grattan Institute report (2023) found that by 2050, Australian revenue from critical minerals could be worth roughly double the value of Australian revenue from coal today.

In addition to the contributions to global decarbonisation set out above, the growth of new green industries can also help Australia to decarbonise domestically. Whole of economy modelling by CSIRO shows how positive feedback loops within Australia can accelerate decarbonisation, with increased local production of low emissions metals and concrete supporting infrastructure roll-out in the energy production and built environment sectors (Brinsmead et al. 2023).

With a ramp up in activity on industrial and trade policy creating global competition for investment and skills, the Australian Government can use a strong emissions reduction target, supported by commensurate and credible policies, to signal to investors that Australia is committed to decarbonisation and ready to invest in the production of new green exports. Managing this change requires planning and transitional arrangements in a sequenced process, involving the development of new technologies, production processes, and engagement with industries, communities, trading partners and competitors.

An advantageous target is one that brings co-benefits to Australians

The authority's 2035 Targets Advice and 2024 Annual Progress Report will explore how reducing emissions can bring a range of co-benefits for individual Australians and communities. For example:

- Air quality – California has a small but growing proportion of electric vehicles (EV), and evidence demonstrates an increase of 20 EVs per 1000 residents results in the local community experiencing a 0.41 parts per billion reduction in NO_2 and a 3.2% decrease in annual age-adjusted asthma related hospital visits (Garcia et al. 2023).

- Human health – A trial program in Victoria found that minor energy and thermal efficiency upgrades not only reduced emissions from residential buildings and energy costs for consumers, but also saved $887 per person in healthcare costs over the winter period (Sustainability Victoria 2022).
- New opportunities, particularly for First Nation communities, vulnerable people, the workforce and regions.

Climatic and economic changes affect people differently depending on their circumstances, income, place of residence, ethnicity, nationality, age, culture, disability and gender. With careful planning and by placing those who experience vulnerability at the centre of transition solutions, governments can build broad, society-wide resilience, and ameliorate the challenges faced by Australia's most vulnerable people while also improving their access to the opportunities of the transition.

As traditional custodians of Australia's land and sea, First Nations people are positioned to drive emissions reduction and determine their futures. First Nations are creating opportunities to own and partner on decarbonisation projects, which can generate economic, social and environmental benefits for their communities and for Australia (First Nations Clean Energy Network (FNCEN) 2024; Indigenous Carbon Industry Network (ICIN) 2024; CER 2024b). Governments must prioritise the resourcing necessary for more communities to access these opportunities, including access to funding and capital, information, expertise and capability development (ASIC 2023; ILSC 2022; Woods et al. 2021; Chubb et al. 2022).

Reaching net zero requires a substantial transformation in Australia's workforce to new jobs, skills, qualifications, training pathways, technologies and industries. Given the size of the economic transformation required to reach net zero by 2050, Australia will need to consider structural changes to its education, training, migration, procurement and workplace systems (Jobs and Skills Australia 2023a).

Industries with low levels of diversity in the workforce are at risk of not having the labour supply to meet the demands of the transition (Jobs and Skills Australia 2023b). Currently, in both high and low emission sectors, workforces are male-dominated and women and First Nations people are underrepresented in highly skilled roles. Women working in clean energy generation are largely confined to white-collar and cleaning operations, with very low representation in trade-qualified and engineering roles (Jobs and Skills Australia 2023b). First Nations people are represented in emissions-intensive industries at a higher rate (3.4%) than the labour force average of 1.9%, while employment in clean energy is at the national average (1.9%) (Jobs and Skills Australia 2023a). An advantageous target will support First Nations people access education opportunities (particularly in regions) while ensuring that the clean energy sector provides skilled and paid operational employment.

Regions where emissions-intensive industries are the 'lifeblood' of the community face more economic and social challenges from the transition. These regions encounter risks of higher unemployment, economic contraction and population decline as industries phase out (CCA 2020). Careful and long-term transition management between governments and affected regions can help manage these risks and leverage the advantages of the target. For example, through early identification of opportunities to establish new industries, and retraining workforces.

Major developments of wind farms, solar farms and transmission lines in farming regions also create impacts and risks that will need active and well-resourced management (AEMO 2023a, McRobert and Fox 2023). Farmers in rural areas often benefit financially from renewable energy and transmission projects (NSW Farmers 2022, Farmers for Climate Action 2024), but it is important to note the multifaceted task facing farmers in the transition, including accommodating infrastructure, changing farming practices and adapting to the impacts of climate change.

Tracking progress to accelerate achievement

In 2024 the authority will deliver its third Annual Progress Report (APR), tracking Australia's emissions reduction and climate policy progress and providing advice to inform the Minister's third annual climate change statement. The authority's advice and the Minister's statement are both required under the *Climate Change Act 2022*.

The Minister's statement is required to address progress made towards achieving Australia's emissions reduction targets; international developments during the year that are relevant to addressing climate change; climate change policy including the effectiveness of policies and impacts on rural and regional Australia; and risks to Australia from climate change impacts.

In its *2023 Annual Progress Report*, the authority concluded that Australia is not yet on track to meet its 2030 target of a reduction in emissions to 43% below the 2005 level. The authority found that while the government is pursuing a broad and deep climate change policy agenda, that has not yet translated into the emissions reductions needed. The authority put forward 42 recommendations with the main aim of accelerating emissions reduction to the levels required, noting that emissions had not declined recently and needed to be reducing at an average annual rate of 17 Mt CO_2-e.

The government subsequently announced that it accepted the majority of the authority's recommendations and released its official 2023 emissions projections. These show Australia reaching a level of emissions 42% below the level in 2005 in a 'with additional measures' scenario incorporating policy initiatives now being implemented – specifically, an expansion of the Capacity Investment Scheme for renewable electricity generation and storage, and a vehicle efficiency standard for light vehicles. This projected outcome is just shy of Australia's 2030 target.

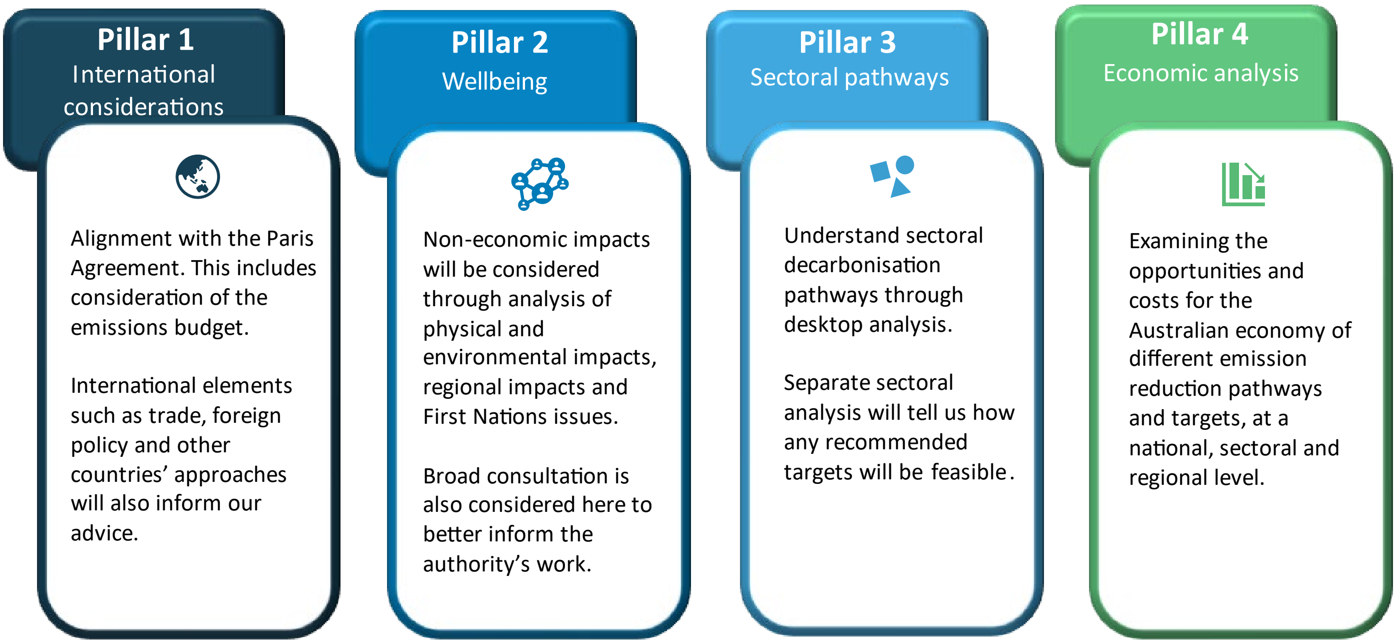
Achieving the 2030 target remains a very significant challenge. In its 2024 Annual Progress Report, the authority will:

- **provide updated analysis of progress towards Australia's 2030 emissions reduction target** – the authority will assess progress in the 2023-24 year towards Australia's 2030 emissions reduction target. This will be reported at a national level and across the six inventory emissions sectors: electricity, industry and resources, transport, agriculture, waste, and land use, land-use change and forestry (LULUCF).
- **assess emissions reductions achieved under the Safeguard Mechanism** – this year's report will include for the first time the authority's advice on whether Safeguard emissions are declining consistently with Safeguard outcomes specified in the objectives of the *National Greenhouse and Energy Reporting Act 2007*. The authority is currently establishing a process for providing this advice on an annual basis, noting the timing of the advice will be determined by the availability of Safeguard Mechanism data.
- **expand its review of climate change policy implementation** – the authority's Climate Policy Tracker identifies and records the status of major Australian Government initiatives aimed at reducing emissions and positioning Australia to be prosperous and resilient in a net zero world. In the third APR, this tracker will be expanded to include emissions reduction and adaptation policies implemented by state and territory governments.

Appendix 1: Analytical framework for Sectoral Pathways Review and 2035 Targets Advice

In developing its review of sectoral pathways and advice on Australia's 2035 targets, the authority is undertaking analysis across 4 areas as shown in Figure A1.1.

Figure A1.1: Areas of analysis



Pillar 1: International considerations

Under the *Climate Change Act 2022*, the authority must explain how the greenhouse gas emissions reduction targets it recommends have 'taken into account the matters set out in Article 2 of the Paris Agreement'. Article 2 refers to:

- the global temperature goals of holding the increase in the global average temperature to well below 2°C above preindustrial levels; and pursuing efforts to limit the temperature increase to 1.5°C above preindustrial levels ('temperature goals')
- increasing the ability to adapt to a changing climate and making finance flows consistent with low emissions
- the implementation of the Paris Agreement to reflect equity and the principles of common but differentiated responsibilities and respective capabilities, in light of different national circumstances.

Australia's status as a developed economy means it has the capacity and obligation to move more quickly to meet the temperature goals and support others to do the same. To support keeping 1.5°C alive, Australia should:

- transition to net zero as quickly as possible
- set interim targets and deliver supportive policies
- additional to domestic emissions reductions, contribute significantly beyond its national borders.

BOX A1.1 – The modified contraction and convergence method of sharing the global emissions budget

In 2014, the authority provided advice on the national 2030 emissions reduction target by identifying Australia's share of the global emissions budget consistent with 2°C or less (CCA 2014). The authority adopted a 'modified contraction and convergence' approach to determine how much of the global emissions budget could be apportioned to Australia. This approach aims to provide an answer for what would represent an equitable share of emissions for each country.

While the authority will not replicate the 2014 approach in its advice by adopting a modified contraction and convergence 2°C fair share approach, it will consider the global emissions budget and Australia's responsibility as a developed country, along with other analysis the authority is undertaking. The authority is considering Article 2 under each pillar of its advice.

Pillar 2: Wellbeing

Wellbeing means 'meeting various human needs, some of which are essential, and includes the ability to pursue one's goals, to thrive and feel satisfied with their life' (OECD 2011).

The wellbeing pillar of our analysis addresses the principle established by the *Climate Change Authority Act 2011* that any measure proposed by the authority be equitable and in the public interest. Measures must take account of the impact on households, business, workers and communities, and boost social, economic and employment benefits. This includes for rural and regional Australia.

The *Climate Change Act 2022* requires the social, employment and economic lens also apply to advice on any new or adjusted greenhouse gas emissions reduction targets, and the physical impacts of climate change on Australia.

Wellbeing is an important lens through which governments make tough decisions about trade-offs and allocate resources equitably, in pursuit of a 'just transition'. The authority defines a just transition as:

> *The process and the outcome in which burdens and benefits are shared equitably as Australia accelerates emissions reductions, adopts new ways of doing things, and prospers as the world transitions to net zero emissions.*

In our 2024 work program, the authority will examine the impacts of the transition – including physical, economic and social impacts, on several priority cohorts. These cohorts were chosen because their diverse experiences will capture a broad range of transition issues and climate impacts common to many other groups.

First Nations people – The authority is considering First Nations perspectives in preparing advice on existing and prospective opportunities to achieve emissions reductions. Our analysis will consider the integration of First Nations science, culture and history into targets and policy responses. The authority welcomes the development of a First Nations Clean Energy Strategy that, when finalised, will seek to stimulate investment and unlock opportunities for First Nations people to lead and benefit from the clean energy transition (DCCEEW 2023h). The authority will also consider the Productivity Commission's review of the National Agreement on Closing the Gap (Productivity Commission 2024).

Women and gender diverse people – The Australian Parliament asked the authority to consider opportunities for women in the workforce in the transition to net zero. While workforce gender representation in Australia has improved, men still dominate the industries most affected by the energy transition (ABS 2022; Sridhar, Lockyer and Kanani 2022).

Regional and rural communities – Regional and rural communities are some of the most at-risk in Australia from the economic impacts of climate change (Climate Council 2016). The authority will consider the implications of the transition on regions, including access to services.

Young people – Young people are increasingly worried about climate change and experiencing climate anxiety (Hickman et al. 2021; Whitlock 2023). A 2023 survey of young Australians (aged 16-25 years) found that 76% were concerned about climate change (Orygen Institute, 2023). Young people are victims of past inaction on climate change and ongoing intergenerational disadvantage as well as valuable contributors to climate action (UN n.d.).

Culturally and linguistically diverse (CALD) communities – Cultural, socioeconomic and linguistic factors can affect peoples' vulnerability to climate change, and impact abilities to participate in the transition (Hansen et al. 2014). CALD communities play a large role in Australian society and thus are a critical part of Australia's transition both as participants and as champions. However, CALD groups are often excluded from policy development, and consequently the transition barriers they experience are not adequately addressed (e.g. higher fuel costs, energy inefficient homes, and expensive transport). Decarbonisation policy measures need to be designed in ways that will both engage and support CALD communities.

Workers – Australia's workforce must undergo substantial structural changes for our nation to reach its targets. The authority will engage industry representatives and workforce experts to examine the barriers and opportunities to the workforce meeting the needs of the transitioning economy.

Through the authority's 2023 Issues Paper, concerns were raised in relation to financial strain, intergenerational inequality, social discrimination, healthcare concerns as well as limited access to information and social services. Such concerns will tend to be concentrated in many of the cohorts identified above as well as low-income households generally. We will look at these issues to examine the importance of building broad, society-wide resilience and sharing the impacts of the transition fairly.

The authority will undertake targeted engagement to capture insights on the transition experience of a range of Australian communities. Through collaboration with the Net Zero Economy Agency (NZEA) and the Department of Climate Change, Energy, the Environment and Water (DCCEEW), we will seek deeper perspectives from First Nations people, experts on gender representation, CALD groups and young people. We will also engage local governments and organisations to inform our understanding of the diverse experiences and priorities of Australians in the transition.

Pillar 3: Sectoral pathways

Referral

The Australian Parliament requested the authority review the potential technology transition and emissions pathways that best support Australia's transition to net zero by 2050 for:

- Electricity and energy
- Transport
- Industry and waste
- Agriculture and land
- Resources
- Built environment

In the review, the authority must identify:

- existing and prospective opportunities to achieve emissions reductions
- which technologies may be deployed in each sector to support emissions reductions
- how public and private finance can support and align with these emission pathways
- barriers to implementation such as short-term or longer-term pressures on cost and supply chains and the pace of technology commercialisation
- workforce matters, including skills and opportunities for women
- any gaps in existing evidence and data
- any other relevant factors.

The review must take into consideration the principle for the authority set out in the *Climate Change Authority Act 2011,* including the global goals in Article 2 of the Paris Agreement and boosting economic, employment and social benefits. The authority must also consider the range of emissions reductions achievable through the deployment of available and prospective technologies.

Sectoral pathways methodology

For the purposes of its Sectoral Pathways Review the authority defines 'sectoral pathways' as:

> *The sets of potential technological and operational changes in each sector, that taken together could potentially deliver net zero emissions in Australia by 2050.*

For simplicity, technologies, operational changes and other types of abatement and emissions reduction activities and opportunities are collectively referred to as 'technologies' in this report.

The authority engaged BCG to assist the authority to develop a methodology for the Sectoral Pathways Review. BCG has experience advising on sector pathways for Germany, South Africa and others.

The authority's Sectoral Pathways Review will draw on the economic modelling exercise (see below) with a focus on the detailed sectoral outputs from the AusTIMES and LUTO models. Research, consultation outcomes and the modelling scenarios will all inform the authority's assessment of the contributions sectors could make to achieve a range of economy-wide emissions reduction targets.

Technologies

The review will identify existing and prospective technologies (including operational changes), focusing on those most important to support Australia's transition to net zero emissions.

Existing technologies are technologies or operational changes currently in use or available to be deployed.

Prospective technologies are emerging technologies or operational changes which are currently in an early phase of development that could play an important role in future emissions reductions if rapid scaling and commercialisation can be achieved. The authority is using a principles-based assessment of readiness, emissions reductions potential and cost to identify the most important technologies from a longer list.

The authority acknowledges the inherent uncertainty in projecting the contribution of specific technologies to Australia's future emissions reductions. The readiness, abatement potential and cost of technologies will not remain static and will evolve over time.

Readiness

Using the ARENA framework (ARENA 2014), technologies were grouped into three phases based on technical and commercial readiness: 'Research and Development', 'Demonstration' and 'Deployment'.

In some sectors, where detailed information on readiness was available, qualitative assessment of technology readiness has also been presented. Operational changes were not assessed for readiness because they generally relate to behavioural shifts.

Technologies at a more advanced level of readiness have a greater capacity to provide short to medium terms emissions reductions and are more likely to be an area of focus for the authority.

Abatement potential

Abatement potential describes the maximum feasible emission reductions that an emissions reductions activity could deliver.

Where possible, the authority has grouped technologies at a similar level of cost and readiness to assess each group's cumulative 'abatement potential'. Technologies (and groupings) with a greater abatement potential are more likely to be an area of focus for the authority.

Cost

Cost per quantum of emissions reductions is a useful metric for comparing the potential of different technologies to contribute to sectoral pathways.

In many cases, it is not possible to assign a 'dollar-per-tonne' figure to a technology. For this reason, quantitative analysis is limited to those technologies where costs are well understood. Nevertheless, qualitative cost comparisons are feasible within each sector and can prove useful for assessing where some technologies are orders of magnitude more expensive than others.

Barriers and enablers

The authority will consider the barriers to and enablers of implementation. Barriers may include workforce readiness, scalability, social licence, climate impacts, storage, cost, research and development as well as other matters. Enablers may include availability and accessibility, innovation, research and development, commercial availability, cost incentives as well as other matters.

Additional technologies

Analysis and discussion will focus on technologies and operational changes identified during the authority's assessment of cost, readiness and abatement potential. However, this is not an exhaustive list of emissions reduction activities. The authority will also make note of, and provide limited commentary on, additional technologies that fall into the following categories:

- activities that address a small source of emissions but are the only option that can feasibly address those emissions.
- potential 'game changers' – where a technology has low readiness today but has breakthrough potential to deliver significant emissions reductions in the longer term.

Pillar 4: Economic Analysis

Economic modelling will complement other analysis in informing the authority's understanding of the effects of different emissions reduction scenarios on the Australian economy, as well as impacts and contributions at the sector level.

The authority will not recommend an emissions reduction target based solely on modelling results or analysis of national economic indicators. It will also use other data sources, consultation and qualitative research to establish a holistic understanding of the socioeconomic impacts associated with possible emissions pathways, and incorporate this into its advice. The modelling is not intended to measure the economic impact of specific emissions reduction policies. For example, the modelling will not assess the relative benefits of different policy mechanisms to encourage increased take up of electric vehicles or installation of renewables.

In August 2023, the authority released the *Economic modelling of Australian emissions reduction pathways* consultation paper outlining its approach to the modelling exercise, including scenarios and key global assumptions.

Modelling for the authority will use a combination of CSIRO's GTEM[9], AusTIMES[10] and LUTO[11] models. GTEM will model whole-of-economy and global effects, while AusTIMES and LUTO will provide greater detail at the sector level. Each of these models is well-established and has been used in previous modelling exercises for the Australian Government.

The scenarios are aligned with relevant underlying narratives consistent with the global and Australian ambition represented in each of them (Figures A1.2 and A1.3).

Figure A1.2: Modelling scenarios

Australian ambition		Global ambition	
Net Zero Year	**2035 net emissions relative to 2005**	**<2°C** (67% chance) Moderate ambition	**1.5°C** (50% chance) High ambition
2035	-100%	*Not modelled*	***Modelled scenario:*** **A100**
2040	-75%	***Modelled scenario:*** **B75**	***Modelled scenario:*** **A75**
2045	-62%	***Modelled scenario:*** **B62**	*Not modelled*
2050	-57%	***Modelled 'Reference' scenario:*** Reference B	***Modelled 'Reference' scenario:*** Reference A

1.5°C scenario

Under 2°C scenario

The Australian emissions trajectories modelled in different scenarios are intended to be stylised and indicative. They are not intended to test specific targets or well-calibrated trajectories, and cannot capture all possible futures. The trajectories are intended to inform understanding of the potential economic effects of various levels of ambition within a broad range that the authority could consider in forming its advice, without binding the authority to any particular trajectory or specific target.

[9] GTEM stands for Global Trade and Environment Model. The data and theory behind GTEM are outlined in detail in Cai et al. (2015).

[10] AusTIMES is an Australian version of The Integrated MARKAL-EFOM System (TIMES) model. The TIMES model has been developed and is maintained under the IEA's Energy Technology Systems Analysis Project (ETSAP). Documentation of the TIMES model is available from the *ETSAP website*.

[11] LUTO stands for the Land Use Trade Offs model. LUTO was developed as a core model of the Australian National Outlook 2015 initiative. More detail on LUTO can be found on the *CSIRO website*.

Figure A1.3: Example underlying narratives for two of the scenarios

	1.5°C scenario	Under 2°C scenario
Global	• World coordinates action to limit warming to 1.5°C. • Rapid decrease in global fossil fuel demand. • Some climate impacts remain despite global efforts. • Very strong global investment in negative emissions, including land-based and technological removals.	• World gradually strengthens its action to limit warming to below 2°C. • Gradual decrease in global fossil fuel demand. • Climate impacts on the economy and wellbeing are heightened. • Strong global investment in negative emissions.
Australia	• Australia sets and achieves more ambitious emissions targets, including net zero in 2040. • Australia's action is consistent with other developed nations. • Australia's fossil fuel exports decline. • Australia overcomes barriers and pursues aggressive emissions reductions across all sectors, including investing in sequestration.	• Australia maintains and achieves current emissions targets, including net zero in 2050. • Australia's action is behind many other developed nations. • Australia's fossil fuel exports decline more gradually than ambitious scenarios. • Australia takes up new opportunities to reduce emissions but fails to reach its full potential.

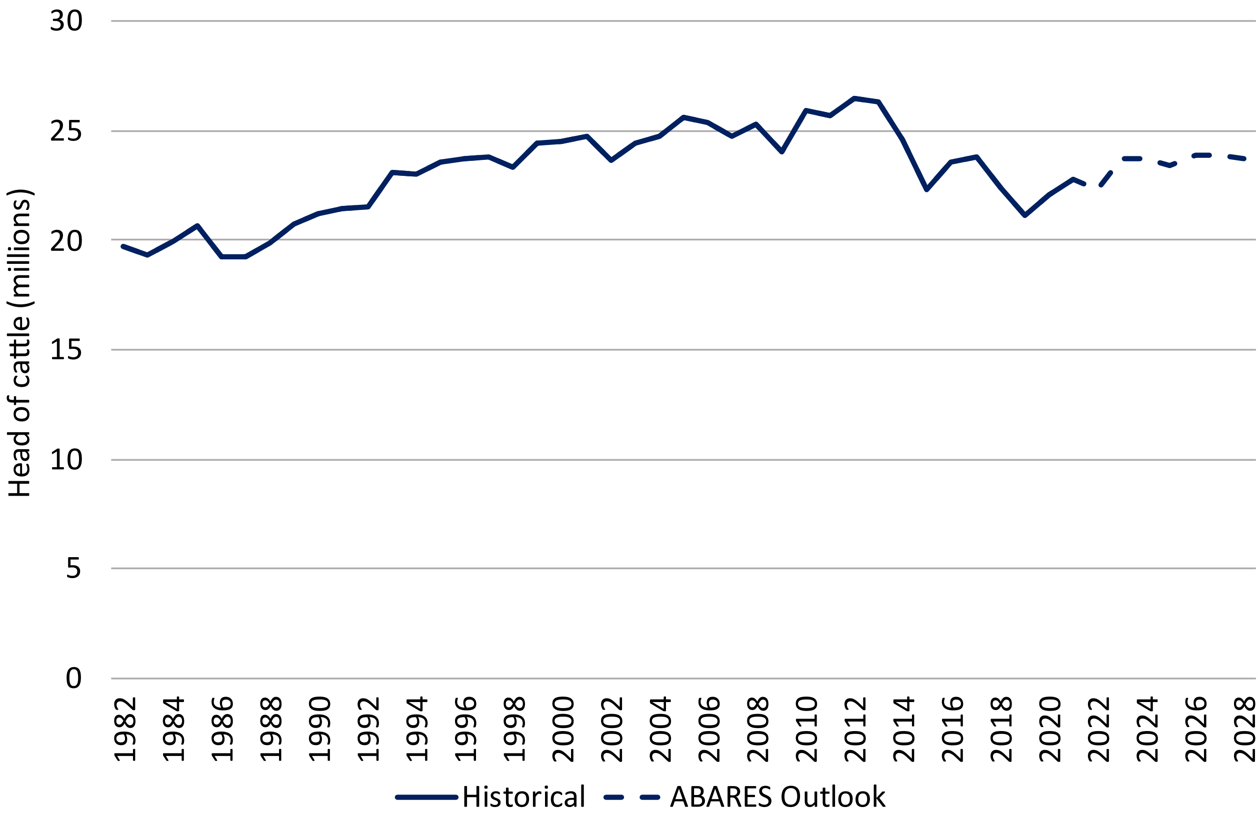
The authority is using assumptions from what it considers to be a range of reputable sources and would welcome feedback on the following assumption sets:

Sectoral technology and cost assumptions (AusTIMES) – The CSIRO and Climateworks Centre jointly maintain the AusTIMES model and regularly update its assumptions. The authority is reviewing the cost and technology assumptions used in the Climateworks Centre's and CSIRO's most recent reports - *Climateworks Centre Decarbonisation Scenarios 2023* (Climateworks Centre 2023) and *Pathways to Net Zero Emissions—An Australian perspective on Rapid Decarbonisation* (Brinsmead et al. 2023).

Land sector assumptions – The Land use trade-offs (LUTO 1.0) model will be used to complement AusTIMES. LUTO takes an agricultural land use map as a baseline, and then combines a range of environmental and economic data to identify potential land use change. CSIRO and Climateworks Centre used LUTO alongside AusTIMES to prepare carbon sequestration forecasts in the *Multi-sector Energy Modelling 2022: Methodology and Results Final Report* (Reedman et al. 2022) for the Australian Energy Market Operator.

The authority will assume cattle numbers remain stable over time, consistent with relatively flat historical trends (ABARES 2022) and ABARES projections (ABARES 2023c) up to 2028 (Figure A1.4).

Figure A1.4: Historical and projected beef cattle numbers

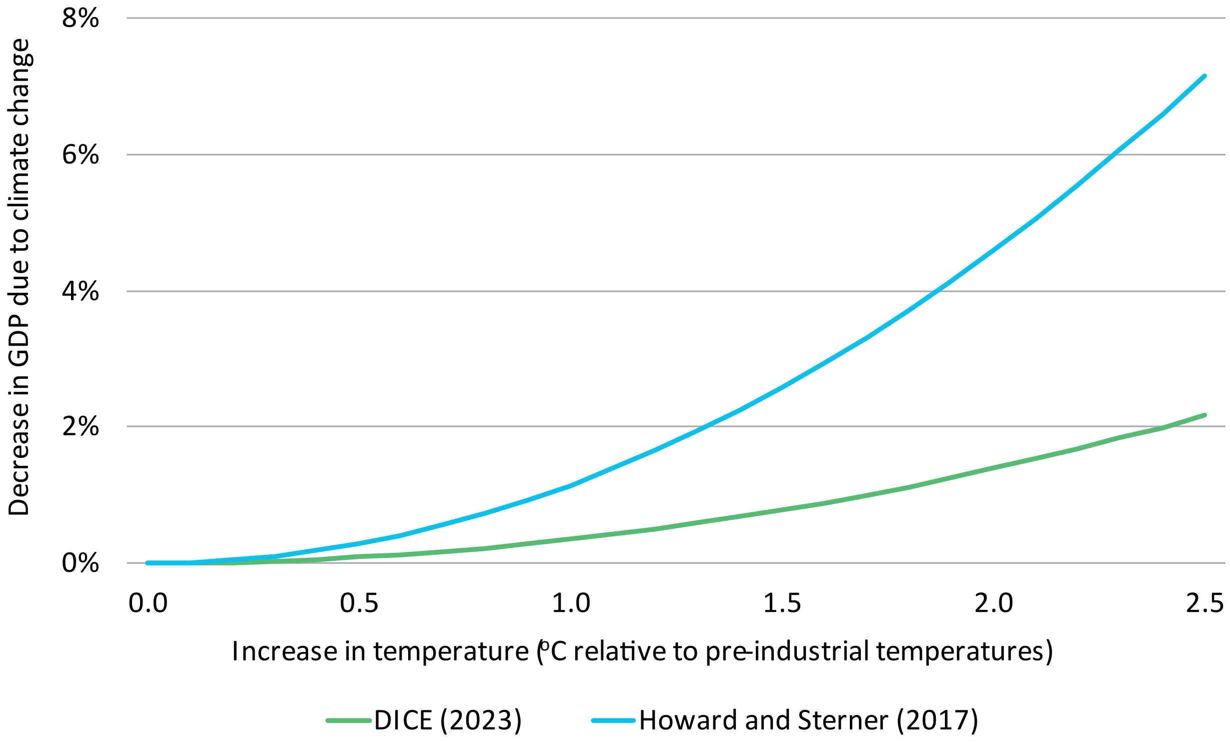


Note: *Combined ABARES historical (ABARES 2022) and projected (ABARES 2023c) estimates of beef cattle numbers.*

Electricity sector assumptions – For electricity sector modelling, the AusTIMES model will largely draw on the most recent figures from the Australian Energy Market Operator, including the most recent *Inputs, Assumptions and Scenarios Report* (AEMO 2023c) and *Draft 2024 Integrated System Plan* (AEMO 2023a), complemented by other sources on electricity outside of the National Electricity Market. Electricity generation costs will also be informed by CSIRO's work for its annual GenCost report (CSIRO 2023a).

Climate damages – In response to the economic modelling consultation paper, multiple stakeholders recommended considering the impacts of climate change on economic prosperity when comparing global scenarios. The authority intends to account for climate damages through off-model analysis. The authority plans to apply climate damage functions, which relate GDP impact to temperature increases compared to base levels, to GTEM's modelled GDP impacts. Quantifying the economic damages of climate change is difficult, and published damage estimates vary widely (IPCC 2022). Robustly quantifying some types of damages is particularly complex, such as biodiversity loss or decreases in quality of life. To capture this variation, the authority proposes using climate damage functions from the DICE 2023 model (Barrage and Nordhaus 2023) and Howard and Sterner (2017) – see figure A1.5 below. These studies are based on meta-analyses of existing damage studies and reflect a range of damage estimates.

Figure A1.5: Climate damage functions



Economic benefits of decarbonisation – Several stakeholders have identified benefits associated with decarbonisation, such as health benefits, the emergence of new industries, and reduced risk. Stakeholders generally preferred that the authority integrate these benefits into the economic modelling directly. However, due to limited time and resources, the authority intends to consider these benefits primarily through off-model analysis.

Cross-cutting analysis

Financing the transition

In the context of the Sectoral Pathways Review, the authority must consider 'how public and private finance can support and align with these emission pathways'. The Australian Government (Treasury 2023b) defines sustainable finance as:

> *financial flows that integrate consideration of impacts on society and the natural environment. This reflects a growing understanding of the role that the financial system must play to address global challenges, including climate change. It also recognises the need for financial system participants to manage emerging opportunities and risks to deliver long-term financial returns and support financial stability.*

The authority will consider the systemic barriers to and enablers of sustainable finance contributing to the whole-of-economy emissions pathways to net zero, as well as sector-specific financial barriers and enablers.

Breaking down barriers

Across the sectoral pathways there are expected to be a range of common barriers. The authority will analyse these to consider ways these could be overcome to improve pathways. For example, challenges with supply chains and short-term cost impacts of high demand for low emissions technologies are anticipated to be common barriers.

Preparing workforces

The authority will consider workforce matters as a cross-cutting issue for all sectors. Transitioning the economy will require the right skills and capacity, and support for Australia's workforce to supply them (Jobs and Skills Australia 2023a). The authority will assess how the workforce presents barriers and opportunities to deploying technologies in the net zero transition.

For example, current and future levels of workforce participation, skills, education and training, job and worker location, and other enabling factors will help to predict how quickly and efficiently sectoral pathways can be pursued.

Climate change hazards

The authority has a legislated requirement to consider 'physical impacts' of climate change in its targets advice (*Climate Change Act 2022)*. According to the Bureau of Meteorology and CSIRO (2022), these impacts include, but are not limited to:

- coastal inundation due to sea level rises
- more frequent and intense heatwaves
- more intense rainfall events causing more damaging floods
- chronic, long-lasting effects, such as sustained increases in average temperature.

The authority will complement the economic modelling discussed above with our research. This research will qualitatively analyse climate change hazards in Australia at selected levels of global warming, specifically 1.5°C, 2°C (aligning with the Paris Agreement goals) and 3°C (representing a warmer future aligned with the ambition of current global climate policies). A key part of this work will be integrating global warming levels with time-based trajectories simulated through economic modelling.

The implications of observed and projected social and demographic trends will inform discussion of future vulnerabilities and exposures across Australia. These trends include changes in generational inequality, an ageing population and the costs of living and housing. These social and economic issues intersect with climate change.

Appendix 2: Emissions classifications table

The authority has made an initial classification of Australia's emissions to the six sectors listed in the Parliamentary referral for the sectoral pathways review. This is based on Australia's inventory submission to the United National Framework Convention on Climate Change (UNFCCC) for the year 2021. At the time of writing this was the most recent fully disaggregated inventory available for compiling emissions totals for the pathways review sectors.

This is an initial experimental approach to this classification which is likely to evolve over time. The authority welcomes feedback on this initial classification of emissions to the six sectors.

Sector	Emissions in 2021 (Mt CO_2-e)	Classification notes
Agriculture and Land	22	UNFCCC sectors (agriculture and land-use, land use change and forestry) plus fuel combustion associated with machinery use.
Built Environment	28	Fuel combustion (gas) in commercial and residential buildings, and in construction, and emissions associated with refrigerant gases. Fugitive emissions from gas distribution and emissions associated with wastewater. This table presents scope 1 emissions; however, the authority has analysed scope 2 emissions as part of this project.
Electricity and Energy	160	The electricity and energy sector contains emissions relating to the production of electricity (except those associated with mining and oil and gas operations which are not grid connected), and the supply of energy to consumers, this includes: • on-grid electricity generation and non-energy emissions associated with the operation of the physical grid (SF6s in insulation of transmission lines) • production of liquid and solid fuels including emissions from refineries • emissions arising from the movement of gas through the distribution network (fugitives and pipeline transport emissions) • military transport

Resources	98	Fugitive emissions associated with coal mining and oil and gas extraction, electricity generation emissions for non-grid connected facilities, fuel combustion in haulage machinery and other onsite activities at mine sites, fuel combustions in LNG processing.
Transport	91	Fuel combustion associated with transport activities, (excluding military and pipeline transport, which is in Electricity and Energy), plus non-energy emissions from the transport industry's refrigeration and air conditioning use (such as at a car maintenance facilities).
Industry and Waste	65	Emissions associated with fuel combustion for manufacturing processes and process emissions associated with chemical reactions in manufacturing processes. Includes some synthetic gas emissions and the UNFCCC waste sector.
Total	465	

Appendix 3: Sectoral pathway technology tables

Electricity and Energy

Technologies[12]	**Readiness**[13]	**Abatement Potential**	**Cost (AUD)**
Wind	Onshore wind has a moderate development timeframe (typically 3 to 5 years) and can takes a further 2.5 years until construction is complete. The timeframes are longer for offshore wind (over 7 years for development and a further 6 years until construction is complete) (Aurecon 2023, pp21-22, 26-27).	Under the government's 2023 emissions projections 'with additional measures' scenario, electricity emissions are projected to decrease from 152 Mt CO2-e in 2022-23 to 60 Mt CO_2-e in 2029-30. Modelling for this scenario assumes that renewable share will increase to 82% in Australia's electricity grids in 2030 (DCCEEW 2023a, p43).	In 2023, CSIRO estimated that the capital cost for onshore wind was $3,038 per kW. The actual technology capital cost for offshore wind ranged from $5,545 per kW to $6,856 per kW in 2023, nearly double the cost for onshore wind (CSIRO 2023a, table B.1).
Solar photovoltaic	Large-scale solar PV projects have a typical development time of 2-3 years and take a further 1.5 years until to construction is complete (Aurecon 2023, p33).		In 2023, CSIRO estimated that the capital cost for large-scale solar PV was $1,526 per kW. Rooftop solar PV was slightly lower at $1,505 per kW (CSIRO 2023a, table B.1).
Battery storage (including virtual power plants)	Shorter deployment timeframe than wind and utility-scale solar, residential systems are extremely fast to deploy (Aurecon 2023, p 145, 153).	Storage and transmission infrastructure are typically understood as a means to 'unlock' potential from zero emissions primary generation, and do not result directly in emissions reductions.	In 2023, CSIRO estimated that the capital cost for large-scale batteries ranged from $1,009 per kWh for a 1-hour duration battery, to $519 per kWh for an 8-hour duration battery (CSIRO 2023a).
Pumped hydro energy storage	Long deployment timeframe with development times ranging from 3 to 5		In 2023, CSIRO estimated that the capital cost for pumped hydro ranged from $ 635 per

[12] All technologies in this sector relate to electricity generation, as such the authority has not included columns outlining the relevant subsector or that subsector's contribution to emissions in this table.
[13] All technologies in this sector's focus list are commercial, the authority has focused readiness instead on deployment timeframes and other barriers where relevant.

	years and a further 4 to 8 years until construction is complete (Aurecon 2023, p138).		kWh for 6 hours storage to $142 per kWh for 48 hours (for Tasmania, the kWh cost for 48 hours was $66) (CSIRO 2023a, p76).
Transmission infrastructure	Long deployment timeframe, with 3-5 years now considered to be short and beyond seven years for projects considered to fall under a 'long' deployment timeframe. (AEMO 2023d, p41).		Transmission costs vary by location and project size, making comparative costs difficult, but they typically range from $100 to $273 per kW for 5 to 10km long grid integration connections (AEMO 2023d, table 9). For a large-scale project, the costs of the Marinus link project have been estimated $3.8bn at 2021 dollars (AEMO 2023d); this project will have a 1,500 MW capacity and include a 255km long subsea cable and a 90km long underground cable (Marinus Link n.d.).
Peaking gas	Moderate deployment timeframe with Open Cycle Gas Turbines taking 2 years to develop and 2 years to construct (Aurecon 2023, p58).	Gas can support very high penetration of renewables by balancing the grid (AEMO 2023a, p61). However, the emissions associated with using gas to generate electricity would need to be addressed in the context of achieving net zero emissions economy-wide.	In 2023, CSIRO estimated that the capital for small open cycle gas was $1,684 per kW, and $1,059 per kW for large open cycle gas (CSIRO 2023a, table B.1).
Additional technologies	Technologies not included in our focus list above include: • **Hydrogen gas turbines** – The Australian Energy Market Operator's (AEMO) Draft 2024 Integrated System Plan (ISP) forecasts only a small contribution from hydrogen, noting it is a 'relatively expensive fuel' to use at scale. The ISP suggests this contribution may increase if hydrogen becomes cheaper or there is greater Government support (AEMO 2023a, p66). • **Nuclear, including small-modular reactors (SMR)** – In 2023, nuclear SMR was the most expensive technology assessed in GenCost, at $31,138 per kilowatt (CSIRO 2023a, table B.1). Evidence suggests that it would take at least 15 years from a decision to build nuclear SMR in Australia to first production, not including the time required to create a nuclear industry (CSIRO 2023a, p18, Switkowski 2019). Capital cost estimates for conventional nuclear plants in Australia are not included in GenCost. The U.S.		

	Energy Information Administration estimates capital costs (expressed as total overnight costs[14]) to be US$7,777 (2022 dollars) per kilowatt (U.S. Energy Information Administration 2023, p. 2), equivalent to AU$11,829 per kilowatt at the time of writing. The authority notes the most recent conventional nuclear power project in the U.S., an additional two units at the Vogtle Electric Generating Plant, began construction in 2009 and is still awaiting full commercial operation of the final unit (with the other units entering commercial operation in 2023) (Georgia Power n.d.). Since 2009, total projected costs for the completion of the units have risen from US$13 billion to US$32 billion, and the schedule for completion has increased by 7 years (U.S. Department of Energy 2023 p. 29-30). GenCost notes advice from stakeholders that SMRs would be the most likely type of nuclear projects deployed in Australia due to the relative size of Australia's grids compared to overseas (CSIRO 2023a, p. 17-18). Nuclear power plants are currently prohibited in Australia under the Environment Protection and Biodiversity Conservation Act 1999 and the Australian Radiation Protection and Nuclear Safety Act 1998. The authority will continue to monitor any significant global developments in nuclear energy and potential implications for Australia. • **Solar thermal, and other less mature storage technologies** – Significant deployment of concentrated solar thermal projects is unlikely in Australia, due to unfavourable cost comparison with other renewable technologies (Aurecon 2023, p43). However, the 2024 Draft ISP states that in future, long-duration storage may potentially be served by emerging technologies like concentrated solar thermal AEMO 2023a, p64). • **Biomass** –Biomass is unlikely to be deployed on any significant scale due to unfavourable cost comparison (CSIRO 2023a, table B.1).

[14] Overnight costs exclude interest accrued during plant construction and development (U.S. Energy Information Administration 2023, p. 1), i.e. as though the project is built overnight. To reach total overnight costs the U.S. Energy Information Administration also apply an additional cost adjustment, reflecting a tendency to underestimate the actual costs of first-of-a-kind power units (U.S. Energy Information Administration 2023, p. 2).

Built Environment

Emissions subsector [%]	Technologies	Readiness	Abatement Potential	Cost (AUD)
Residential and commercial stationary combustion 56% of scope 1	**Electrification** – replacing technologies, processes or products that use fossil fuels with electric equivalents. • Replacement of gas water heaters with electric water heaters and heat pumps • Use of heat pumps for space heating and cooling • Induction and electric cooking	Technologies are commercially available and widely used, however there are barriers to retrofitting commercial buildings.	This large source of emissions could be fully abated if combustion of fossil fuels, primarily gas, is phased out and appliances are replaced with electric alternatives. Using AEMO's Step Change scenario, ASBEC has found that before offsets electrification has the potential to abate 199 Mt CO_2-e to 2050 (ASBEC 2022).	Electrifying a house costs between \$8,000 and \$15,000 (Climate Council 2022), and through consultation the authority heard that electrification of commercial building costs between \$100,000 and \$1 million. Electrification across the sector could save an estimated \$50 billion in operating costs (ASBEC 2022).
All scope 1 and scope 2 emissions 100% of scope 1 and 2	**Energy efficiency and digitalisation** – reducing energy use by upgrading appliances and using digital operational changes to optimise energy use. • Optimising use of existing appliances and replacing with higher efficiency appliances • Real time digital information provision • Use of digital building automation to optimise lighting, heating and cooling systems, and fault detection	Most emissions reductions activities are technically ready and their use has been widely demonstrated, although digitalisation is predominantly at the demonstration stage.	By 2030, existing buildings could cost-effectively reduce their total energy consumption by an average of 34%, saving 340 MJ/m² per building and 40 Petajoules (Common Capital 2020). In addition, building digitalisation could underpin new energy efficiency opportunities that save 6.6 Mt CO_2-e per year at negative abatement cost (CSIRO 2023b).	Upgrading residential appliances and lighting costs approximately \$3,000 (Sustainability Victoria 2015). For commercial buildings, costs are expected to vary depending on the building type, size and upgrades. In one case, a \$33 million investment to upgrade a B-grade commercial office building is on track to deliver a NABERS rating of 5.5 stars, reducing emissions by 55% (CEFC 2022).

Residential and commercial scope 2 emissions 100% of scope 2	**On-site electricity generation and storage** – production of energy at its point of use and storing excess for later use. • Rooftop solar photovoltaic systems • Battery storage of on-site energy production • Vehicle to grid (V2G) storage systems	Generation technology, typically rooftop solar PV, is commercially available. Storage options such as batteries can be expensive. Vehicle-to-grid (V2G; meaning the use of vehicle batteries to provide power to grids) systems have lower technical readiness (ARENA 2023).	Residential buildings have significant abatement potential, with generation and storage systems able to displace nearly all their grid electricity consumption. Stakeholders have noted that many commercial building types have limited options for on-site generation due to space limitations.	Residential solar PV and battery systems can cost between $12,000 and $30,000 (BVR Energy 2023). Commercial systems are larger than residential systems and costs vary depending on the size of the building and system. System costs can begin at $15,000 and exceed $100,000 (Clean Energy Council 2019).
	Grid integration – integrating smart systems and buildings into the grid and optimising their energy consumption. This can reduce energy use by efficiently balancing electricity supply and demand. • Storing energy produced onsite and feeding the electricity back into the grid during peak demand hours • Enabling grid flexibility services	Technology exists, but deployment at scale is limited due to local grid infrastructure, social license and approvals (e.g. cybersecurity concerns), data access and system integration (particularly for retrofits) challenges.	Load shifting (moving energy consumption to other parts of the day) one third of the electricity demand in buildings for just three hours a day, five days a week, would reduce Australia's annual emissions by 0.6% (equivalent to 180,000 homes), without decreasing energy use (GBCA 2023). It could also underpin 1 GW of dispatchable flexible demand, helping to stabilise the grid and drive down electricity supply costs (CSIRO 2023b).	Costs are unknown due to limited grid scale deployment around the world. However, load shifting with grid-interactive buildings could reduce the cost of supplying electricity to Australia's buildings by $1.7 billion each year (GBCA 2023). Furthermore, grid-integrated buildings could enable dispatchable flexible demand at less than 20% of the cost of batteries (CSIRO 2023b).
	Thermal efficiency – making improvements to reduce the amount of heating or cooling	Technologies are commercially available with numerous consumer choices.	In a conservative scenario, thermal upgrades to the residential housing stock can save between 1.57 Mt and	Across Australia's climate zones it costs an average of <$2,000 to upgrade a home (Class 1 dwelling) from a NatHERS 6-star standard to a

	required to make a building a 'comfortable' space to be in. • Insulation • Infiltration and ventilation • Curtains • Window systems, including glazing • Exterior changes, such as using light exterior colours and planting vegetation • Improving air-tightness • Fixed seasonal shade devices • Ceiling fans • Limiting space conditioning system capacity • Chilled beam solutions or underfloor displacement systems for commercial buildings		3.6 Mt CO_2 per year (RACE for 2030 CRC 2023).	NatHERS 7-star standard. The only exception was homes in Canberra, with a total average cost of $2,516 (Isaacs 2021). To upgrade a home to a 6-star energy efficiency rating, a retrofit could cost between $10,000 and $20,000 for a semi-detached house or between $40,000 and $60,000 for a detached house (based on a study examining housing stock in Melbourne) (Harrison 2018). There are benefits to upgrading housing no matter the rating – four-stars will always be better than three, six stars will always be better than five. There is minimal cost difference and similar payback time between these different upgrades (Harrison 2018). Limited data is available for commercial buildings, but a 1 NABERS star improvement in an office building has an average payback period of less than 3 years (Sustainability Victoria 2016).
Residential and commercial refrigeration,	**Refrigerants** – switching to lower GWP refrigerants to reduce emissions throughout the lifecycle	Stakeholder consultation has indicated that technologies are rated between	Significant reductions are possible due to the lower GWP of alternative gases (Smith et	Stakeholders have indicated that retrofitting existing systems is rarely possible, meaning that users would

stationary air-conditioning 32% of scope 1	of refrigeration and cooling systems. This replacement is being incentivised by Australia's HFC phase-down.	demonstration and commercially available, as some technical limitations exist. For example, ammonia is widely used as a refrigerant in commercial settings but not in residential settings.	al. 2021). However, it is not feasible to abate all refrigerant emissions through retrofits or appliance upgrades.	need to pay upfront cost for new systems. Key barriers to greater uptake are refrigerant price differentials and additional costs to retrofit.
Additional technologies	Embodied emissions (scope 3) were not included in the built environment sector pathway technology prioritisation process. Emissions from manufacturing building materials are addressed in other sectors in this review. Also, there is a lack of reliable data available on scope 3 emissions. Although outside the scope of this focus list, the authority is considering the significant role of the built environment as a user of emissions-intensive materials such as cement, steel and aluminium. This issue will be discussed in greater detail in the final report. In addition, while scope 1 construction emissions are a small component of the built environment's emissions profile, the decarbonisation activities are covered by other sectors. For example, the transport sector will explore biofuels and hydrogen vehicles.			

Industry and Waste

Emissions subsector	**Percentage of sector scope 1 emissions** (DCCEEW and DISR unpublished; CER 2023)	**Technologies**	**Readiness**	**Abatement Potential**	**Cost (AUD)**
Alumina and aluminium	23%	Electrification of digestion for alumina refining (electric boilers or mechanical vapour recompression)	Range from demonstration to deployment, depending on temperature required (ARENA 2022)	Up to 98% of alumina refining emissions (ARENA 2022)	Capital costs are estimated to be up to $700 million for electrified alumina refining and hydrogen calcination. These costs for electric calcination are expected to be greater than $700 million (ARENA 2022).
		Electric or hydrogen calcination for alumina refining	Demonstration (ARENA 2022)		

					The cost of decarbonising the whole Australian alumina industry is estimated to be $4.5-16.4 billion (Chatfield 2022, AIETI 2023).
		Inert anodes for aluminium smelting	Demonstration (Rio Tinto 2023)	Up to 15% of aluminium smelting emissions (AIETI 2021)	Data not available as it is an emerging technology under development.
		New cell design for aluminium smelting	Research and Development (AIETI 2021)	Indirect emissions benefits by allowing greater use of renewable electricity	Data not available as it is an emerging technology under development.
		Secondary production	Commercial	Up to 95% of emissions from energy use (AIETI 2021), limited to availability of scrap	Dependent on market rate of scrap aluminium.
Iron and steel	16%	Direct reduction of iron with electric arc furnace using hydrogen (using natural gas before hydrogen becomes available)	Demonstration (IEA 2023c) (commercial using natural gas)	Up to 95% of emissions from steel production for hydrogen (MPP 2022) (approximately 40% of emissions for natural gas (WSA 2023))	Levelised costs of steel production are estimated at US$500-860/tonne when using hydrogen (US$410-580/tonne using natural gas) (IEA 2020)
		Secondary production	Commercial	Over 95% of emissions from steel production (WEF 2023, MPP 2022), limited to availability of scrap	Dependent on market rate of scrap steel
Lime and cement	13%	Electric or hydrogen kiln for clinker production	Research and Development	Up to 26% of emissions from cement production (VDZ 2021; MPP 2023)	Data not available as it is an emerging technology under development.
		Material substitution	Commercial	Up to 25% of emissions from cement by reducing the amount of clinker in cement (assumes a change in	Variable, limited to availability of substitution materials

				Australian standards) (MPP 2023; ECRA 2021)	
		Carbon Capture Utilisation and Storage (CCUS)	Demonstration	Up to 52% of emissions from cement production (VDZ 2021; MPP 2023)	Net-zero emissions concrete is expected to increase cement costs by 40-120% and concrete costs by 15-40%, approximately 95% of these additional costs are from CCUS (MPP 2023).
Ammonia	8% for ammonia and derivatives (from Safeguard facilities)	Green hydrogen for ammonia	Commercial	Approximately 65% of emissions from ammonia production (IRENA 2022)	Total capital cost for electrolysis-based ammonia plant estimated at US$2 billion (IEA 2021).
		Steam methane reforming (SMR) with CCS to generate hydrogen for ammonia	Demonstration	Approximately 65% of emissions from ammonia production (IRENA 2022)	Production cost for ammonia from SMR with CCS is estimated to be US$235-465/tonne, depending on natural gas costs (IRENA 2022).
		Electrified steam generation for ammonia	Demonstration	Approximately 33% of emissions from ammonia production (IRENA 2022)	Data not available for standalone equipment as typically part of an integrated plant.
Waste	18%	Diversion of organic waste from landfills	Commercial	Over 90% of emissions from solid waste disposal (German Environment Agency 2023)	Indicative costs for treatments other than landfill (e.g. composting and incineration) of waste range from US$18-156/tonne of waste (Bogner et al. 2007). This can vary widely depending on the treatment, location, type of waste.

Additional technologies	• **Energy efficiency** will provide incremental emissions reduction by driving energy savings. • **Electrification** of low temperature heat is likely to occur at the end of asset life, removing emissions from combusting fuel. • **Thermal storage** is expected to be deployed as part of electrification or energy efficiency upgrades, particularly for medium to high temperature heat processes. • **Biofuels** could be used in existing assets to decarbonise high temperature heat processes in the short to medium term.

Resources

Emissions source	**Percentage of sector scope 1 emissions** (CCA unpublished)	**Technologies**	**Readiness**	**Abatement Potential**	**Cost (AUD or USD)**
Fugitive emissions from coal mines[15]	27%	Ventilation air methane (VAM) abatement technologies (including thermal oxidation, catalytic oxidation, concentrators, chemical looping and safety enablers)	Varies from research and development to demonstration	Applicable to a significant portion of the fugitive emissions from underground coal mines. Up to 23% of coal mine methane using VAM oxidation in Australia (IEA 2024).	Current cost estimates vary between USD$6 – 15 per gigajoule of methane (IEA 2024).
		Drainage systems	Varies from research and development (for open cut mines) to commercial (for underground mines).	Up to 17% of coal mine methane using degasification systems (through coal mine methane utilisation and flaring) in Australia (IEA 2024).	Current cost estimates vary between USD$0 – 50 per gigajoule of methane (IEA 2024).

[15] The majority of fugitive emissions are from underground coal mines.

Fuel combustion in mining[16]	19%	Electrification of haulage and other mining equipment (including trolley assist)	Demonstration	Maximum potential for electrification of other mine site equipment up to 100% of fuel demand (AIETI 2023). Up to 2.7 tonne CO_2-e emissions avoided per 1000 litres of diesel use displaced by battery electric haulage when 100% renewable electricity is used (CEFC and MRIWA 2022).	The CEFC rates the CAPEX intensity as high and OPEX intensity as low for battery electric haulage (CEFC and MRIWA 2022).[17]
		Fuel cell electric trucks	Demonstration	Up to 2.7 tonne CO_2-e emissions avoided per 1000 litres of diesel use displaced by fuel cell electric haulage when 100% renewable electricity is used (CEFC and MRIWA 2022).	The CEFC rates the CAPEX and OPEX intensities as high for fuel cell electric haulage (CEFC and MRIWA 2022).[17]
		In pit crushing and conveying	Commercial	Up to 2.7 tonne CO_2-e emissions avoided per 1000 litres of diesel use displaced by in pit crushing and conveying when 100% renewable electricity is used (CEFC and MRIWA 2022).	The CEFC rates the CAPEX intensity as very high and OPEX intensity as low (CEFC and MRIWA 2022).[17]
Fuel combustion in oil and gas extraction and processing, and LNG production	22%	Electric Drives	Commercial	Applicable to 66% of the LNG sector's energy use (AIETI 2023).	CAPEX estimated to be $12 per tonne LNG and OPEX is estimated to be $0.8 per tonne LNG (AIETI 2023).
		Post combustion Carbon Capture and Storage (CCS)	Research and development	Applicable to 100% of liquefaction energy emissions (AIETI 2023).	Estimated additional current cost of $156 per tonne CO_2-e (AIETI 2023).

[16] The majority of energy consumed in the mining sector is associated with diesel use for haulage and mining equipment (Advisian 2022).

[17] This is a qualitative assessment that is made relative to an internal combustion engine with a CAPEX rating of low and OPEX rating of medium.

Fugitive emissions in oil and gas extraction and processing, and LNG production (venting, flaring and leaks)[18]	19%	Reservoir Carbon Capture and Storage (CCS)	Commercial	Up to 90% of non-energy emissions from gas extraction (AIETI 2023).	Estimated additional current cost of $75 per tonne CO_2-e (AIETI 2023).
		Fugitive abatement measures (including installation of new equipment, replacement of existing equipment and LDAR programs)	Commercial	Up to 33% of fugitive emissions from leaks, flaring and other venting activities (AIETI 2023).	Estimated cost varies between $0-200 per tonne LNG based on a range of technology options (AIETI 2023).
Onsite electricity generation	11%	Onsite renewable electricity or hydrogen production, and storage	Commercial	Up to 2.7 tonne CO_2-e emissions avoided per 1000 litres of diesel use displaced by onsite renewable electricity or renewable hydrogen production (assuming availability of renewable hydrogen externally, or through onsite production) (CEFC and MRIWA 2022).	Solar PV and wind turbines have medium CAPEX and low OPEX (CEFC and MRIWA 2022).[19]
		Post combustion Carbon Capture and Storage (CCS)	Research and development	No data available.	Estimated additional current cost of $156 per tonne CO_2-e (AIETI 2023).
Additional technologies	• **Energy efficiency measures** (including operational performance improvements and technological improvements) across all subsectors which are expected to reduce costs and emissions associated with electricity production and fuel consumption • **Hybrid technologies** in the short to medium term, such as diesel-electric haulage in mining and gas-electric turbine drives in the gas processing and LNG subsectors • **Fuel switching** including the use of biofuels in mining haulage • **Photocatalytic oxidation** of coal mine methane from underground and open cut coal mines				

[18] A significant portion of these emissions in the gas processing and LNG subsectors are due to: (1) venting of the CO_2 which is removed during processing, and (2) flaring.
[19] This is a qualitative assessment that is made relative to a diesel gen-set with a CAPEX rating of low and OPEX rating of high.

Transport

Emissions subsector	Percentage of sector emissions	Technologies	Readiness	Abatement potential	Cost
Light vehicles (including light commercial vehicles)	64%	Electric vehicles (EVs)	EVs made up an estimated 8.4% of all new Australian car sales in 2023 (EV Council 2023). EV sales are growing internationally, and research and development is improving the technology (IEA 2023d). Modelling indicates it is possible to phase in EVs by 2050 (AEMO 2023b).	If internal combustion engine (ICE) vehicles are phased out and EVs are phased in by 2050, this large source of emissions could be fully abated.	Purchase costs of EVs are currently higher than internal combustion engine (ICE) vehicles but are forecast to reach price parity by the 2030s in major markets (BNEF 2023). Forecasts indicate total ownership costs will decline. EVs will have lower total costs of ownership than ICE vehicles by the late 2020s in major markets (BNEF 2023).
		Mode shift to active and public transport	Mode shifting, underpinned by expanding public and active transport infrastructure, or other ways of increasing accessibility are a ready to deploy option.	Urban rail transport is less emissions intensive than private vehicle transport (BITRE 2022). The level of abatement depends on how active and public transport networks can replace private vehicle journeys.	Active or public transport is cheaper than owning a private vehicle (Rural and Regional Affairs and Transport References Committee 2014). Every $1 invested in active transport or bus and urban rail can result in over $2 in returns (McKinsey and Company 2020).
Heavy vehicles	24%	EVs	EVs are available for purchase now but with low model numbers. EVs can be deployed now for urban use and light payloads (EV Council 2022) but are still in the early stages of development for large haul trucks (DCCEEW 2024).	EVs do not have tailpipe emissions (Green Vehicle Guide 2024a). Many rigid trucks and some articulated trucks have use cases that can be electrified.	Purchase costs of heavy EVs are higher than internal combustion vehicles (EV Council 2022) but are predicted to decline. The total cost of ownership for heavy EVs is expected to decline due to lower servicing and refuelling costs (AEMO 2022).
		Hydrogen fuel cell electric	FCEVs are in early commercialisation stages with limited models available. FCEVs are more suitable for long	FCEVs can abate heavy vehicle tailpipe emissions (Green Vehicle Guide 2024b). FCEVs are likely to be adopted in trucks	Internationally, FCEVs are more expensive to purchase than internal combustion models (Transport and Environment 2020). Australia's hydrogen vehicle

		vehicles (FCEV)	distances with heavy payloads and have faster refuelling compared to electric recharging (CSIRO 2023d).	that cannot be electrified. This is likely to be articulated trucks.	market is at an early stage of development so price comparisons are still emerging (CSIRO 2023d).
Domestic aviation	5%[20]	Sustainable Aviation Fuel (SAF)	SAF is a drop in fuel that can be used in existing planes. Production of some SAF types is in commercial stage, but many are in early development stages (CSIRO 2023e).	SAF can reduce lifecycle emissions by up to 94% compared to conventional jet fuel depending on feedstocks and production methods (Prussi et al. 2021).	The levelised cost of SAF production could be 1.6-4.5 times higher than conventional jet fuel in 2023 (CSIRO 2023e).
Domestic shipping	2%	E-fuels (e-diesel, e-methanol)	E-fuels are in early stages of development globally with only a small number of production facilities operating.	E-methanol can reduce lifecycle emissions by between 90 and 100% compared to conventional fuel (Methanol Institute 2022).	E-methanol is projected to be approximately 3-5 times higher cost than conventional fuel in 2025, and requires 2.4 times the volume of fuel to carry the same amount of energy (IRENA 2021; Lloyd's Register 2023).
		Green ammonia	Ammonia as a shipping fuel is in the early stages of development globally (European Maritime Safety Agency 2023).	Green ammonia can reduce emissions by 100% compared to conventional fuel (European Maritime Safety Agency 2023).	Green ammonia is currently 7 times higher cost than conventional fuel, and requires 3 times the volume of fuel to travel the same distance (European Maritime Safety Agency 2023).
Rail	5%	Electric rail	There is already overhead electric rail in Australia for most public transport. 11% of Australia's heavy rail network are electrified (BITRE 2022)	Battery electric and electric rail can abate 100% of rail emissions where deployed (IEA 2023e).	Battery electric rail upfront costs are higher than diesel rail. Maintenance is cheaper for battery electric, however there are charging infrastructure and battery replacement costs (Popovich et al. 2021).
Additional technologies	Other technologies are expected to support the transport sector decarbonisation but were not included in the focus list above for the following reasons:				

[20] 2021 aviation emissions were lower than proceeding years due to activity impacts from COVID-19

	• Hydrogen rail, and electric and hydrogen powered aviation were not included due to low readiness and expected small contribution to emissions reductions by 2050 (CSIRO 2023f; IEA 2023f). • Fuel efficiency, operational efficiencies were excluded because they can only reduce emissions, not entirely abate them. Renewable diesel was excluded on the grounds that competing technologies are more likely to contribute more emissions reductions in terms of pathways to net zero 2050 (IEA 2023a).

Agriculture and Land

Emissions subsector	Percentage of sector emissions	Focus technology and practice change	Readiness	Abatement Potential	Cost (AUD)
Enteric fermentation	63% of agriculture emissions	Feed supplements	- Limited supply of 3-NOP is commercially available. Research suggests no negative effects on animal productivity (MLA 2022). - *Asparagopsis* is available but scaling up of *Asparagopsis* production will be required to allow for widespread adoption in the feedlot industry (AgriFutures 2022). - Further research is required to determine the effects of *Asparagopsis* on animal productivity (Wasson, Yarish & Hristov 2022, MLA 2023). - Delivery mechanism for grazing ruminants is required to ensure appropriate dosing for achieving significant and ongoing emissions reductions (MLA 2018).	- Emissions from enteric fermentation in Australia were 54 Mt CO_2-e in 2021 (DCCEEW 2023e (ANGA website)) - A small subset of these emissions are produced by cattle in feedlots (2 Mt CO_2-e) - Studies on feed supplement use in feedlots report a wide variation in abatement and are dependent on time in feedlot and rate of dosage. Abatement in feedlot settings are reported to be in the range of 28% to 99% (MLA 2022, MLA 2023)	- Costs of feed supplements are reported to be between 30 cents to over $1 per cow per day (Macdonald 2021).

				- Applying these rates of abatement to all feedlots indicates an abatement potential of 0.5 to 1.9 Mt CO_2-e - Application of feed supplements within a broadacre grazing setting would require the development of an effective delivery mechanism for dispersed herds. Further development is needed to identify possible delivery mechanisms for feed supplements in these settings.	
Fertiliser	6% of agriculture emissions	Slow-release and nitrification inhibitor coated fertilisers	- Nitrification inhibiting fertilisers are more expensive than untreated fertiliser, which can discourage broad uptake by farmers (Fertilizer Australia 2023). In the 2023 Annual Progress Report, the authority recommended that the Government explore the potential for incentives to support broad uptake of fertilisers with nitrification inhibitors (CCA 2023b).	- Emissions from nitrogen fertiliser were 6 Mt CO2-e in 2022-23 (CCA 2023b) - Application of nitrification inhibitors can more than halve emissions from nitrogen fertilisers (Grace et al. 2023, Meng et al. 2021).	- Cost of urea fertiliser coated with nitrification inhibitor is around 14% more expensive per unit of nitrogen compared with conventional urea (Fertilizer Australia 2023). - Marginal cost of abatement of $37/t CO2-e (EY 2021). - Nitrification inhibiting fertilisers provide a very small saving to farmers that

					is often not agronomically significant for farmers (Fertilizer Australia 2023).
Manure management	8% of agriculture emissions	Improved manure management practices	- Technologies to reduce emissions such as anaerobic lagoons with methane capture, composting and aerating manure piles are commercially available.	- Methane reduction for manure management for cattle and sheep in pasture is low/unviable. Emissions from manure management from these sources were 3.5 Mt CO_2-e in 2021. - Net Zero Australia (2023) assumes 100% methane reduction potential and 100% uptake of manure management methods at feedlots, piggeries and poultry facilities. Under these assumptions, methane reductions by 2050 could be 3.4 Mt CO_2-e.	- Abatement cost can be negative, where methane can be combusted to produce energy or composted (EY 2021, Energetics 2019). - Nitrification inhibitors applied to animal effluent could have an abatement cost of \$414/t CO_2-e (Energetics 2019).
Fuel use on farms	7% of agriculture emissions	Replacement of fossil fuels with renewable fuel sources or renewable electricity	- Commercial and protype options are available now in international markets for applications such as pumps and tractors, and the range of products in the domestic market is expanding. However capital costs exceed traditional equipment (Acclimate Partners and AFI 2022). - Further development may be required to address issue of	- Applying EY's assumed electrification rate of 60% by 2050 would result in emissions reductions of 4.7 Mt CO2-e (also assuming a decarbonised electricity grid) (EY 2021).	- Transitioning to electric farm equipment is estimated to cost \$113/t CO2-e (EY 2021). - Renewable energy on farms is estimated to cost -\$42/t CO_2-e (EY 2021).

			increased downtime due to charging speed and battery capacity (Acclimate Partners and AFI 2022). - Renewable diesel and biodiesel fuels are available on international markets and some biodiesel is produced domestically. Both renewable diesel and biodiesel can be used in current diesel machinery (Acclimate Partners and AFI 2022).		
Forest land converted to grassland and cropland	4%[21]	Limitation of land clearing Limitation of native forest harvesting	- Avoided land clearing activities are well established (CSIRO 2022).	- Analysis of the sequestration potential associated with the Avoided Clearing of Native Regrowth Australian Carbon Credit Unit (ACCU) scheme methodology indicates that approximately 8 Mt CO_2-e per year is possible, assuming a carbon price of $30/t CO_2-e (CSIRO 2022).	- Avoided clearing of native regrowth is estimated to cost $5-$10/t CO_2-e (CSIRO 2022).
Forest land remaining forest land	-7%				
Land converted to forest land	-9%	Reforestation: Plantation forestry and permanent plantings	Plantation forestry - Technologies and practices for managing plantations are well established in Australia (CSIRO 2022). Permanent plantings	Plantation forestry - The sequestration potential of commercial plantations is approximately 31.8 Mt CO_2-e per year,	Plantation forestry - $10-30/t CO_2-e (CSIRO 2022). Permanent plantings

[21] Sub-sectoral land sector emissions proportions are expressed as a percentage of Australia's total emissions for 2020-21.

			- Revegetation and reforestation activities are well established in Australia (CSIRO 2022).	assuming a carbon price of \$30/t CO_2-e (CSIRO 2022). Permanent plantings - Environmental block and belt plantings could sequester 16 and 0.4 MtCO_2-e per year, respectively, assuming a carbon price of \$30/t CO_2-e (CSIRO 2022). - Other sequestration estimates include 10.7 Mt CO_2-e from on-farm plantings by 2050 (Climateworks Centre 2023) and 21-51 Mt CO_2-e by 2050 (DCCEEW 2021).	- \$20-\$30/t CO_2-e (CSIRO 2022; EY 2021).
Other technologies			There are limited existing solutions that can substantially reduce emissions from livestock, with cost-effective feed additives available at scale still being developed. However, there are a range of other current practice and emerging emissions reductions actions for lowering livestock emissions, such as herd management techniques, pasture management, improved genetics and early life programming, and methane vaccines. Beyond slow-release and nitrification inhibitor coated fertilisers, there are multiple emissions reductions actions for minimising emissions from agriculture, such as digital and precision agriculture. Farming practices that increase the storage of carbon in soils and vegetation include low- or no-till cropping, cover cropping or the addition of biochar or minerals which absorb atmospheric carbon dioxide. There is also increasing attention on the potential impacts of trends in consumption of alternative, low-emissions protein sources, such as plant protein sources (e.g. legumes), lab-grown or cultured meat, or animal meats with lower emissions intensity (e.g. kangaroo, pork or chicken). Changed management practices in relation to farms dams, as well as the preservation and restoration of blue carbon ecosystems, can also help to reduce emissions and increase sequestration.		

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Note: *In addition to peer-reviewed, published articles and books, the authority makes use of literature that has not been published commercially, such as government reports, submissions, data and statistics, as well as information conveyed through oral, visual and audio communications. These sources are particularly important when information is only available as grey literature, covers newly emerging research areas, and contains expert opinions. The authority carefully considers the sources it uses, including relevance and value in a particular context.*

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