Sector Pathways Review

2024

CLIMATE CHANGE AUTHORITY

Ownership
Published by the Climate Change Authority
www.climatechangeauthority.gov.au

ISBN: 978-0-6486349-8-0

Accessibility
The authority makes its documents and information available in accessible formats. If you have problems accessing the document, please contact us at www.climatechangeauthority.gov.au/contact-us or phone 1800 475 869.

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.

Acknowledgements

The authority would like to thank the many individuals and organisations who contributed time and expertise to the development of this report.

In 2024, the authority received 220 submissions, conducted over 220 stakeholder meetings and held numerous roundtables and workshops. The authority also received over 320 submissions in response to its 2023 Issues Paper. These are among the contributions that helped inform the authority's analysis and advice for this special review and will continue to shape our advice throughout 2024. Public submissions are available via the authority's consultation portal.

The authority would also like to thank several government agencies for their assistance, including: the Commonwealth Scientific and Industrial Research Organisation; the Department of Climate Change, Energy, the Environment and Water; the Department of Agriculture, Fisheries and Forestry; the Net Zero Economy Agency; the Department of Industry, Science and Resources; the Department of Infrastructure, Transport, Regional Development, Communications and the Arts; and the Treasury.

The views expressed in this Sector Pathways Review are the authority's own and should not be taken as the views or positions of the entities listed above.

Contents

Summary

Every sector of the economy must play its part in Australia's transition to net zero emissions by 2050. The pathways that best support this transition require Australia to accelerate the deployment of mature, low emissions technologies while rapidly developing emerging technologies. Governments – working together and with businesses, communities and households – need to plan and act to overcome the barriers, take the opportunities, and ensure Australia's rapid, orderly and just transition.

At the request of the Australian Parliament, the Climate Change Authority has identified the potential technology transition and emissions pathways in six sectors – electricity and energy, transport, industry and waste, agriculture and land, resources and the built environment – that best support Australia's transition to net zero emissions by 2050.

The authority has identified the range of emissions reductions that are achievable through the deployment of available and prospective technologies, and examined the relevant barriers, opportunities and enablers for each sector. In identifying possible technology and emissions pathways for each sector, the authority utilised whole-of-economy and sectoral modelling to provide a 'top-down' view and undertook 'ground-up' analysis to complement the modelling, drawing on a range of inputs from research, analysis and extensive consultation.

The modelling undertaken for the authority by the CSIRO, Australia's national science agency, examined several scenarios, two of which are featured in this report. The 'A50/G2' scenario is consistent with Australia achieving its current emissions reduction targets—a 43% reduction on the 2005 level by 2030 and net zero by 2050—in a world tracking to a global warming outcome of less than 2°C. The 'A40/G1.5' scenario is consistent with greater ambition and more rapid emissions reductions in a world on a trajectory to limiting global warming to 1.5°C with no or limited overshoot, in which Australia reaches net zero by 2040.

Working to reduce emissions now, using existing technologies, is far more efficient and effective than waiting and hoping that bigger breakthroughs will do all the work.

Waiting for new, better, cheaper technologies is tantamount to choosing to continue to emit. Waiting means greenhouse gases will continue to accumulate in the atmosphere, trapping more heat and causing more of the impacts already being felt. 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). The most sensible thing to do is to stop emitting greenhouse gases as much and as quickly as possible. It would be a mistake to wait.

The transition to net zero is not just about technologies themselves.

It involves the operational and behavioural choices governments, businesses, communities, households and individuals make about which technologies are used, when and how. It includes adopting new business models and circular economy principles, shifting transport modes, and making different choices about how much and what we consume.

For the purposes of this report the authority defined '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 pathways that best support Australia's transition to net zero emissions by 2050 involve accelerating deployment of mature zero and low emissions technologies, and the rapid development and commercialisation of emerging technologies.

Mature and proven technologies can substantially reduce Australia's emissions this decade and represent the lowest-cost way forward. Accelerating their deployment represents the 'low-hanging fruit' of the net zero transition. Decarbonising Australia's electricity supply as soon as possible will address Australia's largest source of emissions and is vital to unlocking emissions reductions in other sectors through electrification—replacing vehicles, appliances and industrial equipment powered by fossil fuels with new, efficient electric versions.

This will mean generating more electricity than ever before while transitioning to renewables connected by transmission and firmed with batteries, pumped hydro and gas generators, and potentially hydrogen over the longer term. Successfully managing the challenges of sequencing, integrating and optimising the deployment of these technologies, and the risks to reliability and security of supply, is crucial for ensuring an orderly transition.

Table S.1: Summary of key emissions reductions technologies by sector

	ELECTRICTY AND ENERGY	TRANSPORT	INDUSTRY AND WASTE	AGRICULTURE AND LAND	RESOURCES	BUILT ENVIRONMENT
Mature technologies	Wind, solar, pumped hydro, lithium batteries, gas-fired generation, synchronous condensers.	Battery electric light vehicles, mode shift, overhead electric rail.	Electrification (low/medium temperature process heat), energy efficiency, circular economy, diversion of organic waste from landfill.	Forest/ vegetation protection, carbon farming, enhanced fertilisers, improved herd and pasture management, manure management, off-grid renewable energy.	Electrification, energy efficiency, carbon capture and storage, off-grid renewable energy and storage, fugitive abatement measures in oil and gas extraction, underground coal mine gas drainage and utilisation.	Electrification (hot water, cooking, air conditioning), rooftop solar and battery storage, energy/thermal efficiency.
Demonstrated and early-stage technologies	Hydrogen production and turbines, new battery/long duration storage solutions.	For transport other than light vehicles: electrification, hydrogen, renewable fuels.	Electrification/ hydrogen for high temperature process heat, hydrogen (in ammonia, alumina, iron), carbon capture and use, direct air capture/ engineered removals.	Renewable fuels, battery electric farm vehicles, feed supplements, methane vaccines, early-life nutrition, new forms of protein.	Electrification (mining haulage), ventilation air methane abatement measures, renewable fuels, open-cut coal mine gas drainage.	Grid integration.

Note: Nuclear power generation is not included here as it is currently prohibited in Australia (see section EE.2.6).

A greater focus on boosting energy efficiency and incentives for energy demand to respond to supply signals in the electricity market will help. This includes bringing together consideration of 'demand-side' measures under the National Energy Productivity Strategy with planning for the supply of electricity through such processes as the Integrated System Plan for the National Electricity Market. Increased energy efficiency will produce benefits for energy consumers, contribute emissions reductions while the supply of electricity decarbonises, and lessen the overall amount of investment required in new clean energy infrastructure.

Demonstrated and early-stage technologies are within reach and will address more difficult to abate emissions over time, including from heavy transport, industrial processes and agriculture. Policy support and investment are needed to accelerate the deployment of these technologies, so they can have a meaningful impact in the 2030s and 2040s. These technologies include hydrogen and its derivatives, biofuels, solutions for livestock emissions (e.g. *Asparagopsis*), and carbon capture and use.

A range of sector pathways can combine to achieve net zero by 2050. All require significant effort.

The authority's ground-up analysis of each sector and the CSIRO's modelling of potential sector pathways are summarised in Figure S.1 below, with green bands illustrative of the range of potential pathways.

For some sectors, the authority's ground-up analysis and the two modelled scenarios closely align. In the electricity and energy sector, the technologies exist, the transition is well underway, and there is more certainty about what can be achieved with the right policies. This is also the case for the transport and built environment sectors, although their transitions are less well progressed.

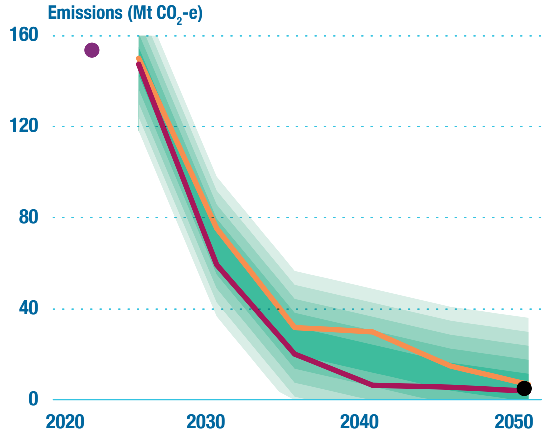
For other sectors there is more uncertainty, reflected by the range of outcomes across the modelling scenarios and ground-up analysis. In the resources, and agriculture and land sectors, the authority's ground-up analysis found that there are considerable real-world barriers that make the modelled outcomes difficult to achieve. Conversely, the authority's view is that there are opportunities in the industry and waste sector to achieve greater emissions reductions than the modelling suggests.

Technologies that are still experimental or generally unknown today could be 'game changers' in coming decades, completely redefining how countries think about achieving net zero. Cost breakthroughs in existing technologies could also pave the way for faster action to reduce emissions.The authority has not attempted in this report to examine how, where or when such future breakthroughs could occur. However, Australia has proven that it can both lead the world in scientific discoveries and quickly adopt game-changing technologies developed overseas, and it should seek to do both in the net zero transition.

Each sector is on a different emissions reduction pathway to Australia's net zero goal. For some, the pathway will be steep and rapid because technologies are mature and ready to scale (e.g. electricity and energy). Others face a slower and more gradual route because technologies are at an earlier stage of development or more barriers stand in the way (e.g. agriculture). Many sectors are dependent on the progress of others, particularly those reliant on the supply of renewable energy from the electricity and energy sector (e.g. transport, built environment).

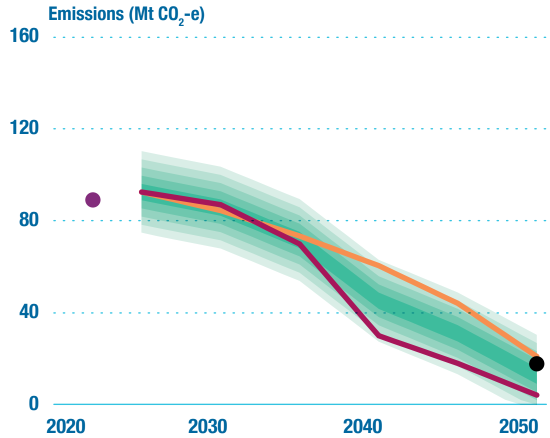
Figure S.1: Sector insights and potential pathways

Electricity and Energy



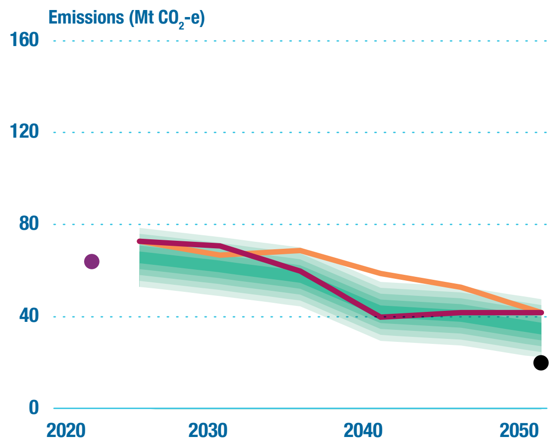
- Decarbonising electricity will address Australia's largest source of emissions and is vital to unlocking emissions reductions in other sectors.
- A massive construction effort is required to install renewable capacity, and poles and wires, to supply two-to-three times more electricity than generated today by 2050.
- Action is required to ensure there is enough storage in the system for system reliability.
- New sources of essential system services will be needed to maintain system security.

Transport



- Global manufacturers can supply the electric vehicles to decarbonise the passenger and light commercial vehicle fleet, which accounts for roughly half of Australia's transport emissions.
- Roll-out of charging infrastructure needs to lead the rapid uptake of electric vehicles.
- A mix of solutions will be required in other transport categories, including alternative liquid fuels and potentially hydrogen. Biofuels, such as biodiesel and Sustainable Aviation Fuel, will play an important but niche role—further planning and clarity are needed on the growth of this industry.

Industry and Waste

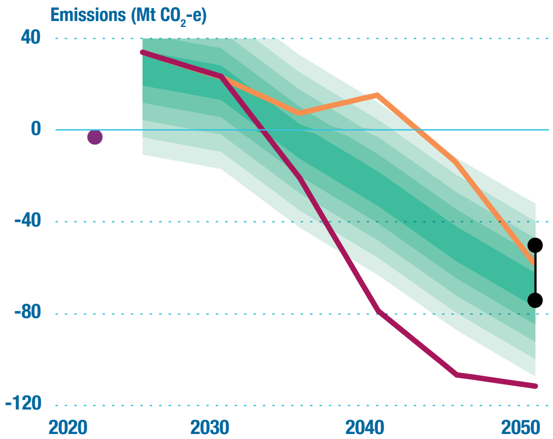


- Australia can secure a prime position as a manufacturer and exporter of low emissions alumina and aluminium by converting current high emitting processes to renewable electricity and hydrogen.
- Australia can achieve emissions reductions in the manufacture of steel with available lower emitting technologies, using natural gas in the short term. Low or zero emissions hydrogen will enable deep decarbonisation of domestic steel and ammonia production.
- The progress of hydrogen in achieving projected cost and production levels to displace fossil fuels in domestic markets needs to be closely monitored.

A50/G2 A40/G1.5 CCA GROUND-UP ANALYSIS
POTENTIAL PATHWAYS 2022 ACTUAL SECTOR EMISSIONS

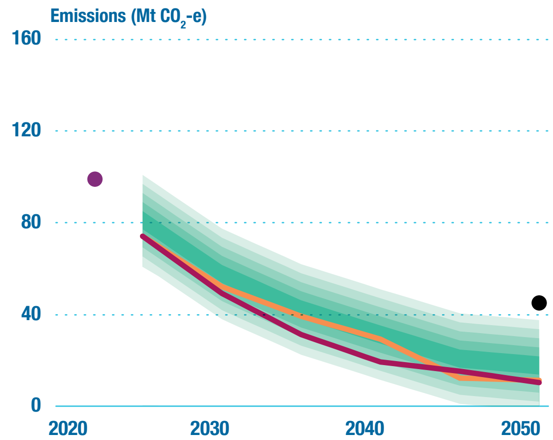
Figure S.1: Sector insights and potential pathways (continued)

Agriculture and Land



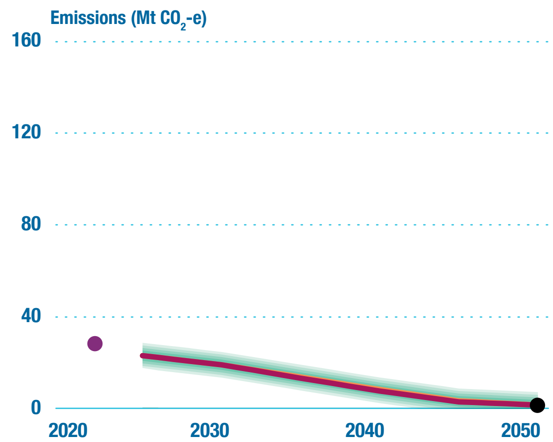
- Reducing livestock emissions, which account for more than half of agricultural emissions, requires changes in the way protein is grown.
- Major reductions in livestock emissions may not be realised until the late 2030s and in the 2040s. More investment in R&D is needed.
- Achieving Australia's net zero emissions reduction target may require the conversion of land to forest and this would require careful planning.
- The supply of suitable land for reforestation is limited, highlighting the need to focus on directly reducing emissions in all sectors.

Resources



- Australia can continue as a world leading resource producer. However, there will be a shift to increased iron and other metals and minerals production, and away from coal and eventually gas.
- The electrification of LNG processing with low or zero emissions electricity and deployment of carbon capture and storage to sequester reservoir CO_2 can lower the fuel combustion and fugitive carbon dioxide emissions footprint of Australia's gas industry.
- Electrification of mining haulage and ore processing are significant opportunities for Australia to build on its strengths as a resource exporter and position itself as an exporter of low emissions resources.

Built Environment



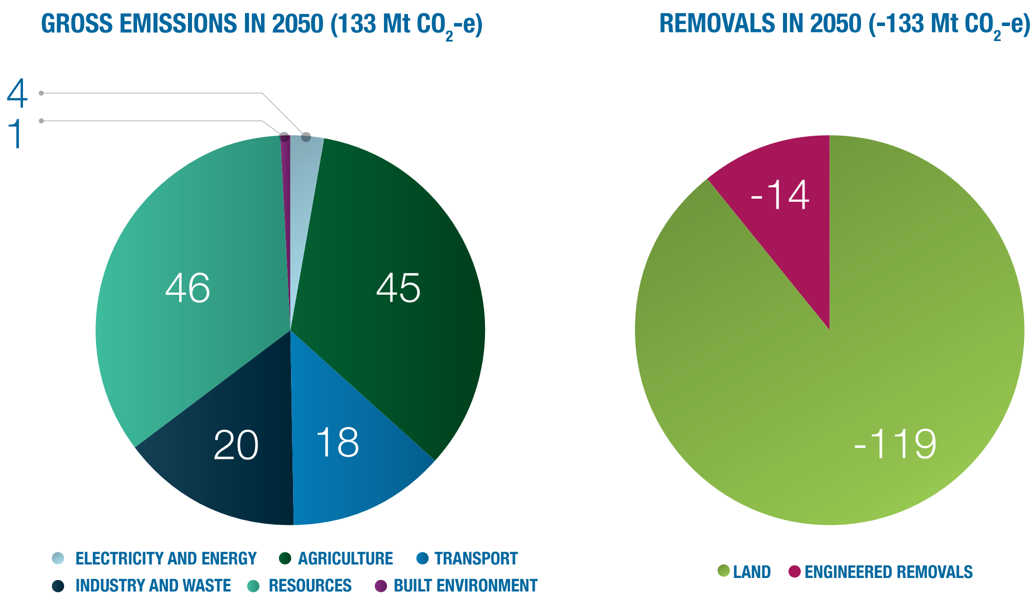
- Energy efficient, electrical appliances for hot water, heating and cooking can lower emissions and save money for households and businesses. Stronger regulation and targeted funding to address upfront costs can drive faster outcomes.
- The energy efficiency of the building stock can be improved by extending standards and reporting to a wider range of commercial buildings, and implementing a mandatory residential building efficiency scheme.
- Boosting energy efficiency and valuing demand response can reduce emissions while the supply of electricity decarbonises and can lessen the investment needed in new clean energy infrastructure.

A50/G2 — A40/G1.5 ● CCA GROUND-UP ANALYSIS
● POTENTIAL PATHWAYS ● 2022 ACTUAL SECTOR EMISSIONS

Only the land sector is projected to achieve net negative emissions, and it does so by removing carbon from the atmosphere through the age-old technologies of managing soils and vegetation. New, engineered technologies to remove carbon from the atmosphere are under development but are likely to remain expensive, energy- and water-intensive, and require access to land.

The more emissions remain in the system by 2050, the more removals will be required to counteract (or offset) them if net zero is to be achieved. And the more removals are required, the greater the impacts on energy supply, water, and other land uses. The authority holds the view that it makes sense to minimise the need for removals by reducing emissions directly as much as possible and as soon as possible. Figure S.2 shows the possible sectoral composition of net zero in 2050 based on the authority's ground-up analysis.

Figure S.2: Sectoral composition of net zero in 2050 (Mt CO_2-e) – ground-up analysis



Source: CCA analysis.

Notes: The authority's ground-up estimate of gross emissions in 2050, totalling 133 Mt CO_2-e (left). Estimated sink from the land sector and potential role for engineered removals to offset gross emissions in 2050 (right). The authority's upper estimate for the net sink from the land sector was 119 Mt CO_2-e and the remaining 14 Mt CO_2-e is consistent with the authority's analysis of the potential role engineered removal technologies, such as direct air capture and storage, could play in achieving net zero. See Box IW.2 in the Industry section of this report and the authority's examination of carbon dioxide removals in its 2023 insights paper, Reduce, remove and store: The role of carbon sequestration in accelerating Australia's decarbonisation.

Ultimately, there are many sets of sector pathways that can combine to achieve net zero by 2050. Like nations under the Paris Agreement, sectors can be thought of as having 'common but differentiated responsibilities and respective capabilities' when it comes to meeting Australia's national targets. This report does not recommend specific emissions reduction targets for each sector. Instead, it sets out the abatement potential of each sector on Australia's pathway to net zero emissions by 2050.

A clear conclusion from the authority's analysis is that none of the potential sets of pathways will be easy and every sector will need to play a unique but important role. Across all sectors, a significant and urgent ramp up in effort, investment and coordination is required and there are barriers that will need to be overcome if Australia is to achieve its target.

The transition to net zero involves much more than each sector moving along technology-based decarbonisation pathways. A zero-carbon mindset must become the new normal so that it permeates operational, policy and investment and purchasing decisions across governments, businesses and households.

It requires actively managing a major reorganisation of public and private finance, supply chains, production systems, industrial zones, energy sources, infrastructure and workforces within Australia.

It means close collaboration between governments, businesses, First Nations people, landholders, communities and households, and between Australia and its Pacific neighbours and international trading partners.

It means making trade-offs between alternative uses of limited resources including energy, water and land, and working towards a circular economy to reduce the need for virgin resource extraction.

It means actively ensuring an equitable transition so that the burdens and benefits are fairly shared between governments, sectors, businesses, regions and communities.

And it means judiciously deploying every tool in the policy toolkit, including information, markets, regulations, planning, investment, and international engagement, towards achieving Australia's net zero goal.

The federal government is in the driver's seat for Australia's transition to net zero emissions by 2050. The Net Zero Plan will need to bring together sectoral plans and a whole of economy strategy to reach net zero, and set out how the Australian Government will work with the states and territories given the crucial role they play.

The government has stated that its Net Zero Plan will articulate Australia's transition to net zero, including the government's priorities, policies and measures for driving down emissions and supporting ongoing and new investment in low emissions and renewable activities.

The opportunity for the government is to prepare a Net Zero Plan that provides clear, long-term signals to businesses, investors and households on the transition of the Australian economy in a world moving to net zero emissions. It can set out the roles to be played by the different parts of the economy and provide foundations for supporting regions and the disadvantaged with the transition.

All levels of government must work together in planning for and coordinating the transition to net zero emissions, to ensure policy architecture, investment horizons and regulatory environments are aligned. The states and territories have a significant role to play given their authority over many energy, infrastructure and transport projects. Close cooperation between the Australian Government and states and territories will therefore be necessary to ensure policy and legislative alignment. Similarly, responsibility for skills, education and training is shared between the federal and state and territory governments. Local governments play a significant role in land use planning and development within their jurisdiction, and are often best-placed to engage with the community to provide education and gather input and feedback on planning and development matters.

Australians can achieve net zero by 2050 only by working together to overcome the barriers that stand in the way.

There are barriers that stand in the way of the timely deployment of technologies needed to secure Australia's transition to net zero emissions by 2050. The key barriers identified by the authority are:

- lack of willingness to pay the 'green premium' – the higher cost of low and zero emissions technologies relative to the high emissions technologies they must replace, which often face no penalty for the harm caused by the greenhouse gas emissions they generate
- slow and complicated development approval processes for renewable energy and enabling infrastructure projects
- a lack of community support (referred to as 'social licence') for changes such as deployment of key clean energy infrastructure like wind farms and transmission lines
- constraints in supply chains for important low emissions technologies including renewable energy generation, electric mining and haulage equipment and low emissions liquid fuels
- workforce shortages, particularly in regional areas and highly skilled new industries
- information and data gaps that impede planning for decarbonisation, the workforce it will require, and the investment decisions that could finance it.

Below the authority sets out the strategies and actions that can be incorporated in the Net Zero Plan for overcoming the barriers to Australia's transition to a prosperous, net zero economy. In addition to the (mainly) cross-sectoral strategies and actions listed below, sector-specific enablers and opportunities are described throughout the report.

The future is inherently uncertain. Plans need to facilitate bold and urgent action while being sufficiently flexible to accommodate new technologies and knowledge as they emerge. By adopting an adaptive approach, Australia's plan to reach net zero can offer a reliable way forward, empowering businesses, investors and communities to navigate uncertainties with confidence.

Strategies and actions for the net zero plan

1. Overcome the 'green premium' through fit-for-purpose policy interventions, including regulation, market-based mechanisms and government finance to leverage private investment

The Australian Government has in place a suite of mechanisms that mandate or put a value on reducing greenhouse gas emissions and channel finance to low and zero emissions activities. These include market-based mechanisms (e.g. the Safeguard Mechanism and ACCU Scheme), and institutions and programs such as CEFC and ARENA, the National Reconstruction Fund, and the Capacity Investment Scheme that support achievement of net zero objectives. States and territories have programs of their own.

There are also standards that regulate emissions or energy use, including the New Vehicle Efficiency Standard for light vehicles and the Greenhouse and Energy Minimum Standards for consumer appliances. Some states encourage energy efficiency through 'white certificate schemes' and grant programs.

However, these foundations must be built upon if Australia is to get on and stay on the pathway to net zero. Some sources of emissions are not covered by policy interventions, or where policies are in place they need strengthening or complementary measures to ensure barriers are overcome. The government should plan for the scope, scale, pace and sequencing of technology deployment that could achieve net zero at least cost and risk, and implement policies accordingly. Plans should be adaptive and implemented effectively and efficiently through judicious use of every tool in the policy toolkit, including information, markets, regulations, planning, investment, and international engagements.

Actions

- Expand the scope of key existing policy frameworks such as the Safeguard Mechanism, ACCU scheme and National Greenhouse and Energy Reporting Scheme.
- For the electricity and energy sector—to provide greater certainty and stronger signals for investors—strengthen the Capacity Investment Scheme (which could be legislated, administered by a standalone statutory agency and increased in size and pace) and establish policy settings and market design arrangements that will continue to drive the clean energy transition beyond 2030.
- Further promote efficient decision-making and resource allocation by harmonising signalling across the economy on the cost of carbon (value of emissions reductions), through standardised guidance developed by the Treasury for use in government and regulatory decision-making.
- Set interim goals and guiderails within each sector that strive for ambition while promoting an orderly transition, based on the principle of common but differentiated responsibilities and respective capabilities.
- Tighten and broaden mandatory emissions and energy efficiency standards for consumer and commercial products.
- Establish a 'one stop shop', which could be within the Net Zero Economy Authority, to help people find and access the federal, state and territory emissions reduction financial support programs that best suit their circumstances and needs.
- Pursue an orderly phase-out of government policies and programs that support emissions-intensive activities while redirecting resources— including skills and capital—to support clean energy and low emissions alternatives.
- Develop a National Carbon Market Strategy that includes setting out how carbon offsetting will be used to channel finance towards deployment of removals technologies without substituting or delaying direct emissions reductions.

2. Accelerate the deployment of net zero infrastructure by reforming planning and approvals processes, coordinating business engagement within and across jurisdictions, and identifying and fast-tracking the development of renewable energy zones and clean industrial hubs.

Planning and approvals processes are slowing the necessary expansion of renewable energy generation and related and essential infrastructure such as energy storage projects and transmission lines. Taking an integrated, place-based approach to the challenges and opportunities of the net zero transition will enhance Australia's prospects for success. For example, identifying 'zones' or 'hubs' where facilitating combinations of projects in renewable generation, hydrogen production and carbon capture and storage can bring together the ingredients for decarbonising existing activities and facilitating new green industries. Coordinating across levels of government to address these challenges and leverage these opportunities will be essential.

Actions

- Prioritise net zero transition projects in a principled, planned approach with input from the Net Zero Economy Authority and in collaboration with state, territory and local governments.
- Simplify, coordinate and expedite approval processes for priority projects within and between jurisdictions.
- Use sector plans and National Energy Transformation Partnerships as the basis for building a set of government-industry agreements, with principles, time limits on decision making and agreements under which governments and businesses navigate approvals together.
- Develop low emissions industrial precincts, including pre-evaluation of regions for suitability for priority activities and new net zero industries, and of the renewable electricity generation and other infrastructure needed to power them, based on principles including environmental and community impacts.
- Accelerate access to firmed, off-grid renewable electricity, including by developing common user infrastructure.
- Ensure sufficient energy storage and synchronous generation is deployed in the electricity system for system reliability and security to be preserved, without slowing the closure of coal-fired power stations and deployment of renewables and storage.

3. Strengthen the foundations for social licence and a just transition to net zero

through enhancing climate literacy, building capacity in business and communities to negotiate benefit and burden-sharing arrangements, and working with communities to support the net zero transition.

The impacts of climate change and climate-related policies affect the wellbeing of Australians in different ways. Climate-related wellbeing in turn affects the social licence granted by communities and the people who live in them for the changes required for decarbonisation to proceed, such as support for new renewable electricity projects and installation of transmission lines. The Net Zero Plan should promote a just transition – whereby the means and ends of the net zero transition entail an equitable sharing of the burdens and benefits as Australia accelerates emissions reductions and adopts new ways of doing things.

Actions

- Develop a dedicated, independent information and engagement campaign to combat mis- and dis-information and to build climate literacy and understanding of the Net Zero Plan.
- For priority transition projects, work with state, territory and local governments to adopt a best-practice benefit and burden sharing framework.
- Make available a toolkit to help governments, project developers and communities (including remote, rural, regional and First Nations communities) negotiate agreements with free, prior and informed consent.
- Adopt a strategic, place-based approach to urban planning and regional development so, where viable, the benefits of new industries can be co-located with burdens of declining industries and infrastructure.

4. **Think global, act local** for Australia to prosper in a net zero world.

Australia is a small, open trading economy. Global decarbonisation presents both challenges and opportunities for Australia, and Australia's net zero transition has consequences for how we interact with the rest of the world, including via the international competitiveness of our businesses and industries. International cooperation can yield substantial benefits for Australia while supporting our trading partners' emissions reduction efforts.

Actions

- Negotiate bilateral decarbonisation agreements with key trading partners to help secure supply chains for essential net zero technologies and inputs and support an orderly transition away from fossil fuels for mutual benefit.
- Plan for and signal early investment in the infrastructure necessary for the transformation of the energy system, to retain Australia's spot in the global supply chain queues.
- Develop and implement plans for the decarbonisation of Australia's exports and to support more rapid emissions reductions overseas, leveraging our comparative advantages (e.g. renewable energy, critical minerals and sequestration potential) and preparing for the inevitable decline in demand for fossil fuel exports.
- Implement a carbon border adjustment measure to maintain the competitiveness of Australian businesses as decarbonisation accelerates.

5. **Rapidly address workforce shortages** by diversifying and deploying a rapid skills program and enhancing workforce mobility.

The rapid transformation to a net zero economy necessitates a rapid capability build. Workforce and skills shortages are already emerging as a barrier to decarbonising almost every sector of the economy.

Jobs and Skills Australia has found that if workforce pipelines are not adjusted, skills shortages could prevent Australia reaching net zero by 2050, and from realising opportunities to broaden its industrial base.

Actions

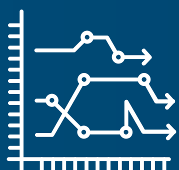
- Reinstate and expand the ABS Employment in Renewable Energy Activities statistics to enable better workforce planning in clean energy and low carbon activities, particularly in regional areas. Data collection should include renewable energy construction, energy efficiency construction, energy generation and low and zero carbon transport workforces. See more on information and data gaps below.
- Embed workforce planning in sector plans, with governments working together with businesses to prioritise workforce diversification and ensure a fit-for-purpose education system.

6. **Address information and data gaps** by expanding, simplifying and automating data collection and dissemination.

Information is crucial for effective planning and for well-functioning markets. There is already a range of schemes in place to ensure policymakers, consumers, businesses and investors can be well-informed of the consequences of their decisions in terms of emissions outcomes and energy use. However, there is much more that could be done.

Actions

- Expand the suite of government resources that enable individuals and businesses to make better informed purchasing decisions (like the Green Vehicle Guide, the National Australian Built Environment Rating System, GEMS, and Guarantee of Origin) and put them in one place as a one stop shop to provide tailored information, including on:
    - the benefits and risks of investments in electrification, energy efficiency, and fleet electrification
    - the value proposition for farmers and businesses of adopting low emissions practices and technologies
    - the cost-of-living benefits to households of adopting energy efficiency and electrification.
- Following the implementation of mandatory climate-related financial disclosures, prioritise establishing mandatory digital reporting as a next step to give investors, financial institutions, businesses, developers, governments and end-users ready access to data about emissions in their supply chains.
- Incorporate a net zero data strategy in the Net Zero Plan, which expands the collection of, and enhances the availability of, the data that consumers, businesses and investors require to make informed decisions in keeping with Australia's net zero goals.



Introduction

Australia's transition to a net zero economy is necessary, inevitable and urgent. Among developed countries, Australia is one of the most vulnerable to the impacts of climate change. The impacts of nearly 1.5 degrees of warming can already be seen in trends of declining rainfall in the south-east and south-west, an increase in extreme fire weather and longer fire seasons, higher sea surface temperatures, rising sea levels and increasing ocean acidification.

A temperature rise of 2.9°C[1] – 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 (2023) – would present severe risks to Australia's economic, social and environmental life (Australian Academy of Science, 2021; Lawrence et al., 2023).

Australia can prosper in a world with lower emissions, and not only because it would deliver a more hospitable climate. With its plentiful solar and wind resources, Australia can generate large amounts of renewable energy relative to the size of its population. 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.

With these advantages, Australia can 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, 2023). The emergence of new, low and zero carbon industries can counterbalance the loss of jobs, income and international competitiveness associated with declining demand for Australia's fossil fuel exports.

1 The uncertainty range around the 2.9°C figure is 2.0 – 3.7°C, with a 66% chance of remaining within this range. The data underpinning the range include all 'unconditional' Nationally Determined Contributions (those that are not contingent on international support such as finance, technology transfer or capacity building) announced up to 25 September 2023 (UNEP 2023, pp. 23-31).

Australia in 2050

The future is inherently uncertain, but a net zero world in 2050 will undoubtedly be different from the one we live in today.

In a net zero 2050 world, Australians would be living and working in more efficient and comfortable buildings, with improved health and greater resilience to climate-related hazards. Transport would continue to be affordable, accessible, reliable, safe while also being zero emissions. People would easily and quickly charge their electric vehicles at home, work, along highways and at many other destinations. A large increase in public and active transport infrastructure would give people greater access to transport and better health, reducing congestion, traffic noise, and reliance on private vehicles.

Australia's economy would be powered by the secure and reliable supply of renewable electricity, and the export of products manufactured using that energy. Fossil fuel industries would have largely phased out, replaced by rising critical minerals and 'green' metals industries, like green iron, that harness Australia's natural endowments and a circular economy. In doing so, Australia would have created new jobs and opportunities in rural and regional communities. Australia's agricultural lands and biodiversity would be strong, vibrant, productive and integrated. First Nations people would benefit as leaders and partners in the transition on the First Nations estate, and by undertaking traditional and cultural land management practices on Country.

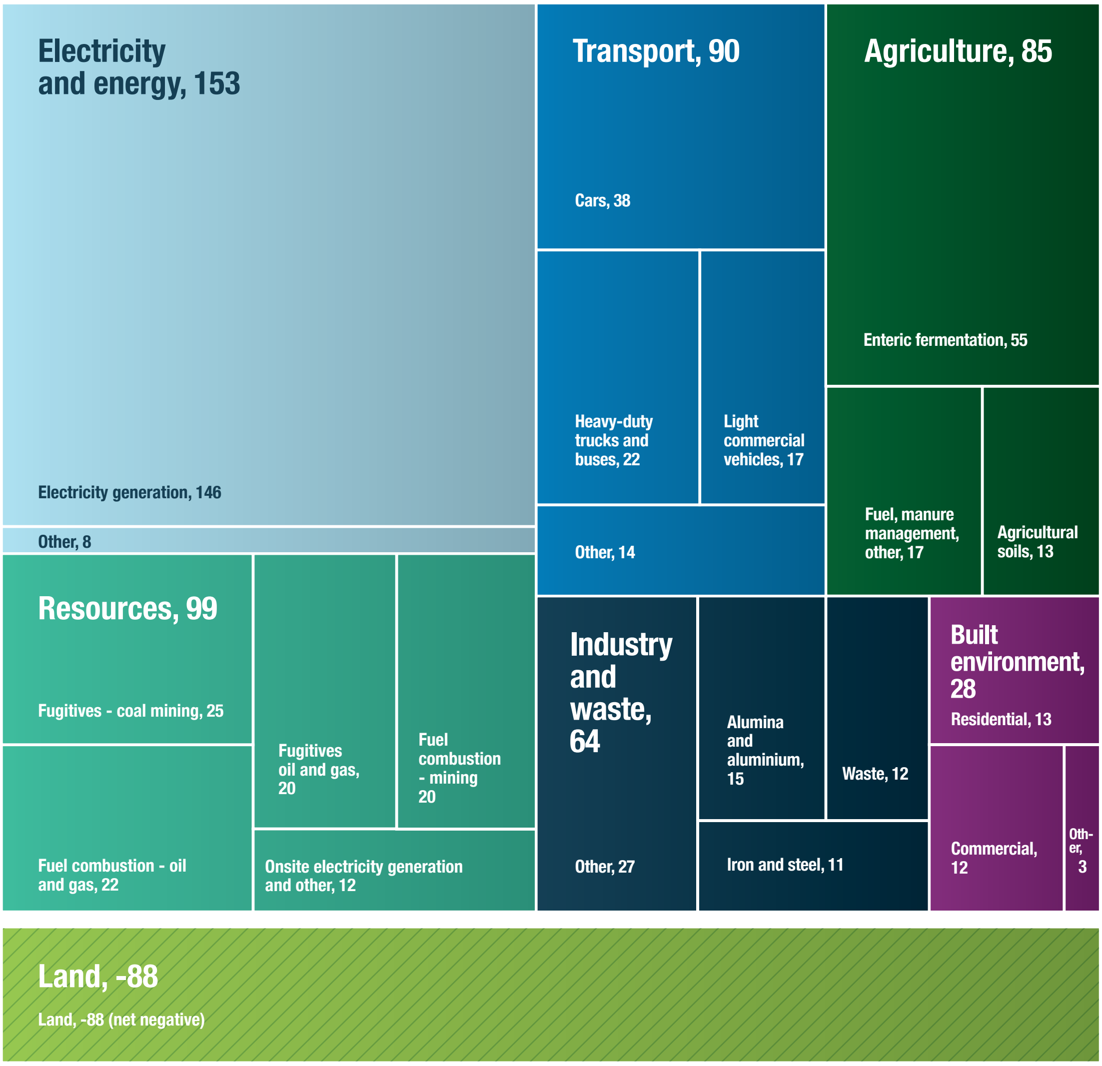
Australia stands to benefit by following a planned, orderly pathway to net zero. The Australian Government, as well as state, territory and local governments, are already setting emissions reduction targets and rolling out policies to achieve them. Australian businesses and households are adopting low emissions technologies such as rooftop solar, heat pumps and electric vehicles. Australia's peer countries and trading partners, including those who currently rely on Australia's fossil fuels for their energy security, have also announced emissions reduction targets and are ratcheting up action towards meeting them.

Australia risks being left behind if it acts too slowly or fails to successfully navigate the global transition. As the rest of the world continues to decarbonise, global demand for the significant fossil fuel component of Australia's exports can be expected to decline and the demand for green products will increase. Australia will face a world that, increasingly, no longer wants its coal, gas and oil, and that is seeking zero emissions versions of other key exports like iron ore, bauxite and alumina. Without alternative green metals, minerals and energy exports, Australia will be left with a hole in its economy.

The emissions reduction task and the authority's approach to this review

Australia is committed to achieving net zero greenhouse gas emissions by 2050, a 433 Mt CO_2-e decline from 2021-22 levels[2]. Figure I.1 shows how Australia's emissions were distributed across sectors of the economy in 2021-22. The challenge for Australia is to reduce emissions in each sector as much as possible, as soon as possible, and to remove as much carbon dioxide from the atmosphere as fast as possible.

Figure I.1: Sectoral share of Australia's emissions (Mt CO_2-e), 2021-22



Source: Sector totals from authority national sectoral pathways emissions mapping based on Australia's National Greenhouse Accounts and emissions reported under the National Greenhouse and Energy Reporting Scheme.

Notes: See Appendix B for more information about the authority's mapping of emissions to sectors, and the sector chapters in Part 1 for more information about the breakdown of emissions within sectors. This figure separates the agriculture and land sector into agriculture and land subsectors. Subsector emissions may not sum to sector totals due to rounding.

2 2021-22 is the most recent year with final data. Sources: CCA analysis based on Australia's National Greenhouse Accounts.

The authority focused its modelling analysis for this report on two emissions reduction scenarios representing potential Australian and global ambition, summarised in Table I.1.

Table I.1: Emissions reduction scenarios modelled by the CSIRO to frame the analysis for this report

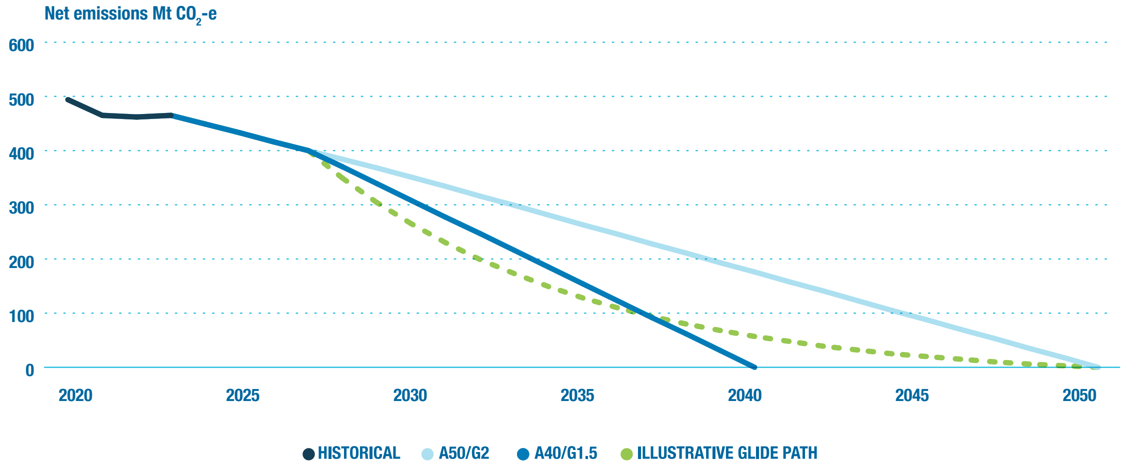
A50/G2	A40/G1.5
• Australia achieves its current 2030 target and reaches net zero in 2050 • Global emissions are consistent with limiting the average temperature increase to under 2°C	• Australia overachieves on its 2030 target and reaches net zero in 2040 • Global emissions are consistent with limiting the average temperature increase to 1.5°C
This scenario is consistent with Australia achieving its current 2030 and 2050 emissions reduction targets in a less than 2°C world. Although these targets are challenging, Australia is not a leader in decarbonisation in this world and reaches net zero in 2050, while many other developed nations reach net zero in 2040 or 2045. The global energy mix retains more fossil fuel demand than the 1.5°C world, and Australia's fossil fuel production declines gradually. There is a strong global investment in negative emissions (land-based and technology-based emissions removals) to support the achievement of this goal.	This scenario is consistent with the world cooperating to limit warming to 1.5°C. Australian targets are consistent with greater ambition from other developed nations. Australia achieves a 75% reduction on 2005 levels in 2035 and net zero by 2040, reflecting greater ambition and more rapid emissions reductions. Fossil fuel demand falls more rapidly globally and in Australia, and there is even stronger investment in negative emissions technologies.

These two modelling scenarios assume Australia's emissions decline in a straight line to net zero in either 2040 or 2050. The straight-line trajectories are simplified, indicative representations of different average levels of ambition across the entire Australian economy. These two trajectories are shown in Figure I.2. More information about the modelling is at Appendix C and in the accompanying CSIRO modelling report.

Australia's emissions will not follow a straight line, and nor should they. The curved line in Figure I.2 is an example trajectory that contributes similar total cumulative emissions reductions by the time it reaches net zero in 2050 as the straight line trajectory to net zero in 2040. The cumulative emissions over time are represented by the areas under the three lines. Greater, early effort will mean less total emissions (a smaller emissions budget) over the period to 2050. Delaying efforts increases the risk of several adverse outcomes for Australia:

- a later, more expensive and less orderly transition
- missed or delayed opportunities for cost-of-living relief through energy efficiency and electrification
- missing new green export opportunities
- attracting carbon tariffs to Australia's exports
- impacts on Australia's reputation, particularly in the region
- slower global momentum towards reducing emissions and hence heightened risks of dangerous climate change impacts.

Figure I.2: Stylised trajectories to net zero – modelled straight line trajectories and an illustrative curved trajectory



Source: Authority analysis of DCCEEW (2023).

Note: Historical emissions are from DCCEEW's Quarterly Update of Australia's National Greenhouse Gas Inventory: June 2023 as this was the most recent when the modelling was undertaken.

The modelling does not provide forecasts of the future, but it does provide insights about possible developments in each sector and across the economy under different emissions pathways. It has limitations in that results depend on input assumptions, including about technology costs, and it is a simplified representation of the economy that cannot take all relevant factors into account. It is one line of evidence that sits alongside detailed analysis and consultation the authority undertook in each sector to inform this review.

In its ground-up analysis of each sector, the authority considered the range of real-world factors not well captured by economic modelling that enhance understanding of the unique emissions trajectories available to each sector and their respective roles in the economy as a whole achieving net zero. Potential impacts on jobs, communities, rural and regional areas, businesses and Australia's economy, as well as ways to mitigate and manage them, are considered throughout the report. See Appendices B and C for more information about the authority's analysis and modelling approaches.

When combined, the sector trajectories will result in a real-world pathway to net zero that is unlikely to be linear. Greater or faster emissions reductions could be achieved if barriers to technology adoption are more quickly overcome, new 'game changing' technologies emerge, or technology costs decline faster than incorporated in the modelling – as evidence suggests could well be the case (Way et al., 2022).

An economy-wide 'net zero' target does not mean that all emissions from a sector, facility, business or household are necessarily eliminated by 2050. The authority's analysis is not unique in finding that, based on our knowledge of technologies today, there will very likely be residual emissions across the economy that will need to be counterbalanced with carbon dioxide removals to achieve net zero emissions (see Part 2).

In the electricity and industry sectors, emissions reductions can be lumpy as a relatively small number of high emitting pieces of capital equipment, such as coal-fired generators, are replaced. The land sector has already achieved net negative emissions, and there are opportunities in the electricity (renewables), transport (light electric vehicles) and built environment (heat pumps for space and water heating) sectors to make relatively fast and steady progress.

Technologies to address some emissions sources in the agriculture (methane emissions from enteric fermentation), mining (fugitive methane emissions) and industry (high heat) sectors will take longer to implement. More emissions may remain in 2050 in those sectors. The extent to which barriers to the adoption of new technologies can be overcome will also impact how steep and smooth the trajectory of emissions reductions in each sector is. These factors are discussed further in the sector chapters in Part 1 and in Appendix C.

For simplicity, individual technologies (such as solar photovoltaics), clusters of technologies (such as renewable energy), and operational changes (such as using appliances more in the middle of the day), as well as other types of abatement and emissions reduction activities and opportunities are collectively referred to as ‘technologies’ in this report. Technologies referred to throughout this report can be categorised into three broad categories of readiness:

Mature technologies are ready and available to be deployed now. Mature technologies are already being widely adopted, but barriers may prevent their full, rapid deployment in some circumstances.

Demonstrated technologies are available but not yet widely adopted. Barriers need to be overcome for these technologies to become widely available and deployed to their full potential.

Early-stage technologies are still in the research, development and demonstration stage or are not yet ready to be deployed due to significant barriers that will take some time to overcome.

Under both scenarios and both analytical approaches, sector pathways are heavily reliant on the electricity sector decarbonising quickly, and more than doubling its output to support increased electricity demand from electrification across the economy. Energy efficiency in every sector, including the built environment, can help smooth the transition by reducing costs for consumers and pressure on the electricity system.

In the transport, resources, industry and waste, and electricity sectors, hydrogen can play a key role to reduce emissions beyond what is possible with renewables and electrification alone. It will also be an enabler of new export opportunities such as green metals and critical minerals.

The resources sector remains an important and significant part of the Australian economy, with an increasing role for the critical minerals and metals required to produce batteries, solar panels, wind turbines, electric vehicles and green manufactured products.

Australia’s agricultural businesses, including exporters of Australian livestock and crops, continue to be an integral part of the economic landscape. Agriculture is likely to be the largest source of remaining emissions in 2050.

The remainder of this report outlines sector pathways to net zero, the barriers that stand in the way, and the means to overcome them.

- Part 1 sets out the potential technology and emissions pathways in each sector and the barriers and opportunities they entail.
- Part 2 provides an economy-wide view of Australia’s pathways to net zero emissions by 2050, the barriers that affect all sectors, and Australia’s pathway to prosperity.

References

Australian Academy of Science. (2021). The Risks to Australia of a 3°C Warmer World. https://www.science.org.au/files/userfiles/support/reports-and-plans/2021/risks-australia-three-deg-warmer-world-report.pdf

CCA (Climate Change Authority). (2023). Reduce, remove and store: The role of carbon sequestration in accelerating Australia's decarbonisation. https://www.climatechangeauthority.gov.au/publications/reduce-remove-and-store-role-carbon-sequestration-accelerating-australias-decarbonisation

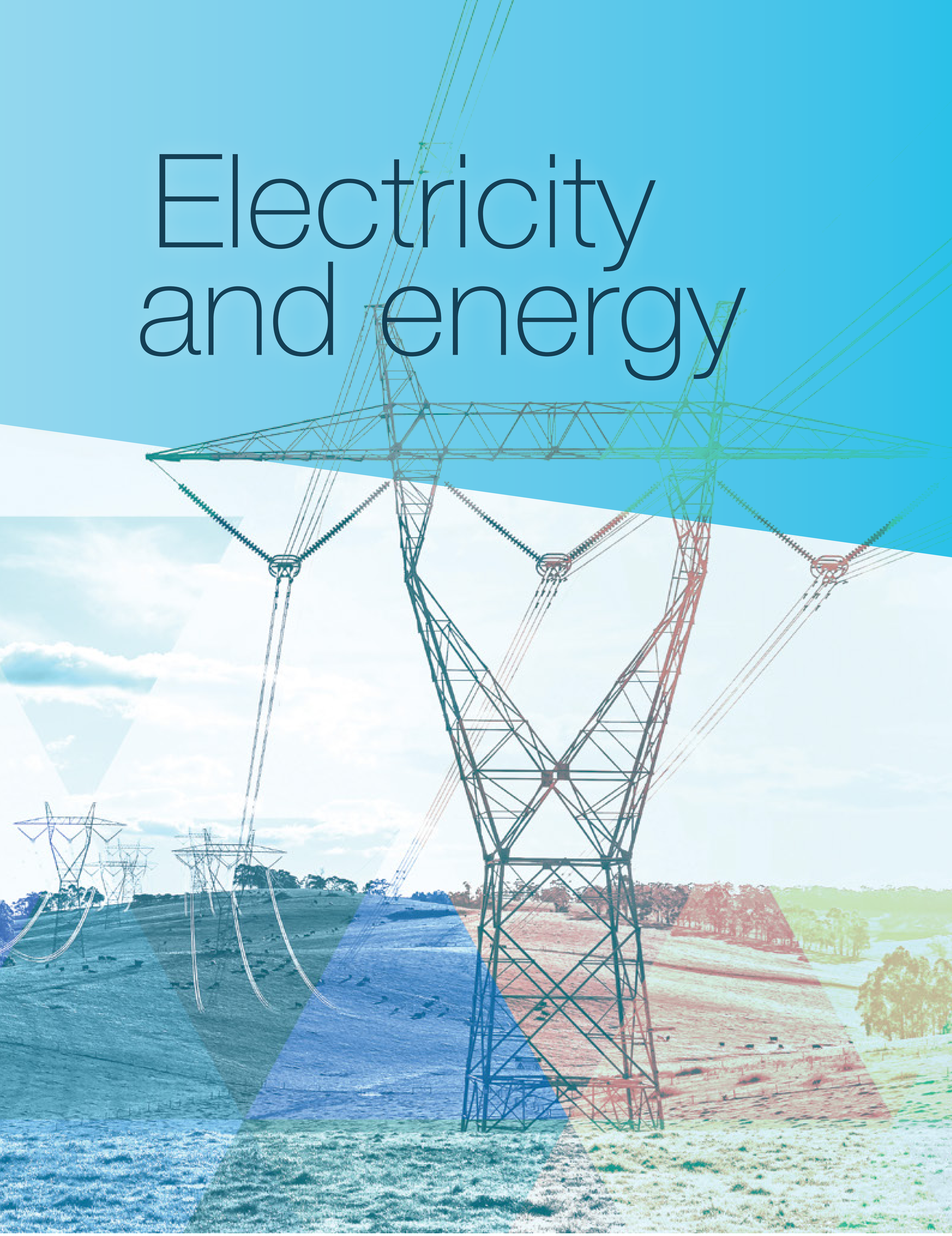
DCCEEW (Department of Climate Change, Energy, the Environment and Water). (2023). National Greenhouse Gas Inventory Quarterly Update: June 2023. https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-gas-inventory-quarterly-update-june-2023

Lawrence, J., Mackey, B., Chiew, F., Costello, M. J., Hennessey, K., Lansbury, N., Nidumolu, U. B., Pecl, G., Rickards, L., Tapper, N., Woodward, A., & Wreford, A. (2023). Australasia. In Climate Change 2022 – Impacts, Adaptation and Vulnerability (pp. 1581–1688). Cambridge University Press. https://doi.org/10.1017/9781009325844.013

UNEP (United Nations Environment Programme). (2023). Emissions Gap Report 2023: Broken Record – Temperatures hit new highs, yet world fails to cut emissions (again). https://doi.org/10.59117/20.500.11822/43922

Way, R., Ives, M. C., Mealy, P., & Farmer, J. D. (2022). Empirically grounded technology forecasts and the energy transition. Joule, 6(9), 2057–2082. https://doi.org/10.1016/j.joule.2022.08.009

Electricity and energy



ELECTRICITY AND ENERGY

Sector summary

Rapid decarbonisation and expansion of the electricity and energy sector is the key to meeting Australia's economy-wide emissions reduction targets. There is a clear and viable decarbonisation pathway for the sector that relies on known technologies to deliver very large emissions reductions and facilitate reductions in other sectors.

The electricity and energy sector accounts for 35% of Australia's emissions – higher than any other sector. Further, the decarbonisation of several other sectors (such as industry and transport) will not be possible without rapid transformation of the energy system. Energy loads in those sectors will need to be switched to electricity or derivatives of electricity, such as electrolytic hydrogen.

Renewable electricity generation and storage capacity must substantially increase through to 2050 if Australia is to meet its emissions reduction targets, and even more so if Australia is to contribute to global goals through clean energy intensive exports. The sector's decarbonisation technologies are well established: wind, solar PV, batteries, pumped hydro, with most of that generation capacity interconnected with transmission infrastructure. These technologies are commercial, but they will now need to be deployed at much greater scale. Uncertainty or delays in deployment will put emissions reduction ambitions at real risk.

The necessary infrastructure roll-out in this sector is complex, resource intensive and requires considerable planning and coordination. To ensure electricity is available when needed and is stored when demand is lower, firming and storage technologies that complement renewable generation must be deployed at pace and at scale. The reliability and security services provided by retiring coal-fired power generation must be replaced by new system security technologies, including some that have not yet been tested at grid-scale. Natural gas will be required for some time for firming and back-up supply. Additional transmission infrastructure will also need to be established to efficiently transmit electricity to distribution networks or storage.

There are persistent barriers to progressing this transformation at sufficient scale and pace. Global demand for transition materials will grow enormously over the long term, at times placing great pressure on supply chains. Government and industry must earn social licence from electricity consumers and from communities impacted by infrastructure. Planning and approvals processes must become better resourced, more efficient and transparent and strike an appropriate balance between climate and broader environmental objectives. Traditional Owners must be included as partners in the deployment of infrastructure on their land. The skilled clean energy workforce will need to grow substantially, and soon.

The sector's pathway requires government intervention to stimulate, broker and convene investment in technologies, update rules that govern Australia's energy markets, acquire social licence and support the stability of grids that will be under pressure from new demands.

EE.1 Sector state of play

EE.1.1 Economic contribution

In 2022-23, the electricity and energy directly added a gross value of $30 billion (rounded and based on current prices) to Australia's economy, which amounted to 1% of GDP. While this is only a small proportion of economic output, the essential services the sector provides support the operation of the entire economy. In 2022-23 the sector's workforce comprised 91,000 individuals, 24% of whom were female (Appendix B).

EE.1.2 Sources of emissions

In 2022, the electricity and energy sector's emissions were 153.4 Mt CO_2-e or 35% of Australia's total emissions (Table EE.1) (CCA unpublished).

Electricity generation on Australia's grids contributes approximately 95% of the sector's emissions. Emissions from the manufacture and supply of energy products (e.g. the refining of petrol) is captured in the sector, noting the end use of these products mainly occurs in other sectors, such as transport. The sector will also include any emissions resulting from the production of hydrogen in the future, which is not currently mass-produced in Australia and for which such emissions are negligible.

The deployment of renewable energy generation and storage has driven emissions reductions in the electricity subsector. The emissions intensity of Australia's largest grid, the National Electricity Market (NEM), has reduced from 0.95 tonnes of carbon dioxide equivalent per megawatt hour (CO_2-e/MWh) in 2005 to 0.59 tonnes of CO_2-e/MWh in 2022 – a decline of 37% (Open NEM, 2024). This has been driven by the exit of coal-fired generation and growth in output from renewables, which increased from approximately 1,200 gigawatt hours (GWh) in 2005 to 81,000 GWh in 2023.

Table EE.1: Emissions sources in the electricity and energy sector

Sub sector	Mt CO_2-e	Subsector share (%)
Electricity generation[1]	145.9	95.1%
Petroleum refining	2.4	1.6%
Other energy industries	0.4	0.3%
Petroleum and coal product manufacturing	1.3	0.9%
Military transport	0.7	0.5%
Distribution of natural gas	1.2	0.8%
Transmission of natural gas	0.4	0.3%
Pipeline transport	0.9	0.6%
Electrical equipment	0.2	0.1%
Total	153.4	100%

Note: Mt CO_2-e and Subsector share (%) may not sum to the totals due to rounding.

1 Emissions associated with off-grid electricity are not captured in electricity generation. These emissions are captured in the Industry chapter

Box EE.1: Achieving 82% renewable electricity generation by 2030

To continue supply of electricity while coal generators reach end-of-life and are withdrawn from the grid, Australia will need to rely on renewable electricity generation technologies such as wind and solar PV.

The Australian Government has a target of 82% renewable electricity by 2030. In 2023, in the electricity generation from renewables in the NEM averaged 39%. Rapidly increasing the share of renewables will provide a significant boost to the decarbonisation of the whole economy.

In its 2023 Annual Progress Report the authority raised concerns about progress to the 82% renewable electricity target and made a series of recommendations aimed at addressing delays. In the 9 months since, the government has taken important steps towards enhancing the prospects of achieving its target, including significantly expanding its Capacity Investment Scheme for encouraging new investment in renewable generation capacity and energy storage. As noted elsewhere in this chapter, there are still barriers to overcome.

The authority will update its assessment of progress to the 82% target in its 2024 Annual Progress Report.

EE.2 Existing and prospective technologies

To identify the technology transition and emission pathways that best support Australia's transition to net zero emissions by 2050, the authority first applied criteria of cost competitiveness on a capital cost basis and prospective deployment timeframes. Other considerations, including abatement potential, barriers, finance, workforce matters, data gaps and the principles set out in the *Climate Change Authority Act 2011*, are discussed in later sections. Selected technologies are at Table EE.2.

Table EE.2: Technologies to support emissions reductions in the electricity and energy sector

Emissions reduction opportunity	Deployment timeframe[2] (Aurecon 2024)	Cost:[3] BESS and PHES: $/KWh. All other rows: $/KW. (Graham et al., 2024, except where noted)
Wind	Onshore Development: 3 to 5 years Construction: 2.5 years Offshore Development: over 7 years Construction: 6 years	Onshore: $3,038 Offshore wind: $5,545 to $7,658
Solar photovoltaic (PV)	Rooftop 2-3 days Utility-scale Development: 2 to 3 years Construction: 1.5 years	Rooftop: $1,505 Utility-scale: $1,526
Battery Energy Storage Systems (BESS)	Residential 90 days Utility: 1-2 hr capacity Development: 1-2 years Construction: 1.5 to 2 years Utility: 4-8 hr capacity Development: 1-2 years Construction: 2 years	Residential: $14,400 installed (Aurecon, 2024) Utility: 1-2 hr capacity 1 hr: $1009; 2 hr: $731 Utility: 4-8 hr capacity 4 hr: $592; 8 hr: $519
Pumped hydro energy storage (PHES)	Development: 3 to 5 years Construction: 4 to 8 years	6 hr: $635; 8 hr: $517 12 hr: $363 24 hr: $242 (mainland) - $150 (Tas) 48 hr: $142 (mainland) - $66 (Tas)
Gas Turbines	Development: 2 years Construction: 2 years	Small turbine: $1,684 Large turbine: $1,059
Hydrogen	Project contingent	Project contingent
Transmission	Project contingent	Project contingent

With uptake of the technologies outlined in Table EE.2, the share of renewable electricity generation in the grid is projected to reach more than 99% by 2050, according to a number of modelling studies (Table EE.3). By 2035, these analyses project Australia's renewable share reaching between 81% to over 99%.

2 All year data are approximations rounded to the closest year or half year.
3 Figures are capital cost and are for 2023. The cost for Residential BESS is total cost.

Table EE.3: Share of renewable energy as primary generation

Author	Scenario description	2035 Renewable generation	2050 Renewable generation
Net Zero Australia	Rapid electrification with full renewables rollout	99.8%	100%
AEMO	Green Energy Exports	99.3%	99.8%
Net Zero Australia	Rapid electrification	98.8%	99.6%
Climateworks	1.5 degrees aligned	98.2%	99.8%
AEMO	Step Change	95.6%	98.6%
CSIRO for CCA	AusTIMES modelling (A40/G1.5)	93.2%	99.3%
Climateworks	well below 2 degrees aligned	93.3%	99.7%
CSIRO for CCA	AusTIMES modelling (A50/G2)	89.5%	98.8%
Net Zero Australia	Rapid electrification with constrained renewable roll-out	88.3%	99.2%
DCCEEW	Projections baseline	83%	Not available

Sources: Calculated from (AEMO, 2024d; Climateworks Centre, 2023a; Davis et al., 2023; DCCEEW, 2023)

Note: Climateworks figures included under 2035 are for 2036. AEMO ISP figures are for 2034-35.
Note: Net Zero Australia scenarios are domestic electricity generation only.

EE.2.1 Wind

EE.2.1.1 Onshore wind

Onshore wind power stations are a proven zero emissions source of electricity generation in Australia. The costs of installed wind generation are forecast to decline, however, limitations in global supply chains may mean these cost declines are not realised in the near term.

EE.2.1.2 Offshore wind

The offshore wind industry in Australia's is still in its very early stages. The Australian Government has awarded feasibility licenses for six potential offshore wind projects off Gippsland's coast in Victoria, with a further six in Gippsland and one in the Hunter off NSW that are subject to consultation with First Nations communities. Further licensing will be required before construction and operation commence. Offshore wind is also the most expensive technology, by capital cost, in Table EE.2 and has a projected 10-year readiness timeframe.

Offshore wind resources can offer advantages over onshore wind, including stronger and less turbulent winds with generation profiles that are complementary to other technologies, such as solar PV. The location of offshore wind can negate some of the social licence impacts present with much of the sector's onshore infrastructure (Aurecon, 2024), including visual and noise pollution concerns. However, offshore wind also presents unique social licence challenges, including impacts on Sea Country for Traditional Owners (GLaWAC, 2022) and concerns over the impact of on-land infrastructure such as transmission lines necessary to connect offshore wind generation to the grid (AEIC, 2023).

EE.2.2 Solar photovoltaic (PV)

EE.2.2.1 Utility-scale solar PV

Utility-scale solar PV power stations are a proven zero emissions source of electricity generation in Australia.

EE.2.2.2 Distributed solar PV

Mass deployment of distributed solar PV is a proven zero emissions source of electricity generation in Australia. Distributed solar provides system security benefits through reducing demand on the grid during the day. As more coordinated consumer energy resource battery systems are installed, rooftop solar could play a role smoothing demand outside daylight hours.

EE.2.3 Energy storage

The Australian Energy Market Operator has forecast for the Optimal Development Path in its Step Change Scenario a quadrupling of firming capacity from sources alternative to coal that can respond to the changing output from variable renewable generation (AEMO, 2024a). Much of the forecast growth is in residential batteries (consumer energy resources forming 'virtual power plants'), which becomes increasingly important alongside utility-scale batteries and pumped hydro. The Australian Energy Council's submission (2024) stated that long duration storage requires policy support to provide certainty to investment decisions that factor in long build times, high capital expenditure and prospects of delay.

EE.2.3.1 Battery energy storage systems (BESS)

AEMO's 2024 Integrated Systems Plan projects significant growth in residential batteries, to facilitate intra-day storage of rooftop solar during times of excess supply of electricity (AEMO, 2024a). Installed capacity of residential battery systems is projected to exceed total capacity of shallow (under 4 hours), medium (4 to 12 hours), and deep (12 hours plus) utility-scale BESS by 2035-36.

EE.2.3.2 Pumped Hydro Energy Storage

Pumped hydro storage, capable of providing dispatchable generation more than 12 hours, can smooth out inter-day variations in demand and renewable supply in Australia's future high variable renewable energy grid. Pumped hydro is currently the most expensive form of available generation and storage on a capital cost basis and is a mature technology with limited expectations of deployment-driven cost reductions.

The Snowy 2.0 pumped hydro project is currently under construction with a forecast completion date of 2029 (AEMO, 2024a). There are a wide range of views on the benefits that this project may, or may not, deliver to electricity production and reliability in the NEM. Based on the current completion timeframe this project will come online when the NEM is reaching long run renewable energy generation of well above 50%, when the need for back-up and firming will be high.

EE.2.4 Gas turbines

Open cycle gas turbines (OCGT) are currently a widely deployed technology in Australia and many modelling exercises see this role continuing through to 2050. As the Hunter Power Project in Kurri Kurri NSW has demonstrated, it takes considerable time to plan and deploy gas-fired generation. Forward planning is needed to identify whether, and if so how, the deployment of firming generation, including gas-fired power, is deployed in the system so that it is established at the required time and scale to enable the timely closure of coal power, without slowing deployment of renewables and storage.

To 2030, peaking infrastructure may be developed and operated as capable of running multiple fuels, such as natural gas and hydrogen (authority consultation with AEMO, 2024). While all new gas turbine projects could include provision for hydrogen blending and eventual conversion to hydrogen firing (AEMO, 2024a), 100% hydrogen gas turbines are not yet commercially available (Gilmore et al., 2023).

EE.2.5 Hydrogen

There are two options available for the creation of zero emissions hydrogen as a fuel for electricity generation: electrolysis of water and stream methane reforming (SMR) of natural gas with CCS. Neither of these are in mass production in Australia in 2024.

Chevron Australia's submission (2024) suggested the use of hydrogen as a fuel for electricity generation can be pursued to lower the emissions intensity of dispatchable power, finding that the first uses of hydrogen for power generation will likely be in co-firing with natural gas. AEMO has assessed that hydrogen's ability to replace or blend with natural gas as a peaking fuel is constrained by the cost, as it is a relatively expensive fuel to produce at scale (AEMO, 2024a). The ISP notes the viability of green hydrogen as an alternative fuel to natural gas may increase if the cost-efficiency of hydrogen increases or there is greater government support for hydrogen turbines (AEMO, 2024a).

The Clean Energy Regulator (CER) and Department of Climate Change, Energy, the Environment and Water (DCCEEW) are developing a Guarantee of Origin (GO) Scheme to track emissions intensity for production of products (CER, 2024a). A GO Scheme is currently being developed for hydrogen (CER, 2024b).

EE.2.6 Nuclear

Nuclear was not included in the authority's list of technologies to support emissions reductions in the electricity and energy sector (Table EE.2). The authority received seven submissions in response to its issues paper that discussed nuclear energy. The Minerals Council of Australia (2024) and the National Farmers' Federation (2024) both proposed that the existing legislative prohibitions on approval of nuclear power generation should be removed to facilitate its evaluation against other technology options. Five stakeholders provided submissions that stated that nuclear is not a technology solution for consideration due to its high cost and long lead times for deployment (EnergyAustralia, Farmers for Climate Action, IEEFA, Bushfire Survivors for Climate Action, Australian Conservation Foundation, submissions 2024).

Nuclear power generation is presently banned under federal legislation and there are also prohibitions at the state and territory level. The prospects for nuclear power stations in Australia are further diminished because of its high cost relative to other low carbon generation technologies. Australia's lack of experience in building and managing nuclear power stations may reasonably lead to additional costs for a first-of-a-kind unit deployed in Australia. The estimated lead time of 15 to 20 years before operation (Graham et al., 2024) suggests this technology cannot make a timely contribution to replacing the generation capacity of retiring coal-fired power stations or to helping Australia achieve its carbon budget targets to 2050.

Nonetheless, the size of Australia's decarbonisation tasks means where technologies are competitive and can make a material contribution to decarbonisation, they should be considered. For example, a future dramatic cost reduction in new build nuclear plants would necessitate a re-evaluation of this technology for deployment in Australia. In this context, nuclear should continue to be monitored as an option.

EE.2.7. Transmission infrastructure

The NEM consists of approximately 40,000 km of transmission lines and cables. Achievement of AEMO's Optimal Development Path (ODP) as outlined in the 2024 ISP would require around 10,000 km of new transmission lines by 2050 (AEMO, 2024a). Additionally, West Australia's South West Interconnected System requires an additional 4,000 km in network augmentation to support an estimated 50 GW of new generation (WA Government, 2023b).

In addition to the large transmission growth needed to connect renewable energy zones and storage sites to demand centres, AEMO modelling has indicated the need for the construction of four interconnectors to transmit variable renewable electricity.

> Once investors have sufficient confidence that the transmission build-out is occurring, there can be efficiency gains from construction of generation infrastructure in parallel or near-parallel to the construction of transmission infrastructure.

EE.3 Barriers, opportunities and enablers

EE.3.1 Green premium

The authority's research found commercially mature technologies are struggling to move through the regulatory and policy environment, creating uncertainty for investors in Australia.

The Government's expanded Capacity Investment Scheme (CIS) is intended to deliver 32 gigawatts of renewable and clean dispatchable projects worth $67 billion, with the first tender process run in May 2024 (DCCEEW, 2024a). While stakeholders noted the size and scope of the CIS is sufficient for incentivising investment out to 2027, the authority notes that the design is unlikely to:

- attract tenders from long duration storage options such as pumped hydro storage, which will be necessary to balance the seasonal operation of the grid in the longer-term, but has lead times of over 8 years and relatively high upfront costs (CCA, 2022)
- support more nascent technology in the electricity and energy sector that may be needed longer term to reduce residual emissions in the sector
- provide the longer-term signals needed for investment in the sector beyond 2030.

The authority heard from stakeholders that public investment through grants, debt and equity options, is required to support private capital to varying degrees, depending on the level of maturity of a technology (IGCC submission, 2024). Some stakeholders noted equity investments in shared infrastructure of significant national value such as transmission and generation should be considered (Chevron Australia, Anonymous, submissions, 2024), while another noted long-term finance beyond 2030 is necessary to ensure a stable investment environment (Southerly Ten submission, 2024).

Box EE.2: Producing and consuming more efficiently

Producing and consuming more efficiently can not only reduce emissions but also moderate the cost pressures on all six sectors as they decarbonise. This is particularly important to help minimise the build out of the electricity system required to support the substitution of clean electricity for fossil fuels. Enhancing efficiency also reduces costs for businesses and households and can provide health benefits (e.g. wellbeing effects from public and active transport, and thermal efficiency of housing) and environmental benefits (e.g. less waste).

There are many mature energy efficiency technologies. In the built environment, improvements to building thermal efficiency and appliance efficiency can reduce energy demand. Building energy demand can be further reduced by managing electricity loads through digitalisation and grid-integration of buildings. In the industry sector, energy efficiency can include process improvements and equipment upgrades, and technologies such as waste heat recovery.

The goal of a circular economy is to decouple economic growth from the negative impacts of resource depletion and environmental degradation (Hofmann, 2019). Transitioning to a circular economy has been receiving increased recognition for its potential to reduce emissions by decreasing material extraction, production, and transport (Bashmakov et al., 2023; Wang et al., 2022). A circular economy minimises waste, retains the value of materials, reduces the use of primary resources and keeps products, parts and materials circulating within supply chains (Morseletto, 2020). Examples include recycling organic material to recover nutrients, recycling ferrous scrap metal and batteries to reduce the need for ongoing resource extraction, and employing improved design to use less material in buildings.

On a pathway to net zero emissions, there will remain circumstances where fossil fuel use can facilitate a transition to zero emissions where lower emissions technologies are not yet available. In these cases, improving the efficiency of fossil fuel use may be the best way to reduce emissions. For example, gas will play an ongoing role in the electricity system as a firming technology to support an accelerated transition to renewables. Using lower emissions gas to replace metallurgical coal in steelmaking furnaces may be preferable if lower emissions technologies are not yet viable for a given facility. In some locations, continued use of gas as a feedstock in hydrogen production, particularly when combined with carbon capture and storage (blue hydrogen), may provide a low-cost source of hydrogen for decarbonising industries and smooth a transition to hydrogen produced with renewables and electrolysis (green hydrogen) as that industry develops.

EE.3.2 Planning, approval and coordination

Several stakeholders have stated that a key barrier to deployment at the pace required are planning and approvals timeframes (Australian Energy Council, Stromlo Energy, Blue Carbon Lab, AGL, submissions 2024).

Approval timeframes can vary considerably between jurisdictions (CCA, 2023). Extended approval timeframes can be driven by factors including lengthy and inconsistent assessment processes involving multiple steps, poor coordination between agencies, frequent and unclear requests for information from agencies and approvals processes that are subject to changing expectations and implementation of new guidelines after applications have been lodged (HSF & CEIG, 2024).

> Several stakeholders have stated that a key barrier to deployment at the pace required are planning and approvals timeframes… Extended approval timeframes can be driven by factors including lengthy and inconsistent assessment processes involving multiple steps, poor coordination between agencies, frequent and unclear requests for information from agencies and approvals processes that are subject to changing expectations…

The process of seeking and obtaining approval to connect to the electricity grid may also be a barrier to investment in generation and storage capacity. The CEC raised concerns regarding uncertain timeframes, governance and the transparency of how decisions are made when generation applicants provide studies of expected plant performance (the 'R1' stage), finding these may cause investors to price in premiums associated with these risks, decrease or delay investment (CEC, 2023).

The Australian Government has options to expedite renewable projects. The *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) approval processes could include processes to streamline applications and grant them a priority status (CCA, 2023). The Review of the EPBC Act found that 'improved community participation in processes can save time by ensuring that the right information surfaces at the right time and can be considered in the decision-making process.' (Samuel, 2020). Reform proposals for the EPBC regime include better community consultation, increased transparency and modernised regulatory practice, such as devoting more departmental resources to assist project proponents improve outcomes for the environment.

The CEIG recommends addressing planning and assessment bottlenecks under the EPBC regime and pointed towards its recent publications (HSF & CEIG, 2023, 2024) which identify a host of opportunities to speed up planning and approval processes at state levels. In New South Wales, these include using ministerial powers to declare any relevant categories of clean energy and transmission development to be considered Critical State Significant Infrastructure to enable an accelerated and streamlined approval process under the *Environmental Planning and Assessment Act 1979* (NSW).

The CEIG and Herbert Smith Freehills have also recommended the integration of renewable energy zones and strategic assessments with regional planning under the EPBC Act. This aligns with the Clean Energy Council's submission (2024) that timeframes and costs can be reduced by undertaking region-wide environmental and social assessments for renewable energy zones in place of a project-by-project basis. The Clean Energy Council further submitted that governments will need additional administrative capacity to expedite assessments; and that coordination within governments must be improved.

EE.3.3 Supply chain constraints

Strong global competition for the components and materials of renewable energy generators poses a risk to the cost-effective and timely supply of electricity and energy infrastructure in Australia (AEMO, 2024a). Stakeholders have indicated to the authority that a whole-of-Commonwealth procurement strategy could avoid outcomes where Australian jurisdictions and project developers compete against each other for critical components and equipment which presents risks to project costs, viability, and timelines.

AEMO suggests that early investment in infrastructure to retain Australia's spot in the global supply chain queues and avoid out-year supply squeezes is an effective risk mitigation option (AEMO, 2024a).

An example of a supply chain risk is the availability of synchronous condensers and the time it take for these to be ordered and delivered. AEMO modelling has indicated that to maintain system strength in a NEM capable of sustaining 100% renewable penetration the equivalent of 40 synchronous condensers would be needed to provide inertia, frequency response, system strength and voltage control requirements (AEMO, 2022). The global market is highly competitive for large synchronous condensers, resulting in lead times in excess of five years to plan, order and deliver (AEMO, 2023).

EE.3.4 Gaining social licence

Finding a suitable approach to engaging communities and landholders to earn trust and acceptance – social licence – is a key element for the successful roll-out of Australia's energy infrastructure (CCA Consultation 2024; AEMO, 2024a; Dyer, 2023).

The narrative regarding infrastructure's role in the energy transition, together with perceived benefits, are the two single most important factors in predicting social acceptance of living near renewable energy infrastructure (CSIRO, 2024a). Numerous stakeholders highlighted the importance of securing and maintaining social licence for enabling the buildout of energy infrastructure projects (Investor Group on Climate Change, Chevron Australia, Australian Conservation Foundation, Sydney Environment Institute, Griffith University, AGL, APA Group, Climate Integrity, submissions, 2024). However, the pathway for the electricity and energy sector is not well understood in Australia and people have relatively low levels of confidence on their knowledge of renewable energy infrastructure and its role in the transition (CSIRO, 2024a).

> Finding a suitable approach to engaging communities and landholders to earn trust and acceptance – social licence – is a key element for the successful roll-out of Australia's energy infrastructure…Stakeholders emphasised that putting a premium on benefit-sharing for host communities is key to removing social licence barriers.

The buildout of renewable energy generation, storage capacity and transmission infrastructure to support the achievement of Australia's emissions reduction targets will place significant pressure on impacted communities across Australia. Growing recognition across the Australian Government has driven seven different reform and consultation efforts dedicated to addressing this challenge (AEMO, 2024c), including the government's independent Community Engagement Review.

Stakeholders emphasised that putting a premium on benefit-sharing for host communities is key to removing social licence barriers. In consultation with the authority, RE-Alliance emphasised the importance of active community participation in the transition and the distribution of benefits. Next Economy submitted that communities have been asking proponents to approach community benefit sharing with the intention to meet genuine needs of the community and support development goals.

Next Economy submitted several examples of community benefit-sharing: creating shared value out of direct investments such as workers housing used for social housing after short-term use, developing new training facilities in the region, investing in local business and procurement, community funds, grants and scholarships, and landowner and neighbour payments. Offers of benefit-sharing that are not accompanied by sufficient community engagement risk being perceived by host communities as attempts to 'buy' social licence (CPA, 2023). Stakeholders have reflected this to the authority, finding that inability to access electricity from generation infrastructure can cause resentment among hosting communities.

Much of Australia's renewable energy infrastructure and energy supply chains will be located on land and sea to which First Nations have a legal right or interest[4] (AEMO, 2024b; CSIRO, 2024b). Engaging Traditional Owners as partners can reduce the material risk that unconstructive relationships create for projects and ensure that First Nations communities have opportunities to lead in Australia's clean energy transformation (ACSI, 2021; Evans & Polidano, 2022). Poor engagement can increase project costs, delay approval timelines and threaten project viability (Joint Standing Committee on Northern Australia, 2021).

As at July 2024, 16 Traditional Owner groups have partnered with proponents to lead or take equity stakes in renewable energy projects (FNCEN, 2024b). Barriers remain for such equitable partnerships to be widely

4 Collectively referred to as the 'First Nations Estate' or Australia's Indigenous land and forest estate

replicable across Australia, including exclusion from the finance system (ASIC, 2023; Evans & Polidano, 2022); inadequate public funding for representative body corporates (Woods et al., 2021); and absence of requirements for proponents to engage effectively through obtaining Free, Prior and Informed Consent (FPIC). Through its consultation processes, the authority heard that there is also a lack of access to capacity and capability development.

A small number of institutions that provide, or regulate, finance for the electricity and energy sector have committed to implementing FPIC as a condition of providing future finance or investment (ARENA, 2023; ASIC, 2023; ASFI, n.d.; Westpac, 2022). While the Clean Energy Council and KPMG (Clean Energy Council & KPMG, 2024) have released an industry-led guide for engaging with Australia's First Nations people on renewable energy projects, and First Nations organisations have published best practice guidelines (FNCEN, 2022), there is no whole-of-government led framework clarifying or requiring FPIC.

The First Nations Clean Energy Network submitted that energy systems planning should recognise First Nations rights, use and occupancy, and adopt an approach of early-stage and substantive engagement and participation in decision-making with First Nations communities (FNCEN, 2024a).

Through access to transparent, detailed and appropriate information about companies, projects and impacts, Traditional Owners can be empowered to guide the preparation, implementation, evaluation, and improvement of planning and approval schemes for the energy system.

EE.3.5 Community-led information

The independent Community Engagement Review, the recommendations of which have been accepted by the Australian Government in principle (DCCEEW, 2024b), contains recommendations on improving complaints handling processes and communicating the impact of renewable energy infrastructure (Dyer, 2023). Recommendation six finds that the design of a communication program should include engagement with local stakeholders (Dyer, 2023).

RE-Alliance, in consultation with the authority, has suggested that an appropriate mechanism to address these recommendations is the presence of local community energy hubs, staffed by community members with strong expertise and local networks. Institutions to support ground-up representation of community interests are a key reccommendation of the Productivity Commission's Transitioning Regional Economies report (Productivity Commission, 2017). The Latrobe Valley Authority (LVA) and the Collie Delivery Unit (CDU) are two examples of transition institutions that have been established to coordinate or represent local community interests in regions impacted by energy infrastructure transitions. The LVA and CDU maintain local stakeholder working groups to guide implementation of transition plans (LVA, 2024; WA Government, 2020).

Anecdotal evidence from Australia (consultation with Macquarie University) supports overseas experience of certain co-benefits flowing from co-locating photovoltaics with grazing sites, reductions in livestock loss from extra shading, and increases in fruit size for certain crops. The shade provided by agrivoltaics can also provide benefits to agriculture through improved water retention and infiltration in soil, and improved microclimate and crop protection (CEC, 2019; Wydra et al., 2023). Uptake of agrivoltaics in Australia has been slow, despite proponents present in Australia, such as Iberdrola, engaging in the practice internationally (Iberdrola, 2023). A report into agrivoltaics in Australia found this has been driven by knowledge gaps, poor planning and a lack of clear policy guidance at the development stage (Stark & Bomm, 2023).

The Australian Government can stimulate the agrivoltaics industry through developing best practice guidance and decision-making frameworks. This would help alleviate risks of misaligned incentives between renewable energy proponents and pastoralists, such as minimum grass heights in grazing paddocks (Stark & Bomm, 2023).

EE.3.6 Workforce shortages

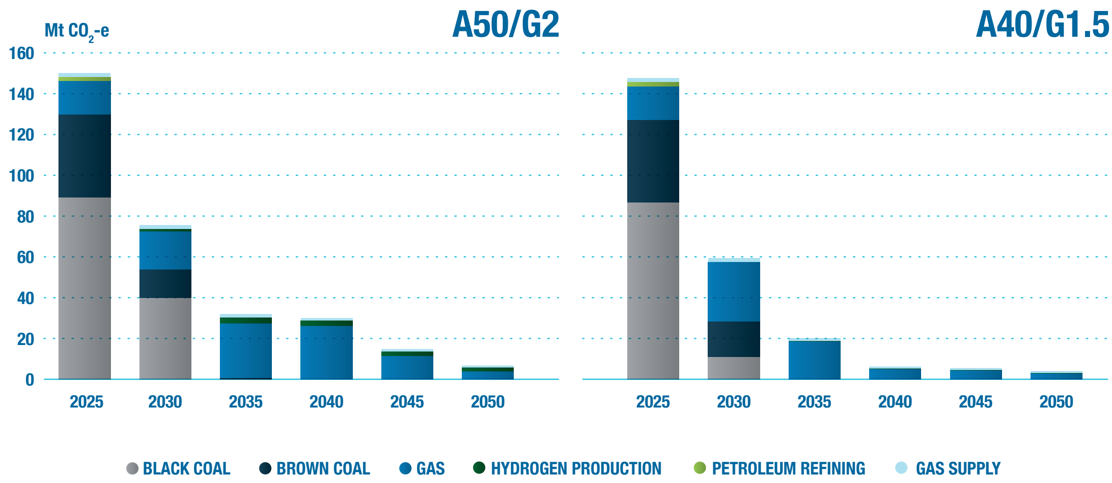
The electricity and energy sector requires a substantial increase of workers for the transition. Modelling undertaken for ARENA indicates that between 2025 and 2030 an estimated 10,400 electricians and 7,900 engineers will be required to roll out the sector's infrastructure (Accenture, 2023). Essential trades, such as electricians, and electrical and electronics engineers are both in a national (JSA, 2023a) and a global shortage (IEA, 2023), placing Australia in competition against international decarbonisation proponents.

The electricity and energy sector's labour demand also exists in competition with demand from other sectors for the same skills and occupations. This demand will exist in a highly competitive market, as sectors seek to decarbonise, often by investing in new technologies and electrifying operations (Climateworks Centre, 2023b). Jobs and Skills Australia's (2023b) modelling indicates that Australia will require close to two million workers in building and engineering trades by 2050.

EE.4 Emissions pathways

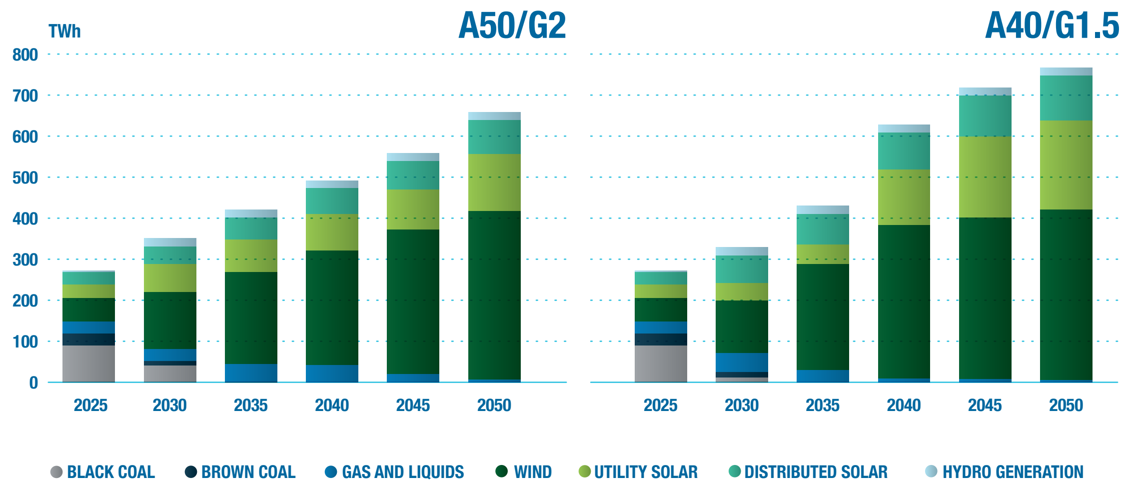
The results of the modelling undertaken for the authority by CSIRO and the authority's review of literature indicate that the electricity and energy sector is projected to undergo rapid decarbonisation over the period to the mid-2030s. The modelling results show emissions falling to approximately 32 Mt CO_2-e under A50/G2 and 20 Mt CO_2-e under A40/G1.5 in 2035 (Figure EE.1) driven by a significant build of renewable electricity generation (Figure EE.2).

Figure EE.1: Sector emissions by scenario



Source: CSIRO modelling in AusTIMES commissioned by the Climate Change Authority.
Note: Includes all electricity and energy sector emissions, including off-grid emissions, as per the description of the sector in this chapter.

Figure EE.2: Generation by technology and scenario



Source: CSIRO modelling in AusTIMES commissioned by the Climate Change Authority

EE.4.1 Electricity generation

Total electricity generation per year, including electricity generated by pumped hydro and battery storage, is projected to increase significantly under both scenarios modelled by CSIRO. Under A50/G2, total electricity generation, excluding generation from pumped hydro storage and battery storage, is modelled to increase to 420 TWh in 2035 and 659 TWh in 2050 (Figure EE.2). Under A40/G1.5, generation is projected to increase to 431 TWh in 2035 and 767 TWh in 2050. CSIRO modelling forecasts that 37 TWh of this will be utilised to produce 0.8 Mt of hydrogen through electrolysis in 2035, and 119 TWh to produce 2.8 Mt of hydrogen 2050 under A50/G2. Under A40/G1.5, 42 TWh is forecast to be utilised to produce 1 Mt of hydrogen through electrolysis in 2035 and 155 TWh to produce 3.7 Mt of hydrogen in 2050.

EE.4.2 Retirement of coal-fired power generation

Grid-connected coal-fired power generation capacity is projected to reduce from approximately 22 GW in 2025 to complete retirement by the mid-2030s under A40/G1.5 and under 0.1 GW remaining in A50/G2. Under its Optimal Development Path, AEMO expects that the remaining coal-fired power stations will retire two to three times faster than current scheduled announcements, with complete exit by 2036-37 (AEMO, 2024a). Such an outcome would be contingent on delivering replacement infrastructure at sufficient speed.

EE.4.3 Reliability of supply

Both market forces and government policy are shaping the generation mix in Australia's major electricity grids. These factors are also supporting investments in firmed renewables, driving investments in grid supporting technologies such as gas-fired generation and pumped hydro, and there is state government policy to retain the reliability services of coal-fired generation.

State governments are taking decisions to support, in the short-term, the ongoing operation of coal-fired power stations. Their assessment has been that the reliability and security services provided by the coal-fired power stations in question are currently needed to secure the operation of the grid (AGL, 2024; NSW Government, 2024; WA Government, 2023a).

In submissions to the development of the Orderly Exit Management Framework, stakeholders report that interventions to extend the life of coal assets past their economic life risks creating policy uncertainty that distorts the investment climate for renewable deployment (Alinta Energy, 2024; CEC, 2024; IEEFA, 2024). The expanded Capacity Investment Scheme and state-government-led schemes that guarantee revenue floors for proponents may address some of this uncertainty. However, investors will require certainty beyond 2030, when the Capacity Investment Scheme and Renewable Energy Target are scheduled to end.

EE.4.4 System security

The NEM is one of the first power systems of its size in the world to face the challenge of balancing high penetrations of renewable energy generation with maintaining system security (AEMO, 2024a). Currently, the synchronous generation of thermal plant provides many services to the grid that maintain system security, including voltage management, system strength, inertia, and frequency control. To successfully transition to net zero emissions these issues will need to be resolved in Australia. Modelling exercises, including that undertaken by AEMO for its integrated system plan indicate that these issues can be managed in the NEM. However, stakeholders are cautious about the ability of these outcomes to be delivered in practice.

It will be necessary to find ways to maintain sufficient system security services as thermal plants retire. The authority sought views from stakeholders on this issue including the Australian Energy Council (AEC). The AEC submission (2024) identified this issue as a gap in knowledge, suggesting that the path to maintaining essential system services for secure operation of the grid is not clear, and that these services must be deployed before synchronous generation provided by fossil fuel power generation can retire. In addition to providing fault current, synchronous generation provides inertia to grids that responds to initial changes in frequency and enable frequency control services to provide longer term system security.

As mentioned above, synchronous condensers can provide services currently supplied by fossil fuel generators. In the future, these services could also be provided by batteries. Tesla advised that utility scale battery systems with grid-forming inverters are being recognised for their ability to provide system security services. However, AEMO has noted that further testing is required to demonstrate utility scale battery systems can provide grid-forming services at scale in the absence of synchronous generation (AEMO, 2021). Addressing these issues will require action from market bodies, market participants, new investors, and jurisdictional bodies.

EE.4.5 Peaking fuels

Peaking fuels are projected to play a firming role during times of peak demand on grids with high penetrations of renewable energy (AEMO, 2024a; Gilmore et al., 2023). If emissions-free gas alternatives such as green hydrogen gas turbines are not deployed, the deployment of gas turbines will result in residual emissions for the sector.

EE.4.6 Residual emissions

Despite the availability of technologies to generate zero emissions electricity, many modelling exercises, including the modelling undertaken by CSIRO for the authority, find that there are likely to be residual emissions in this sector in 2050 (Table EE.4). This is because, based on current understanding, the operation of secure and reliable electricity grids will continue to require some use of fossil fuels mainly for the purpose of supporting the grid during periods of peak electricity demand.

Table EE.4: Residual emissions in 2050[5]

Scenario	Emissions (Mt CO_2-e) in 2050
A50/G2	7
A40/G1.5	4
Climateworks well below 2	1.2
Climateworks 1.5	0.7
2024 ISP Step Change	3.5
2024 ISP Green Energy Exports	0.5

Sources: Calculated from AEMO, (2024d); Climateworks Centre, (2023a).

5 Emissions coverage varies between exercises, with the CSIRO modelling covering all domestic electricity generation plus energy supply, Climateworks covering all domestic electricity generation, and the ISP covering Australia's largest electricity grid, the NEM. Hence, figures are presented for illustrative comparison only.

EE.5 References

Accenture. (2023). *Skilling Australian industry for the energy transition.* https://arena.gov.au/knowledge-bank/australian-industry-eti-delivery-stage-pathways-to-industrial-decarbonisation-phase-3/

ACSI (Australian Council of Superannuation Investors). (2021). *ACSI Policy on Company Engagement With First Nations People.* https://acsi.org.au/wp-content/uploads/2021/12/ACSI-Policy-on-Company-Engagement-with-First-Nations-People.Dec21.pdf

AEIC (Australian Energy Infrastructure Commissioner). (2023). *Considerations for Offshore Wind Industry on Community Engagement.* https://www.aeic.gov.au/sites/default/files/documents/2023-10/aeic-considerations-offshore-wind-industry-community-engagement.pdf

AEMO (Australian Energy Market Operator). (2021). Application of Advanced Grid-scale Inverters in the NEM. https://aemo.com.au/-/media/files/initiatives/engineering-framework/2021/application-of-advanced-grid-scale-inverters-in-the-nem.pdf?la=en&hash=B4E20D68B23F66090ADA5F-D47A50D904

AEMO. (2022). Engineering Roadmap to 100% Renewables. https://aemo.com.au/-/media/files/initiatives/engineering-framework/2022/engineering-roadmap-to-100-per-cent-renewables.pdf?la=en&hash=42E784478D88B1DFAF5D92F-7C63D219D

AEMO. (2023). *2023 System Strength Report.* https://aemo.com.au/-/media/files/electricity/nem/security_and_reliability/system-strength-requirements/2023-system-strength-report.pdf?la=en

AEMO. (2024a). *2024 Integrated System Plan ISP.* https://aemo.com.au/-/media/files/major-publications/isp/2024/2024-integrated-system-plan-isp.pdf?la=en

AEMO. (2024b). *Appendix 3. Renewable Energy Zones. Appendix to the 2024 Integrated System Plan for the National Electricity Market.* https://aemo.com.au/-/media/files/major-publications/isp/2024/appendices/a3-renewable-energy-zones.pdf?la=en

AEMO. (2024c). *Appendix 8. Social Licence. Appendix to the 2024 Integrated System Plan*. https://aemo.com.au/-/media/files/major-publications/isp/2024/appendices/a8-social-licence.pdf?la=en

AEMO. (2024d). *ISP Generation and Storage Outlook.* https://aemo.com.au/-/media/files/major-publications/isp/2024/supporting-materials/2024-isp-generation-and-storage-outlook.zip?la=en

AGL. (2024). *Loy Yang - Structured Transition Agreement*. https://www.agl.com.au/about-agl/media-centre/asx-and-media-releases/2023/august/loy-yang-structured-transition-agreement?rmxt3r=vwt06z

Alinta Energy. (2024). *Orderly Exit Management Framework.* https://www.energy.gov.au/sites/default/files/2024-03/OEMF%20submission%20-%20Alinta%20Energy.pdf

ARENA (Australian Renewable Energy Agency). *(2023). Hydrogen Headstart Guidelines.* https://arena.gov.au/assets/2023/10/Hydrogen-Headstart-Guidelines.pdf

ASFI (Australian Sustainable Finance Institute). *(n.d.). Elevating First Nations People, Perspectives and Outcomes into Finance.* Retrieved 15 July 2024, from https://www.asfi.org.au/first-nations-and-finance

ASIC (Australian Securities and Investment Commission). *(2023). ASIC's Indigenous Financial Services Framework.* https://download.asic.gov.au/media/35wn0xyp/asic-indigenous-financial-services-framework-published-february-2023.pdf

Aurecon. (2024). *2023 Cost and Technical Parameters Review Report.* https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2023/2024-forecasting-assumptions-update-consultation-page/final-documents/aurecon--023-24-cost-and-technical-parameters-review-report.pdf?la=en

Bashmakov, I., Nilsson, L., Acquaye, A., Bataille, C., Cullen, J., de la Rue du Can, S., Fischedick, M., Geng, Y., & Tanaka, K. (2023). Industry. *In Climate Change 2022 - Mitigation of Climate Change (pp. 1161–1244). Cambridge University Press*. https://doi.org/10.1017/9781009157926.013

CCA (Climate Change Authority). *(2022). First Annual Progress Report: The baseline, global context, and methodology.* https://www.climatechangeauthority.gov.au/sites/default/files/First%20Annual%20Progress%20Report%20FINAL%20pdf.pdf

CCA. (2023). *2023 Annual Progress Report.* https://www.climatechangeauthority.gov.au/sites/default/files/documents/2023-11/2023%20AnnualProgressReport.pdf

CEC (Clean Energy Council). *(2019). A Guide to Benefit Sharing Options for Renewable Energy Projects.* https://assets.cleanenergycouncil.org.au/documents/advocacy-initiatives/community-engagement/guide-to-benefit-sharing-options-for-renewable-energy-projects.pdf

CEC. (2023). *Rule change request: Investor certainty in the R1 process.* https://assets.cleanenergycouncil.org.au/documents/CRI-Investment-certainty-in-R1-Final-rule-change-request.pdf

CEC. (2024). *Submission: draft Orderly Exit Management Framework.* https://www.energy.gov.au/sites/default/files/2024-03/OEMF%20submission%20-%20Clean%20Energy%20Council.pdf

CER (Clean Energy Regulator). (2024a). *Guarantee of Origin*. https://cer.gov.au/schemes/guarantee-origin

CER. (2024b). *Guarantee of Origin for hydrogen consultation.* https://cer.gov.au/news-and-media/public-consultations/guarantee-origin-hydrogen-consultation

CEC, & KPMG. (2024). *A leading practice guide for engaging with Australia's First Nations peoples on renewable energy projects*. https://www.westpac.com.au/content/dam/public/wbc/documents/pdf/aw/sustainability/ReconciliationActionPlan.pdf

Climateworks Centre. (2023a). *Climateworks Centre decarbonisation scenarios 2023: Australia can still meet the Paris Agreement.* https://www.climateworkscentre.org/reAustralian Treasury, 2023/climateworks-centre-decarbonisation-scenarios-2023-australia-can-still-meet-the-paris-agreement/

Climateworks Centre. (2023b). *Climateworks Centre decarbonisation scenarios 2023: Paris agreement alignment for Australia*. https://www.climateworkscentre.org/wp-content/uploads/2023/11/Climateworks-Centre-decarbonisation-scenarios-2023-April-2024.pdf

CPA (Community Power Agency). *(2023). Regional Benefit Sharing: Creating strategic impacts for regions that host multiple renewable energy projects.* https://cpagency.org.au/wp-content/uploads/2023/10/Regional-benefit-sharing-paper-2023.pdf

CPA. (2024). I*ncentivising Best Practice Renewable Energy Development: National merit criteria to unlock social licence.* https://cpagency.org.au/wp-content/uploads/2024/03/2024_CPA_Incentivising-Best-Practice-Renewable-Energy-Development.pdf

CSIRO (Commonwealth Scientific and Industrial Research Organisation). (2024a). *Australian attitudes toward the energy transition – Part 2*. https://doi.org/https://doi.org/10.25919/g6cj-xv94

CSIRO. (2024b). *Map of Hydrogen Projects*. https://www.csiro.au/en/maps/hydrogen-projects

Davis, D., Pascale, A., Vecchi, A., Bharadwaj, B., Jones, R., Strawhorn, T., Tabatabaei, M., Lopez Peralta, M., Zhang, Y., Beiraghi, J., Kiri, U., Vosshage, F. B., Batterham, R., Bolt, R., Brear, M., Cullen, B., Domansky, K., Eckard, R., Greig, C., …

Smart, S. (2023). *Net Zero Australia*, . https://www.netzeroaustralia.net.au/>.

DCCEEW (Department of Climate Change Energy the Environment and Water). (2023). *Australia's emission projections 2023.* https://www.dcceew.gov.au/sites/default/files/documents/australias-emissions-projections-2023.pdf

DCCEEW. (2024a). *Implementation Design Paper: Capacity Investment Scheme.* https://consult.dcceew.gov.au/expanded-capacity-investment-scheme-cis-design-paper

DCCEEW. (2024b). *Initial Australian Government Response to the Community Engagement Review.* https://www.dcceew.gov.au/sites/default/files/documents/initial-australian-gov-response-to-the-cer.pdf

Dyer, A. (2023). *Community Engagement Review. Report to the Minister for Climate Change and Energy.* https://www.dcceew.gov.au/sites/default/files/documents/community-engagement-review-report-minister-climate-change-energy.pdf

Evans, M., & Polidano, C. (2022). *First Nations Businesses: Progress, Challenges and Opportunities.* https://www.rba.gov.au/publications/bulletin/2022/jun/pdf/first-nations-businesses-progress-challenges-and-opportunities.pdf

FNCEN (First Nations Clean Energy Network). (2022). *Aboriginal and Torres Strait Islander Best Practice Principles for Clean Energy Projects.* https://assets.nationbuilder.com/fncen/pages/183/attachments/original/1680570396/FNCEN_-_Best_Practice_Principles_for_Clean_Energy_Projects.pdf?1680570396

FNCEN. (2024a). *First Nations Clean Energy Network Submission in response to the First Nations Clean Energy Strategy Consultation*

Paper. https://assets.nationbuilder.com/fncen/pages/505/attachments/original/1708899108/First_Nations_Clean_Energy_Network_-_Submission_in_response_to_the_First_Nations_Clean_Energy_Strategy_Consultation_Paper.pdf?1708899108

FNCEN. (2024b). *First Nations Energy Projects.* https://www.firstnationscleanenergy.org.au/energy-projects

Gilmore, J., Nelson, T., & Nolan, T. (2023). *Firming Technologies to Reach 100% Renewable Energy Production in Australia's National Electricity Market (NEM).* Energy Journal, 44(6), 189–210. https://doi.org/10.5547/01956574.44.6.jgil

GLaWAC. (2022). *Gunaikurnai Land and Waters Aboriginal Corporation (GLaWAC) Submission for Offshore renewable energy infrastructure area proposal: Bass Strait off Gippsland.* https://gunaikurnai.org/wp-content/uploads/2022/11/Offshore-Renewable-Energy-Infrastructure-Area-Submission-GLaWAC-221007.pdf

Graham, P., Hayward, J., & Foster, J. (2024). *GenCost 2023-24 Final report.* https://www.csiro.au/en/research/technology-space/energy/GenCost/2023-24-GenCost-report

Hofmann, F. (2019). *Circular business models: Business approach as driver or obstructer of sustainability transitions? Journal of Cleaner Production, 224*, 361–374. https://doi.org/10.1016/j.jclepro.2019.03.115

HSF (Herbert Smith Freehills) & CEIG (Clean Energy Investor Group). (2023). *Delivering Major Clean Energy Projects in NSW: Review of Statutory Planning Approvals Processes.* https://ceig.org.au/wp-content/uploads/2022/07/HSF-CEIG-Report-Delivering-major-clean-energy-projects-in-NSW-14-December-202380.pdf

HSF & CEIG. (2024). *Delivering Major Clean Energy Projects in Queensland and Victoria: Review of Qld and Vic Statutory Planning Approvals Processes.* https://ceig.org.au/wp-content/uploads/2024/04/HSF-_-CEIG-Report-Delivering-major-clean-energy-projects-in-QLD-and-VIC.pdf

Iberdrola. (2023). *We are awarded four agrovoltaic innovation projects in France.* https://www.iberdrola.com/press-room/news/detail/we-are-awarded-four-agrovoltaic-innovation-projects-in-france

IEA (International Energy Agency). (2023). *World Energy Employment 2023*. https://www.iea.org/reports/world-energy-employment-2023

IEEFA (Institute for Energy Economics and Financial Analysis). (2024). *Orderly Exit Management Framework Consultation*. https://www.energy.gov.au/sites/default/files/2024-03/OEMF%20submission%20-%20IEEFA.pdf

Joint Standing Committee on Northern Australia. (2021). *A Way Forward: Final report into the destruction of Indigenous heritage sites at Juukan Gorge*. https://www.aph.gov.au/Parliamentary_Business/Committees/Joint/Former_Committees/Northern_Australia_46P/CavesatJuukanGorge/Report

JSA (Jobs and Skills Australia). (2023a). *Skills Priority List. Jobs and Skills Australia.* https://www.jobsandskills.gov.au/data/skills-shortages-analysis/skills-priority-list

JSA. (2023b). *The Clean Energy Generation.* https://www.jobsandskills.gov.au/publications/the-clean-energy-generation

LVA. (2024). *About the Transition Plan.* https://lva.vic.gov.au/transition/about-the-plan

Morseletto, P. (2020). *Targets for a circular economy.* Resources, Conservation and Recycling, 153, 104553. https://doi.org/10.1016/j.resconrec.2019.104553

NSW Government. (2024). *NSW Government secures 2-year extension to Eraring Power Station to manage reliability and price risks.* https://www.environment.nsw.gov.au/news/nsw-government-secures-2-year-extension-to-eraring-power-station

Open NEM. (2024). *Open NEM*. https://opennem.org.au/

Productivity Commission. (2017). *Transitioning Regional Economies.* https://www.pc.gov.au/inquiries/completed/transitioning-regions#report

Samuel, G. (2020). *Independent Review of the EPBC Act – Final Report.* https://www.dcceew.gov.au/sites/default/files/documents/epbc-act-review-final-report-october-2020.pdf

Stark, K., & Bomm, A. (2023). Pursuing an Agrivoltaic future in Australia. https://www.farmrenewables.com.au/_files/ugd/484d75_825000a3311249f7b-faf0279a6c88a6a.pdf

WA Government. (2020). *Collie's Just Transition Plan.* https://www.wa.gov.au/system/files/2020-12/Collies%20Just%20Transition_09%20December%202020_web.pdf

WA Government. (2023a). *Muja C Unit 6 in reserve mode and online for summer 2024-25.* https://www.wa.gov.au/government/media-statements/Cook-Labor-Government/Muja-C-Unit-6-in-reserve-mode-and-online-for-summer-2024-25-20230817

WA Government. (2023b). *Swis Demand Assessment 2023 to 2042.* https://www.wa.gov.au/system/files/2023-05/swisda_report.pdf

Wang, K., Costanza-van den Belt, M., Heath, G., Walzberg, J., Curtis, T., Barrie, J., Schroder, P., Lazer, L., & Altamirano, J. (2022). *Circular economy as a climate strategy: current knowledge and calls-to-action.* https://www.nrel.gov/docs/fy23osti/84141.pdf

Westpac. (2022). *Westpac Group Reconciliation Action Plan*. https://www.westpac.com.au/content/dam/public/wbc/documents/pdf/aw/sustainability/ReconciliationActionPlan.pdf

Woods, K., Markham, F., Taylor, J., Smith, D., Burbidge, B., & Dinku, Y. (2021). *Toward a Perpetual Funding Model For Native Title Prescribed Bodies Corporate. Centre for Aboriginal Economic Policy Research, 7*, 33. https://doi.org/https://doi.org/10.25911/6FPY-AV98

Wydra, K., Vollmer, V., Busch, C., & Prichta, S. (2023). *Agrivoltaic: Solar Radiation for Clean Energy and Sustainable Agriculture with Positive Impact on Nature. In M. A. Aghaei (Ed.), Solar Radiation - Enabling Technologies, Recent Innovations, and Advancements for Energy Transition.* https://www.intechopen.com/online-first/87330

Transport

TRANSPORT

Sector summary

The transport sector is a significant and growing source of emissions in Australia. Deep and rapid reductions in these emissions are possible in the near term, but progress in some subsectors will depend on further developments in technology.

Transport was the source of 90 Mt CO_2-e of emissions in 2022 and is currently projected to be Australia's largest source of emissions by 2030. For this sector to best support Australia's transition to net zero by 2050, the deployment of existing technologies will need accelerate and developing technologies will need to be taken up quickly as they mature. This will require changes in the vehicles Australians purchase and the way Australians travel, electrification of other transport types where possible and new liquid fuels or hydrogen where it is not, and new supporting infrastructure.

Technologies are available now to reduce emissions from light vehicles in the form of battery electric vehicles and active and public transport options. Sales of new light vehicles reaching 100% electric ahead of 2040 can ensure there are minimal light vehicle emissions by 2050. Planning and roll-out of new and upgraded public and active transport networks will also support achieving emissions reduction goals.

Global manufacturers can supply the battery electric vehicles to decarbonise the passenger and light commercial vehicle fleet, which accounts for roughly half of Australia's transport emissions. The roll-out of charging infrastructure will need to lead electric vehicle sales for the current high rate in growth in these sales to be sustained.

Aviation, shipping, rail and heavy vehicle transport currently have immature and expensive low and zero emissions technology options. The pathway to minimise these emissions by 2050 will likely involve:

- accelerating take-up of battery electric technology in heavy vehicles and rail, which can occur from 2025 for mature vehicle types such as buses and light rigid trucks
- replacing existing diesel heavy vehicles and rail with hydrogen technology as soon as it matures, where battery electric is not suitable
- switching to renewable fuels where hydrogen and battery electric are not suitable or available, including sustainable aviation fuels in aviation, green ammonia and methanol in shipping, and potentially renewable diesel for remaining road and rail freight.

Challenges to transitioning to low and zero emissions technologies include high upfront costs, lack of supporting infrastructure and appropriate regulation. Technology maturity and long asset lives present further barriers for aviation, shipping, rail and heavy vehicles. There is also inadequate information on the supply and demand and future costs of renewable fuels to inform technology investment decisions. These challenges mean there will likely be some residual transport emissions in 2050.

T.1 Sector state of play

The transport sector includes, for both passengers and freight, road transportation (cars, light commercial vehicles, heavy duty trucks, buses, motorcycles) and off-road transportation (domestic aviation, domestic shipping, rail).

T.1.1 Economic contribution

The transport sector provides essential services for Australia's economy, moving goods to where they are needed and connecting people to families, jobs, education, communities and essential services. The transport sector contributed $125 billion Gross Value Added (GVA) in 2022-23, approximately 5% of Australia's total GDP (Appendix B, ABS (2023)). Road transport contributed 31%, rail contributed 57% and ships contributed 12% of domestic freight transport in 2022-23 (calculated from BITRE (2023a)).

T.1.2 Emissions profile

Transport emissions were 90 Mt CO_2-e (21% of Australia's emissions) in 2022, with on-road vehicles accounting for 85% of the total emissions in the sector. All transport subsector emissions have grown since 2005, reflecting growth in population and the economy, and limited deployment of low emissions technologies.

Table T.1: Emissions in the transport sector, 2022

Sub sector	Mt CO_2-e	Subsector share (%)
Cars[1]	38	42
Light Commercial Vehicles	17	19
Heavy-Duty Trucks and Buses	22	24
Motorcycles	0.2	0.2
Railways	4	4
Domestic aviation	6	6
Domestic shipping[2]	2	3
Mobile air-conditioning and transport refrigeration	2	2
Other transportation	<0.1	<0.1
Total	90	100

Note: Mt CO_2 -e and subsector share (%) may not sum to the totals due to rounding.

Light vehicle road transport is the largest source of transport emissions (60% in 2022) and has mature abatement technology in the form of electric vehicles. However, electric vehicles currently make up less than 1% of Australia's light vehicle fleet (BITRE, 2023c). In 2022, there were approximately 19 million cars in the Australian light vehicle fleet (BITRE, 2023b). In 2021, 91% of households owned at least one vehicle and 55% owned two or more (ABS, 2022). Of vehicle owning households, around 75% have access to off-street parking where charging may be more easily accessed.

1 Including sport utility vehicles (SUVs).
2 "Domestic shipping" means the same as the Australian National Greenhouse Accounts Inventory category "domestic navigation".

Heavy vehicle transport is the second largest source of emissions in the transport sector (24% in 2022) and is made up of emissions from rigid trucks (8.7 Mt CO_2-e), articulated trucks (11.7 Mt CO_2e) and buses (1.6 Mt CO_2-e in 2022). Electric buses and small electric trucks are mature technologies (National Transport Commission, 2023; Electric Vehicle Council & Australian Trucking Association, 2022; Queensland Transport and Logistics Council, 2022) and are being deployed across Australia, but make up less than 1% of the heavy vehicle fleet (BITRE, 2023c). Alternative low emissions vehicles such as hydrogen powered trucks are still at the demonstration stage.

Domestic aviation and shipping are a smaller source of emissions (9%) and no direct abatement options have been deployed in Australia at commercial scale.

The authority considered small sources of emissions in this sector, such as refrigerant gas released from air-conditioning systems keeping passengers and freight cool, but these were not prioritised for deeper analysis. Motorcycle emissions are also not discussed, but there is potential for this technology to follow light vehicles and electrify. International shipping and aviation emissions are not considered within the scope of this review.

T.2 Existing and prospective technologies

The following technologies and operational changes can address the major sources of transport emissions (Table T.2). A key challenge for all transport subsectors, which technological advancements should address over time, is the range that can be achieved by electric vehicles compared to vehicles with internal combustion engines.

Table T.2: Potential emissions reduction opportunities for transport

Emissions subsector	Sector emissions share 2022	Priority abatement lever(s)	Readiness	Barriers to adoption
Light vehicles	60%	Electric vehicles	Commercial (competitive)	Capital cost, charging infrastructure, consumer choices
		Mode shift to active and public transport	-	Capital cost, planning approvals and delays for new infrastructure, consumer choices
Heavy vehicles	24%	Electric vehicles	Commercial (supported)	Regulation, long asset life, capital cost, charging infrastructure, supply
		Hydrogen vehicles	Demonstration	Regulation, capital cost, refuelling infrastructure, hydrogen cost, tech maturity, hydrogen supply
Domestic aviation	6%	Sustainable Aviation Fuel	Demonstration	Regulation, SAF cost, tech maturity, feedstock competition
Domestic shipping	3%	Methanol	Demonstration	Regulation, long asset life, cost, tech maturity, refuelling infrastructure, long asset life
		Ammonia	Research and Development	
Rail	4%	Electric rail and hydrogen rail[3]	Overhead electric: Commercial (competitive) Battery electric: Demonstration Hydrogen rail: Demonstration	Capital cost, recharging/refuelling infrastructure, long asset life

3 Electric rail was included in the authority's Targets, Pathways and Progress issues paper, but the authority since has also considered hydrogen rail.

There are immediate opportunities to reduce emissions in the transport sector, particularly in relation to electrification of the light vehicle fleet (Figure T.1). Harder to electrify transport modes are dependent on developments in technology, availability of supply, and cost (Figure T.2). The transport sector will decarbonise by deploying electric technology first, hydrogen technology where electric is not suitable, and renewable fuels where neither electric or hydrogen are suitable or available.

Figure T.1: Prospective decarbonisation pathways for road transport using battery electric vehicles, mode shift and hydrogen vehicles

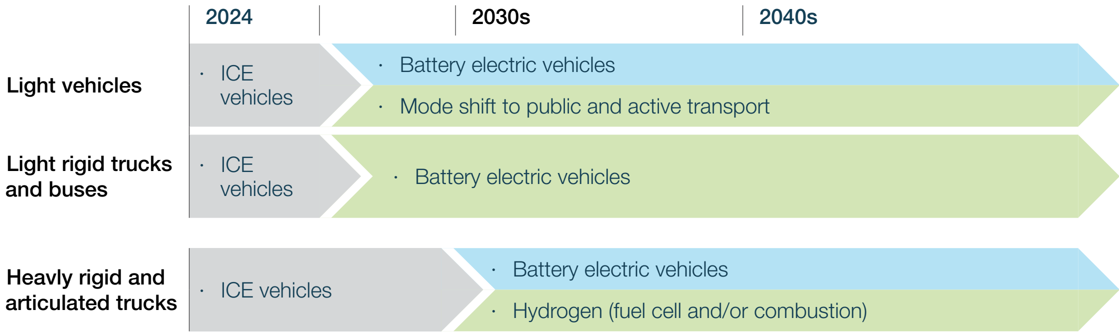
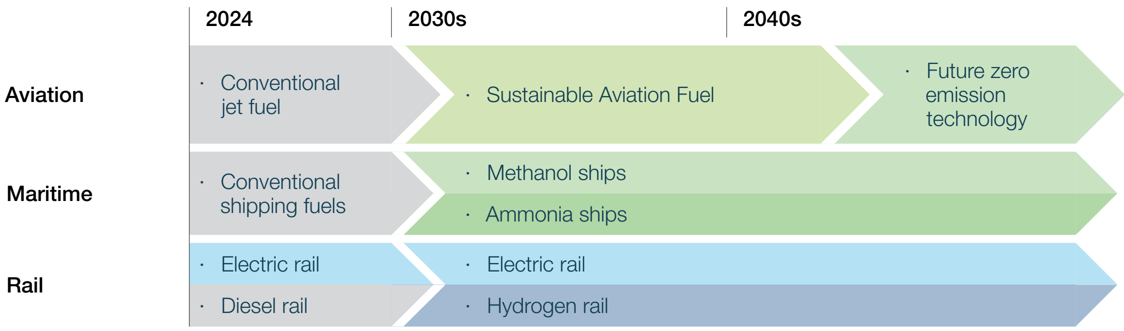


Figure T.2: Prospective decarbonisation pathways for non-road transport using renewable fuels, hydrogen and electric rail



T.2.1 Decarbonising the light vehicle fleet

EVs have emerged as the most suitable technology to replace light internal combustion engine (ICE) vehicles. EVs can do most of the tasks currently performed by ICE vehicles and their share in new car sales is growing rapidly from a low base (CCA, 2023). EVs have no tailpipe emissions. When taking into account scope 2 electricity emissions, EVs charged with electricity at the current average generation mix of fossil and renewable sources across Australia's main grids are lower emitting than ICE vehicles (DCCEEW, 2023). Many EV models have a range of over 400 km before needing to be recharged (Green Vehicle Guide, 2024).

Achieving a high uptake of EVs is dependent on reaching price parity with ICE vehicles, availability of charging infrastructure, and EV model availability across the various market segments. There is evidence indicating that consumers' primary reasons for not purchasing EVs are price and lack of public charging (The Australia Institute, 2023) (see more in T.3 Barriers).

> EVs can do most of the tasks currently performed by ICE vehicles and their share in new car sales is growing rapidly from a low base…There is evidence indicating that consumers' primary reasons for not purchasing EVs are price and lack of public charging…

EV model availability is improving for passenger cars but is lacking in light commercial segments. There were approximately 56 battery electric passenger car models available in Australia in 2023 (Electric Vehicle Council, 2024). However, there was only one electric utility vehicle available (Electric Vehicle Council, 2023). The National Farmers' Federation (2024) has expressed concerns over the lack of electric substitutes for the towing capacity and range of diesel utility vehicles, and it is expected to take time for more models to become available (Electric Vehicle Council, 2023).

T.2.2 Mode shift to public and active transport

Travel by public and active transport is emissions intensive compared to private vehicle travel, is socially beneficial, and can reduce cost-of-living pressures (Centre for Urban Research, 2018; International Transport Forum, 2023; Rural and Regional Affairs and Transport References Committee, 2014). Travel by active transport can provide immediate emissions reduction not dependent on electricity decarbonisation.

> *Facilitating greater use of active, shared and public transport can cut climate pollution further and faster [than electrifying vehicles] - and do so this decade - because the effects are seen immediately through reduced use of private motor vehicle travel.*
>
> Living Streets Canberra submission, 2024

New approaches in infrastructure and city planning are key for developing functional public and active transport networks (Centre for Urban Research, 2018; International Transport Forum, 2023). Encouraging people to choose active and public transport requires adequate transport options, infrastructure and information to address safety, convenience, comfort, and accessibility concerns. For example, Glouias et al. (2002) found in Perth that 31% of private vehicle trips required system or infrastructure improvements to shift to alternative modes, and 34% of trips had subjective reasons against shifting to alternative modes such as lack of information. Through consultation, the authority heard from stakeholders that the key enablers to mode shifting include active and public transport infrastructure investment and appropriate land use planning to make cities more walkable such as improved precinct design.

There are long lead times in planning public investment into active and public transport infrastructure. For example, the first stage of Canberra's light rail project took 6 years to complete (Box T.1). Adelaide's Frome Street Bikeway has yet to be completed, 10 years after public consultation on the project was undertaken (City of Adelaide 2024; Adelaide City Council 2013).

T.2.3 Decarbonising the heavy vehicle fleet

Heavy vehicles (trucks and buses) make up 24% (22 Mt CO_2-e) of transport emissions in Australia. Decarbonising the heavy vehicle fleet is likely to be a long-term task as the turnover of vehicles within the fleet is slow. Over 23% of all trucks and 14% of all buses on the road are older than 21 years in 2023 (BITRE, 2023c). The lack of availability of zero emissions heavy vehicles in the market and the inertia of asset replacement in this sector is a significant barrier to the uptake of new technologies to lower emissions in heavy vehicles and will require policy attention.

> The lack of availability of zero emissions heavy vehicles in the market and the inertia of asset replacement in this sector is a significant barrier to the uptake of new technologies…and will require policy attention.

The authority heard through consultation that battery electric options are currently suitable for a range of heavy vehicle applications, especially where low payloads are moved less than 300 km. The characteristics of mature battery electric technology makes it applicable to most 'return to depot' light rigid truck and bus operations (Global Commercial Vehicle Drive to Zero, 2023). These types of operations are typical of many rigid trucks and are the source of approximately 9 Mt CO_2-e of emissions each year in Australia (DCCEEW, 2022). Globally there have been improvements in the battery electric heavy vehicle market, with growth in model availability for heavy duty trucks in recent years, and the average range of these models has grown by over 10% between 2020 and 2023 (Global Commercial Vehicle Drive to Zero 2023).

Box T.1: The ACT's light rail investments led to emissions reductions, but projects take a long time to complete

The introduction of light rail has reduced the ACT's carbon emissions per capita and contributed to reducing the daily average number of motor vehicles counted at one intersection near the light rail corridor by 21% in 2019 and 18% in 2024 compared to 2016 (Transport Canberra, 2024). The light rail is an 100% emissions reduction compared to each car ride it replaces since the ACT has reached 100% renewable electricity. (Note: The ACT Government offsets its electricity emissions by retiring Large Generation Certificates (Point Advisory, 2023).

These projects require substantial time for planning, consultation, approvals, and construction. Stage 1 of the light rail project was completed in 2019, 6 years from feasibility studies to building completion (ACT Government, n.d.). Expansions of the network are expected to be complete in 2027 and 2033; with stage 2b taking 10 years from public consultation to completion (ACT Government, 2024).

Hydrogen is a promising technology for decarbonising some articulated trucks, some heavy rigid trucks and long-haul buses (BITRE, 2019; NPROXX, 2024). Hydrogen has better energy density characteristics than current battery technology (Copenhagen Centre on Energy Efficiency, 2019), allowing hydrogen vehicles to carry heavier payloads without sacrificing as much range as a battery electric vehicle. Hydrogen is also much faster to refuel than battery electric is to recharge (BITRE, 2019). Hydrogen fuelled heavy vehicles are not yet a commercially mature technology, but this could occur in the 2030s (Hydrogen Council, 2021; Hydrogen Europe, 2024; McKinsey, 2023).

The authority heard through consultation that stakeholders are concerned about whether zero emissions vehicle technology can improve enough to do the longest and heaviest trucking tasks. Australian road freight can be up to 130 tonnes (including the truck weight) on articulated trucks (National Heavy Vehicle Regulator, 2016) which the authority heard through consultation is globally unique. To lower emissions, these uniquely long and heavy freight tasks could be undertaken by running conventional trucks on renewable diesel. However, competition for various renewable fuels from other parts of the economy may affect the affordability and availability of renewable diesel for road transport. Renewable diesel could also be used to reduce emissions in the short- to medium-term, while other low and zero emissions technologies for heavy vehicles mature, subject to fuel availability.

Box T.2: Fossil fuel and infrastructure phaseout for road vehicles

The phase out of fossil fuels and relevant infrastructure needs to be managed carefully for users that could require access to liquid fuels into the future. The IEA projects that global road fuel demand is approaching its peak (IEA, 2024a). In a scenario of the light vehicles transport fleet modelled by CSIRO, 10 years after new light ICE vehicles were no longer available, light ICE commercial services decline rapidly or are no longer viable to operate (CSIRO, 2023a). This decline in the commercial viability of ICE fuel infrastructure may lead to a sparse liquid fuel network by 2050 (Boston Consulting Group, 2019).

The phase out of fossil fuels may also impact the commercial viability of Australia's remaining fuel refineries, noting there may be increasing demand for domestically manufactured renewable fuels such as sustainable aviation fuels.

T.2.4 Decarbonising aviation

Sustainable Aviation Fuel (SAF) is the most promising technology for decarbonising aviation emissions. SAF is a drop-in fuel (i.e., can be used in existing aircraft engines) that can be used instead of conventional jet fuel, made from non-petroleum feedstocks. It can be made from synthetic or biogenic sources, such as biomass, waste products, natural oils and fats, other carbon sources and hydrogen. Other technologies (hydrogen and electric planes) are only at a nascent stage and will initially only be suitable for short and low payload routes which are a relatively small share of domestic aviation emissions (Mission Possible Partnership 2022; ICCT 2022).

The CSIRO found that Australia could play a key role as a source of feedstocks for international production and as a SAF producer, noting that Australia already produces significant quantities of feedstocks exported for biofuel production (for example, canola seed exported to the European Union) (CSIRO, 2023c).

T.2.5 Decarbonising shipping

Green ammonia and methanol[4] are prospective technologies for decarbonising the largest shipping tasks (the largest share of domestic shipping emissions). However, both fuels are only in demonstration phase (ARENA, 2023). In comparison, smaller near-shore vessels may be replaced by or retrofitted to battery electric and hydrogen power (due to shorter distances travelled) (Energy Networks Australia, 2019; Interreg, 2020).

Green ammonia is zero emissions and methanol can reduce tailpipe emissions by 10% and lifecycle emissions by 51-94% compared to conventional fuels used in shipping (European Maritime Safety Agency, 2023; Methanol Institute, 2022). Consultation advice was that vessel asset life varies, but 20 to 30 years is common so this sector will likely decarbonise slowly in the absence of policy measures.

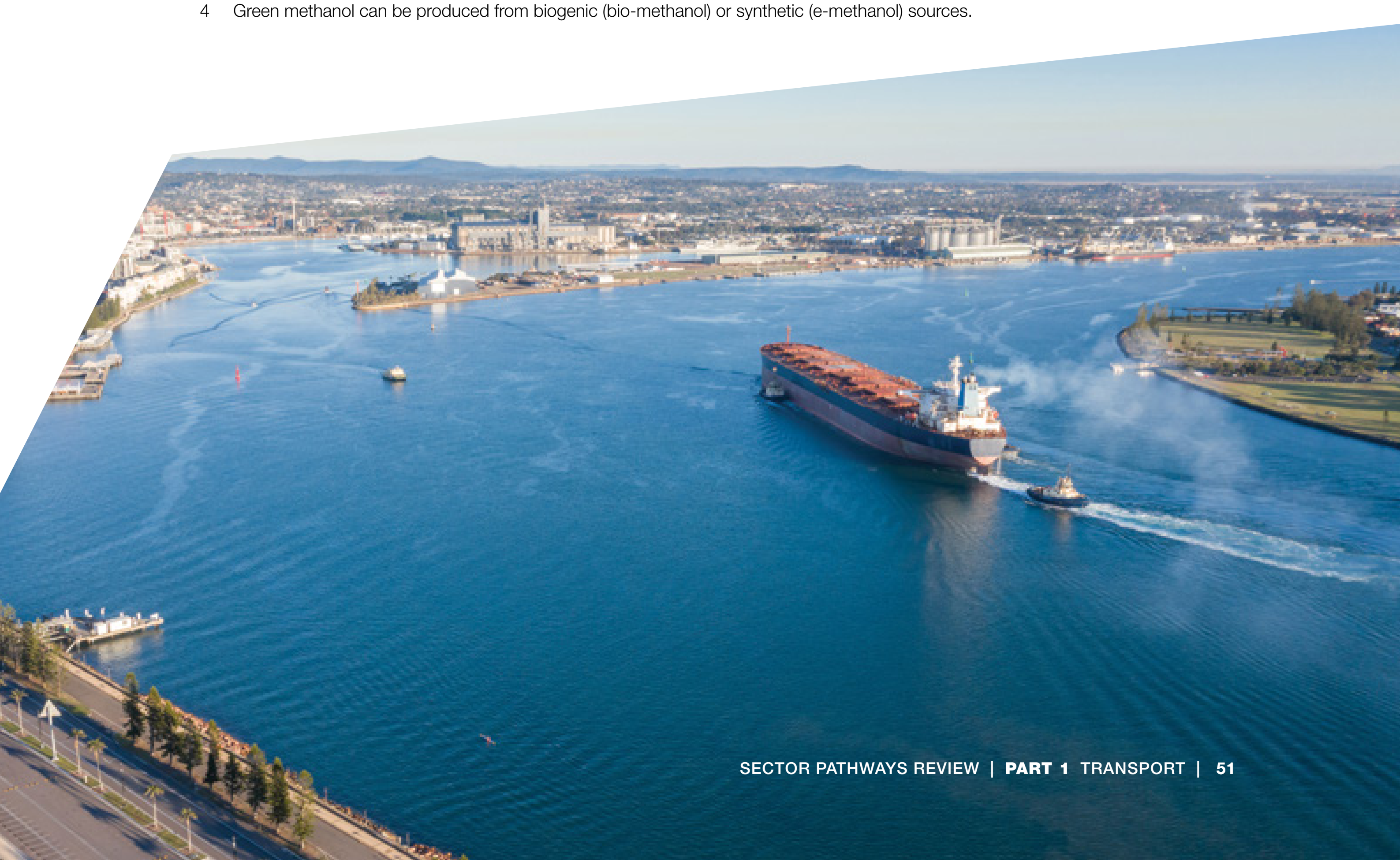
T.2.6 Decarbonising rail

The most promising technologies to decarbonise rail are grid-connected electric, battery electric and hydrogen powered engines. Grid-connected electric rail is a mature technology. Battery electric is maturing now, while hydrogen rail is not expected to mature until the 2030s (CSIRO, 2018; Hydrogen Council, 2021). Renewable diesel presents an opportunity to reduce remaining emissions, but there are barriers to overcome (see below). Ensuring that existing rail locomotives are replaced with zero emissions alternatives, at least at end-of-asset-life, is critical due to their long-lived nature.

> *'Australian rollingstock has an average lifespan of about 25 - 30 years. It is anticipated that about half of the nation's fleet will be due for replacement in the next 8 to 13 years. The rollingstock procured during this period will therefore have an expected lifespan beyond 2050.'*
>
> Australasian Rail Association submission, 2024

Noting that zero emissions rail technology is still maturing, it is possible 20 - 50% of Australia's diesel rail could be transitioned to electric and hydrogen technology by 2050. The authority consulted with a major Australian rail operator who indicated that they were considering adopting battery electric technology in the near term due to its maturity and low running costs, and would consider hydrogen as it matures.

4 Green methanol can be produced from biogenic (bio-methanol) or synthetic (e-methanol) sources.



Box T.3: Renewable fuels

Renewable fuels[5] include diesel, petrol or jet fuels made from biogenic or synthetic feedstocks. Depending on the feedstock and manufacturing pathway, they can be used as a complete replacement for fossil fuels in existing engines or may need to be blended with fossil fuels (NSW Government, 2023; Office of Energy Efficiency & Renewable Energy, n.d.; van Dyk, 2022). Australia imports approximately 90% of its liquid fuel (CSIRO, 2023c). Transitioning to electric drive trains and developing a domestic renewable fuel manufacturing capacity will enhance Australia's energy security.

Renewable fuels are likely to play an important role in decarbonising Australia's economy, particularly for sources of emissions that are difficult to electrify due to energy density requirements, access to infrastructure, or technology readiness. Examples include aviation, the military, remote power generation, shipping and machinery in industries such as construction, agriculture and forestry.

There is the potential for Australia to leverage its advanced farming practices, significant production base, established supply chains and renewable energy resources to develop a domestic renewable fuel industry.

However, there are challenges to overcome in scaling up the availability of affordable renewable fuels. Key inputs—land, water and renewable energy—are also needed for food, maintaining soil carbon and other environmental services, and land sector removals (Becken et al., 2023). Australian feedstocks such as canola and tallow are already being exported for renewable fuel production and this is likely to continue (CSIRO, 2023c). Constraints on the availability of the resources required for the production of renewable fuels means they are likely be in short supply (IEA, 2024b) and will need to be prioritised for industries that lack other options to decarbonise.

> *'Biofuels may also play an important role for hard to decarbonise processes and applications, as well as in a transitional capacity. However, for biofuels to be competitive in Australia, the associated challenges of high capital and production costs, ability to reach efficient scales of production, and managing ongoing competition for feedstocks need to be overcome.'*
>
> BHP submission, 2024

5 Renewable fuels are also referred to as 'sustainable fuels' and 'low carbon liquid fuels'. Some examples of these fuels are sustainable aviation fuel, renewable diesel, biodiesel, bioethanol, and e-fuels.

Renewable fuels typically emit similar tailpipe emissions as their fossil fuel equivalents (European Union Aviation Safety Agency, 2024). The carbon sequestered from the atmosphere to create a biogenic or synthetic feedstock is typically around the same quantity as the tailpipe emissions produced from using a renewable fuel and (Hanaki & Portugal-Pereira, 2018; US Energy Information Administration, 2024). This makes the fuel carbon neutral except for lifecycle emissions from the processing, refining and transporting of feedstocks, and in the case of biogenic feedstocks, land use change (Hanaki & Portugal-Pereira, 2018). Lifecycle emissions from renewable fuels can be up to 90% lower compared to fossil fuels, but can also be higher depending on the processes employed across their production, transport and use (Becken et al., 2023; Prussi et al., 2021).

Renewable fuels can be made from a wide range of biogenic sources such as corn, canola and animal fats (ETIP Bioenergy, 2024). Other biogenic sources such as algae, waste and agricultural residues are promising but production methods for these are immature (bp, 2023; FAO, 2010; IEA, 2024b; Wood Mackenzie, 2022). Renewable fuels can also be made synthetically using green hydrogen and a source of carbon (biogenic, manufactured or captured carbon). These fuels are also referred to as e-fuels due to their reliance on large volumes of renewable energy and are still maturing as a technology (efuel alliance, 2022; Wood Mackenzie, 2024). Government coordination will be needed to manage renewable fuel markets to ensure that sustainable land use is supported, that land use competition issues are managed and that finite fuels are available in sectors of the economy that most need them. As part of the 2024 Budget, the government announced a series of commitments to support a low-carbon-liquid fuels market in Australia. This included a commitment to consult on policy approaches to accelerate investment and incentivise efficient production of renewable fuels with a key initial focus on producing sustainable aviation fuel and renewable diesel.

The government also committed to undertake a regulatory impact analysis of the costs and benefits of introducing demand-side measures for renewable fuels.

A renewable fuels industry would aid in regional job creation in feedstock production, collection and transportation from regional areas to refineries and monetizing existing waste streams as part of a circular economy.

T.3 Barriers, opportunities and enablers

T.3.1 Green premium

New EVs are widely available for sale in Australia and sales are rapidly approaching 10% of the new vehicle market (CCA, 2023). EV sales have grown exponentially, making up less than 1% of the market in 2019. This rate of growth in the EV share of the new vehicle market needs to continue to decarbonise the light vehicle fleet ahead of 2050.

To sustain the rapid growth in new EV sales, it is likely that EVs will need to reach price parity with conventional ICE vehicles well before the end of the current decade. Consumers noted they would be more likely to buy an EV if there was a rebate available (Rosel, 2023). Purchase costs of electric vehicles are currently higher than ICE vehicles but are forecast to reach price parity between 2024 and 2033 in major markets (BNEF, 2023).

Adoption of EVs for passenger transport in Australia will require the installation of a wide-spread network of public EV charging infrastructure. The number of public EV charging locations has been growing in Australia. However, the rapid adoption of EVs that is required to reduce emissions means Australia will need a faster rollout of public chargers of various charging speeds in more locations. A lack of access may be exacerbated in regional areas where charging will be needed but overall use would be lower than in the city, impacting the economic case for regional and remote sites. Strategic investment by governments to ensure adequate coverage across the country can support consumers to choose electric vehicles in regional and remote areas.

The authority has been told that the installation of public charging infrastructure faces barriers in Australia.

> *'For Tesla, Australia is the most difficult country in the region to install direct current (DC) fast chargers, with transformer upgrades and grid connections often taking over 1 year for utilities to complete, compared to just 6-8 weeks in other countries.'*
>
> Tesla Motors submission, 2024

The majority of EV charging is expected to occur at home (Energetics, 2024), so access to home charging is essential. Around three-quarters of Australia households have access to off street parking such as a garage or carport (ABS, 2022).

Home charging is less accessible to homes without off street parking. The majority of apartments also have additional barriers to installing charging infrastructure which could delay EV purchases. Almost all older buildings in Australia will require electrical infrastructure upgrades to support EV charging (Strata Community Association, 2023), which will generally need to be paid equally across each owner in a strata building (Strata Community Association, 2023). Electrical upgrades require a vote, and those in the building who do not own an EV may not agree to installation. As the whole building requires upgrades, an owner cannot pay for their portion of the upgrades alone (Strata Community Association, 2023).

> *'Access to off-street charging is one of the most important enablers of EV adoption, and one of the key equity challenges of EVs, because Australians who are less socio-economically advantaged are less likely to own their homes, have off-street parking, or be able to access workplace charging.'*
>
> Tesla Motors submission, 2024

Over 90% of truck operators are small businesses with less than five staff and less than $2 million in revenue (ABS, 2023a, 2023b), and hence with limited capacity to afford trucks with the higher total cost of ownership (TCO) that is currently associated with zero emissions trucks due to their higher purchase prices (Electric Vehicle Council & Australian Trucking Association, 2022; Transport and Environment, 2020). The cost of hydrogen fuel also adds to the cost of ownership for hydrogen vehicles (Grattan Institute, 2023). The TCO for hydrogen trucks is not projected to meet parity with diesel trucks until the 2030s or later (CSIRO, 2022; Hydrogen Council, 2021; International Council on Clean Transportation, 2022).

Well-configured public finance and public finance policy mechanisms can address the price premium barriers that are holding back the greater uptake of low-carbon transport alternatives. The authority heard from stakeholders that the upfront cost of low carbon transport alternatives remains a significant barrier to uptake. For example, one stakeholder recommended public finance is necessary until 30% of the light vehicle sales are EVs (Electric Vehicle Council, 2023). The authority also heard from stakeholders that higher purchase costs for fuel alternatives such as green hydrogen, ammonia or sustainable aviation fuel for low carbon transport alternatives are a barrier to uptake for heavy vehicles, aviation, shipping and rail. Further, mechanisms are needed to ensure there are sufficient charging and refuelling networks, particularly where the charger is uneconomical and critical to network coverage.

Government has a role to play in supporting the infrastructure that assists low emissions choices of individuals and business. This includes investment in public infrastructure such as for active and public transport and electric vehicle chargers.

> *'The Government must increase investment in infrastructure to support walking and riding. The factors preventing mode shift are not technological, but they are deep and engrained in existing transport planning and decision-making culture.'*
>
> WalkSydney submission, 2024

> Well-configured public finance mechanisms can address the price premium barriers that are holding back the greater uptake of low-carbon transport alternatives.

Box T.4: How financial incentives can drive uptake of low emissions technology

Since 1990, Norway has been providing incentives for the uptake of EVs, with the goal of having all new cars sold zero-emissions (electric or hydrogen) by 2025 (Norwegian Electric Vehicle Association, 2022). In March 2024 battery electric vehicles achieved a 90% market share, positioning Norway as the leader in global EV uptake (European Commission, 2024).

Incentives commenced in the 1990s, such as free municipal parking and no charges on toll roads for EVs. Most of these incentives continued for at least 20 years, while new ones have been added over that period.

Incentive	Time period
All publicly procured cars need to be zero emissions (buses from 2025)	2022-present
All apartment buildings must make charging points available for residents	2017-present
25% value-added tax exemption on leasing EVs	2015-present
Discounted or no charge to take an EV on a ferry	2009-present
25% value-added tax exemption on EV purchases	2001-2022
No purchase or import tax on EVs	1990-2022
No annual road tax for EVs	1996-2021
25-50% reduced company EV tax	2000-2017
Free municipal parking for EVs	1999-2017
No charges on toll roads for EVs	1997-2017

Source: Norwegian Electric Vehicle Association, 2022

National target setting can support policy certainty for public and private stakeholders to invest in the green transition. For example, Norway has also set a target for all new trucks sold in the country to be electric or biogas by 2030. Through Enova – a national funding agency to support late-phase technology development and early market introduction of climate and energy solutions – the Norwegian government has supported the purchase of 420 electric trucks and 115 electric buses, and is investing in national charging infrastructure for heavy vehicles (Norwegian Government, 2023).

T.3.2 Technical constraints

The allowed width of Australian vehicles limits the potential overseas supply of zero emissions heavy vehicles to Australia (Electric Vehicle Council & Australian Trucking Association, 2022). As Australia is a small right hand drive market, it is unlikely to be economical for overseas manufacturers to design a bespoke zero emissions truck to align with Australia's vehicle width regulations. The authority heard similar concerns regarding buses.

> *'The Bus Industry Confederation is seeking an Australian Design Rule Change that allows buses or coaches to be built to 2.55 m body and axle width (in conjunction with an ADR change to allow for the external addons such as cameras and sensors to go to 2.6 m) as part of a package that would not only ensure the ongoing high level of bus and coach safety, but also to address known operating mass issues...'*
>
> Bus Industry Confederation submission, 2024

The authority heard from a range of stakeholders that current axle weight limits are restricting use of low emissions vehicles (which are heavier due to the weight of batteries and hydrogen systems) on Australia's roads. Allowed axle weights are set by the owners of roads, state and territory governments and local councils (Australian Trucking Association, 2019). Queensland, New South Wales, South Australia and Victoria have announced weight regulation changes or are holding trials (NatRoad, 2024; Trucksales, 2024; VicRoads, 2023).

> *'Revising weight limitations to allow LZEHV[6]s on Australian roads is a key part of the transition. At present, there is a lack of consistency in approaches from the states and territories which acts as a barrier to the transition. Consistency in approach and in weight allowances is needed to encourage heavy vehicle operators to transition to LZEHVs.'*
>
> Heavy Vehicle Industry Australia submission, 2024

Heavy vehicles will require a comprehensive electric charging and/or hydrogen refuelling network. However, there is currently almost no dedicated heavy vehicle public charging available in and heavy vehicles often do not physically fit into light vehicle charging bays. There are few hydrogen refuelling stations in Australia (CSIRO, 2023b).

> *Electric vehicle charging stations/ hydrogen refuelling stations often only cater to passenger vehicles, or are not practically located to support existing high-volume freight routes.*
>
> Heavy Vehicle Industry Australia submission, 2024

Stakeholders have raised a range of barriers around the installation of charging infrastructure, including:

- there may not be sufficient energy capacity in the grid which may require expensive electrical upgrades such as getting a second electrical connection.
- electrical infrastructure upgrades are a financial risk for operators and owners in rented depots, where operators are uncertain on a future lease, and owners are uncertain if future tenants will require charging.

T.3.3 Supply chain constraints

There may be global competition for renewable fuels and their feedstocks to decarbonise multiple sectors including transport, agriculture, and mining. This competition will exacerbate land and water use demand pressures (see AL.3 Barriers, opportunities and enablers under the agriculture and land sectoral pathway).

Some renewable fuel production methods are mature, but there is a limited supply of these feedstocks. In the SAF Roadmap, for example, mature SAF production methods[7] can only provide approximately 10% of Australia's 2050 jet fuel demand (CSIRO, 2023c).

Until all renewable fuels production methods mature, supply of renewable fuels will remain limited. Immature fuel production methods include:

- green ammonia as a shipping fuel (Argus, 2020)
- advanced biofuels from algae and agricultural residues (IRENA, 2019)
- synthetic fuels (e-fuels) (S&P Global, 2024)

Renewable fuels for aviation and shipping have significant price premiums compared to fossil fuels (Table T.3). With competition for feedstocks, it is not clear whether these price premiums could be overcome.

6 LZEHV refers to 'Low and zero emissions heavy vehicles'
7 HEFA

Table T.3: Price premium of renewable compared to fossil fuels

Renewable fuel	Price premium compared to fossil fuel
E-methanol (using carbon capture)	3.5-7 times higher
Green ammonia	3.4-7 times higher
SAF	1.6-4.5 times higher
Bio-methanol	1.4-3.4 times higher

Sources: CSIRO, 2023c; European Maritime Safety Agency, 2023; IRENA (International Renewable Energy Agency), 2021.

T.3.4 Information and data gaps

Supporting an orderly transition to low emissions transport will require better data on Australia's current transport activities, as well as how this could change in the future, including on:

- **Supply and demand of fuels:** The use of bioenergy, including renewable diesel and SAF, requires integrated net zero planning across several sectors including transport, resources (mining haulage), agriculture (farm machinery) and industry (high temperature heat). Further work is needed to:

  1. Collect and publish comprehensive statistics on Australia's liquid renewable fuel use and their feedstocks in Australia. This includes annual quantities of:
     a) The production of renewable liquid fuels
     b) The consumption of renewable liquid fuels
     c) The import of renewable liquid fuels and feedstocks
     d) The export of renewable liquid fuels and feedstocks
  2. Based on these data and other sources analyse current capacity of Australia to produce renewable liquid fuels and develop a projection of how this could develop over time.
  3. Consult with the key industries on this analysis and develop a strategic plan for liquid renewable fuel availability in Australia, including the identification of priority uses for this fuel.

- **Unknown costs for operators:** Transport fleet operators raised concerns with the authority about adopting zero emissions vehicles due to unknown pricing impacts including:

  1. repairs or maintenance costs, particularly while there are limited-service providers
  2. insurance costs, vehicle life and resale values
  3. vehicle range and recharging time impacts on operational costs
  4. uncertainty about future road-user charges for low emissions vehicles

T.3.5 Workforce and skills shortages

The transport sector is currently facing significant labour supply challenges. Industry Skills Australia (2023) has identified shortages across the transport sector:

- Ground crew, pilots, and air traffic control staff in aviation
- Train drivers, controllers and signalling technicians, skill shortfalls
- Truck drivers across Australia, which can cause delays to infrastructure projects
- The maritime industry workforce

These shortages are felt more acutely in regional, rural and remote areas where attracting skilled workers is more difficult (Industry Skills Australia, 2023).

The uptake of new technologies can exacerbate or create new workforce shortages. For example, as the deployment of EVs increases, the demand for mechanics to service EVs will increase. The lack of automotive electricians has been linked with accelerated rates of avoidable write-offs of EVs with minor damage (Visontay, 2024). Local manufacturing of renewable fuels like hydrogen and SAF could also require a growing fuel production workforce (JSA, 2023).

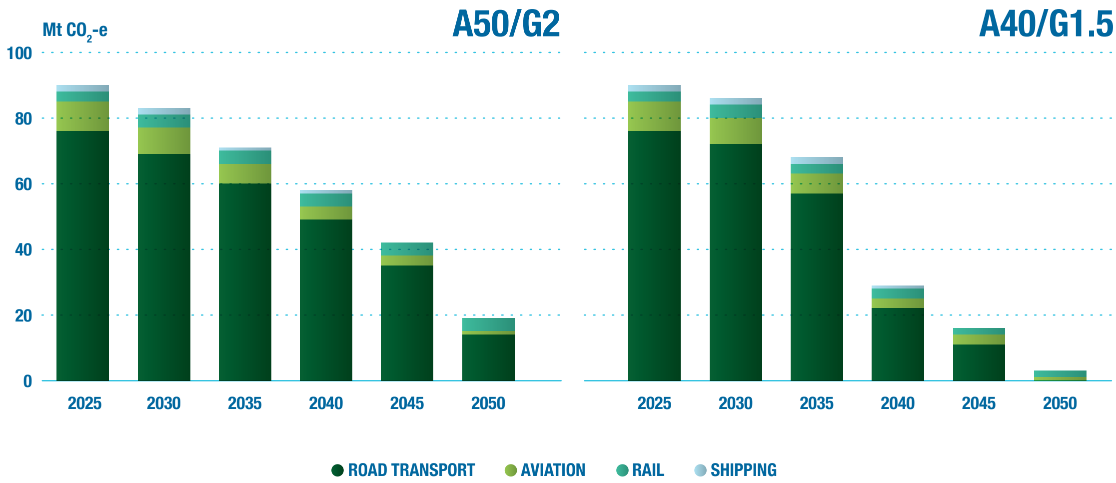
As non-ICE vehicles increase in market share the pipeline of technicians with relevant skills will need to be supported, particularly in regional areas that are more dependent on private road transport (AUSMASA, 2023; JSA, 2023; Leung et al., 2021). Enrolments in electric and hybrid vehicles VET modules are increasing rapidly – from 10 enrolments in 2018 to 597 in 2022 (NCVER, 2024).

The authority's consultation process for this report revealed support for specific training pathways to repair and maintain zero emissions vehicles that do not require workers to undertake traditional ICE mechanical training as well. There was concern about the potential for requiring a worker to be both a mechanic and electrician to work on EVs.

T.4 Emissions pathways

CSIRO modelling commissioned by the authority shows steady decarbonisation of the transport sector in A50/G2 and steep drop in emissions in the A40/G1.5 scenario (Figure T.3).

Figure T.3 Transport sector emissions (AusTIMES), A50/G2 and A40/G1.5



Source: CSIRO modelling in AusTIMES commissioned by the Climate Change Authority

The authority also undertook ground-up analysis to estimate the abatement potential of technologies and compare to the modelling results.

The results of the modelling and ground-up analysis for road vehicles are broadly aligned (Table T.4).

Table T.4: Projected emissions reductions in the transport sector over the period to 2050

	Estimate of abatement to 2050 (Mt CO_2-e)[a]		
Reference: emissions in 2022 were 90 Mt CO_2-e	**AusTIMES modelling (A50/G2)**	**AusTIMES modelling (A40/G1.5)**	**Ground-up estimate**
Road vehicles	62	76	59 (55 from light vehicles, 4 from heavy vehicles)
Domestic aviation	8	9	Not estimated
Domestic shipping	2	2	Not estimated
Rail	0	2	Not estimated
Transport total	71	88	59

Note: Where ground-up analysis was not available, the results of the A40/G1.5 scenario were used for the purpose of estimating total sector abatement to 2050.

a Abatement was calculated as the difference between base year emissions and the projected 2050 emissions from each model. In AusTIMES the base year for the abatement calculation is 2025 and in bottom-up modelling the base year was 2022.

T.4.1 Residual emissions

Total expected residual emissions in 2050 based on both the ground-up analysis and top-down modelling is expected to be between 3 and 23 Mt CO_2-e, comprising of:

- Approximately 0-18 Mt CO_2-e from heavy vehicles
- 1 Mt CO_2-e from domestic aviation
- 2-4 Mt CO_2-e from rail
- Less than 1 Mt CO_2-e from domestic shipping
- 0 Mt CO_2-e from light vehicles

The authority focused on the highest abating technologies for each transport subsector and the take-up of these technologies within the current asset replacement cycle. There is the potential for residual emissions to be addressed through the following additional emissions reduction activities:

- faster asset replacement cycles
- renewable diesel use in the remaining diesel heavy vehicle and rail fleet
- electric and hydrogen propulsion for planes and ships
- mode shifting freight from heavy vehicles to rail
- operational changes and fuel efficiency improvements in vehicles.

T.5 References

ABS (Australian Bureau of Statistics). (2022). Data table of Transport Data Summary. https://www.abs.gov.au/statistics/industry/tourism-and-transport/transport-census/latest-release

ABS. (2023a). Data cube 2: Businesses by main state by industry class by employment size ranges. Counts of Australian Businesses, Including Entries and Exits. https://www.abs.gov.au/statistics/economy/business-indicators/counts-australian-businesses-including-entries-and-exits/jul2019-jun2023/8165DC02_revised.xlsx

ABS. (2023b). Data cube 3: Businesses by main state by industry class by turnover size ranges. Counts of Australian Businesses, Including Entries and Exits. https://www.abs.gov.au/statistics/economy/business-indicators/counts-australian-businesses-including-entries-and-exits/jul2019-jun2023/8165DC03_revised.xlsx

ABS. (2023c). Table 6. Gross Value Added by Industry, Chain volume measures. https://www.abs.gov.au/statistics/economy/national-accounts/australian-national-accounts-national-income-expenditure-and-product/jun-2023/5206006_Industry_GVA.xlsx

ACT Government. (n.d.). Project History. Retrieved June 13, 2024, from https://www.act.gov.au/lightrailtowoden/about/project-history

ACT Government. (2024). Light Rail to Woden. https://www.builtforcbr.act.gov.au/projects/transport/light-rail-to-woden

Adelaide City Council. (2013). Frome Street Bikeway. https://ehq-production-australia.s3.ap-southeast-2.amazonaws.com/a7e60d5b3664ac9f7eb4959c4193b609155b2e9a/documents/attachments/000/002/775/original/Frome_P3_Carr_to_Pirie_Consult_Pack_v04.pdf?X-Amz-Algorithm=AWS4-HMAC-SHA256&X-Amz-Credential=AKIA4KKNQAKIOR7VAOP4%2F20240509%2Fap-southeast-2%2Fs3%2Faws4_request&X-Amz-Date=20240509T033634Z&X-Amz-Expires=300&X-Amz-SignedHeaders=host&X-Amz-Signature=4f172017fe488811e42eb84c217637cfb5626329cae106a246290a11c7b47456

ARENA (Australian Renewable Energy Agency). (2023). Summary of ARENA-funded Hydrogen R&D Projects.

Argus. (2020). Green shift to create 1 billion tonne 'green ammonia' market? https://view.argusmedia.com/rs/584-BUW-606/images/Argus%20White%20Paper%20-%20Green%20Ammonia.pdf

AUSMASA (Mining and Automotive Skills Alliance). (2023). *Workforce Plan The Future is Now.* https://ausmasa.org.au/media/b5mjmwen/ausmasa-initial-workforce-plan-2023.pdf

Australian Trucking Association. (2019). *Economic benefits of improved regulation in the Australian trucking industry.* https://www.truck.net.au/sites/default/files/submissions/DAE%20Economic%20benefits%20of%20improved%20regulation%20in%20the%20Australian%20trucking%20industry%20March%202019%20Final.pdf

Becken, S., Mackey, B., & Lee, D. S. (2023). Implications of preferential access to land and clean energy for Sustainable Aviation Fuels. *Science of The Total Environment, 886,* 163883. https://doi.org/10.1016/j.scitotenv.2023.163883

BITRE (Bureau of Infrastructure and Transport Research Economics). (2019). *Hydrogen as a Transport Fuel.* https://www.dcceew.gov.au/sites/default/files/documents/nhs-hydrogen-as-transport-fuel-report-2019.pdf

BITRE. (2023a). *Australian Infrastructure and Transport Statistics - Yearbook 2023.* https://www.bitre.gov.au/publications/2023/australian-infrastructure-and-transport-statistics-yearbook-2023/freight

BITRE. (2023b). *Road Vehicles 2022 (Re-issue).* https://www.bitre.gov.au/publications/2022/road-vehicles-australia-january-2022-re-issue

BITRE. (2023c). *Road Vehicles, Australia.* https://www.bitre.gov.au/sites/default/files/documents/BITRE-Road-Vehicles-Australia-January-2023.pdf

BNEF (Bloomberg New Energy Finance). (2023). *Electric Vehicle Outlook 2023*. https://www.bnef.com/insights/31517/view

Boston Consulting Group. (2019). *Is There a Future for Service Stations?* https://www.bcg.com/publications/2019/service-stations-future

bp. (2023). *How all sustainable aviation fuel (SAF) feedstocks and production technologies can play a role in decarbonizing aviation.* https://www.bp.com/en/global/air-bp/news-and-views/views/how_all_sustainable_aviation_fuel_SAF_feedstocks_and_production_technologies_can_play_a_role_in_decarbonising_aviation.html

Centre for Urban Research. (2018). *Active Transport.* https://cur.org.au/cms/wp-content/uploads/2018/11/active-transport-policy-brief.pdf

City of Adelaide. (2024). *Building Better Bikeways in the City.* City of Adelaide. https://www.cityofadelaide.com.au/media-centre/building-better-bikeways-in-the-city/

CCA (Climate Change Authority). (2023). *2023 Annual Progress Report.* https://www.climatechangeauthority.gov.au/annual-progress-advice-0

Copenhagen Centre on Energy Efficiency. (2019). *Analysis of hydrogen fuel cell and battery efficiency.* Https://C2e2.Unepccc.Org/Wp-Content/Uploads/Sites/3/2019/09/Analysis-of-Hydrogen-Fuel-Cell-and-Battery.Pdf.

CSIRO (Commonwealth Scientific and Industrial Research Organisation). (2018). *National Hydrogen Roadmap*. https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/energy-and-resources/national-hydrogen-roadmap

CSIRO. (2022). *Electric vehicle projections 2022*. https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2022/2023-inputs-assumptions-and-scenarios-consultation/supporting-materials-for-2023/csiro-2022-electric-vehicles-projections-report.pdf

CSIRO. (2023a). *Electric vehicle projections 2023: update to the 2022 projections report.* https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2023/2024-forecasting-assumptions-update-consultation-page/csiro---2023-electric-vehicle-projections-report.pdf?la=en

CSIRO. (2023b). *Hydrogen vehicle refuelling infrastructure: priorities and opportunities for Australia.* https://www.csiro.au/en/about/challenges-missions/hydrogen/hydrogen-vehicle-refuelling-infrastructure

CSIRO. (2023c). *Sustainable Aviation Fuel Roadmap.* https://www.csiro.au/en/research/technology-space/energy/sustainable-aviation-fuel

DCCEEW (Department of Climate Change, Energy, the Environment and Water). (2022). *Paris Agreement Inventory.* https://greenhouseaccounts.climatechange.gov.au/

DCCEEW. (2023). *National Electric Vehicle Strategy.* https://www.dcceew.gov.au/sites/default/files/documents/national-electric-vehicle-strategy.pdf

efuel alliance. (2022). *What are eFuels?* https://www.efuel-alliance.eu/efuels/what-are-efuels

Electric Vehicle Council. (2023). *State of Electric Vehicles 2023.* https://electricvehiclecouncil.com.au/wp-content/uploads/2023/07/State-of-EVs_July-2023_.pdf

Electric Vehicle Council. (2024). *Australian Electric Vehicle Industry Recap 2023.* https://electricvehiclecouncil.com.au/reports/australian-electric-vehicle-industry-recap-2023/

Electric Vehicle Council & Australian Trucking Association. (2022). *Electric trucks: Keeping shelves stocked in a net zero world.* Https://Electricvehiclecouncil.Com.Au/Wp-Content/Uploads/2022/01/ATA-EVC-Electric-Trucks_Keeping-Shelves-Stocked-in-a-Net-Zero-World-1.Pdf.

Energetics. (2024). *Electric Vehicle Charging Infrastructure Guidance Report.* https://www.aada.asn.au/wp-content/uploads/2024/04/2024.04.10-Electric-vehicle-infrastructure-guidance-report.pdf

Energy Networks Australia. (2019). *E-ferry Concept Implementation.* https://www.energynetworks.com.au/news/energy-insider/2019-energy-insider/beyond-evs-batteries-in-the-water/

ETIP Bioenergy. (2024). *Sustainable Feedstocks for Advanced Biofuels and Intermediate Bioenergy Carriers Production in Europe.* https://www.etipbioenergy.eu/value-chains/feedstocks/biofuels-feedstocks-an-overview

European Commission. (2024). Norwegian EV Market Surges to 91.5% Market Share, Setting a Sustainable Example. *European Alternative Fuels Observatory*. https://alternative-fuels-observatory.ec.europa.eu/general-information/news/norwegian-ev-market-surges-915-market-share-setting-sustainable-example

European Maritime Safety Agency. (2023). *Update on potential of biofuels in shipping.* https://www.emsa.europa.eu/newsroom/latest-news/item/4833-potential-of-ammonia-as-fuel-in-shipping.html

European Union Aviation Safety Agency. (2024). *How sustainable are SAF?*

FAO (Food and Agriculture Organization of the United Nations). (2010). *Algae-based biofuels.* https://www.fao.org/4/i1704e/i1704e.pdf

Global Commercial Vehicle Drive to Zero. (2023, June). *Zero-emission Truck and Bus Market Update*. Https://Globaldrivetozero.Org/Site/Wp-Content/Uploads/2023/06/Final_ZETI-Report-June-2023_Final.Pdf.

Goulias, K. G., Broeg, W. W., James, B., & Graham, C. (2002). *Travel behavior analysis of south perth individualized marketing intervention.* Transportation Research Record, 1807, 77–86. https://doi.org/10.3141/1807-10

Grattan Institute. (2023). *Hydrogen - Hype, hope or hardwork?* https://grattan.edu.au/wp-content/uploads/2023/12/Hydrogen-hype-hope-or-hard-work-Grattan-Institute.pdf

Green Vehicle Guide. (2024). *Electric vehicles.* https://www.greenvehicleguide.gov.au/pages/LowAndZeroEmissionVehicles/ElectricVehicleInformation#:~:text=How%20far%20can%20EVs%20travel,test%20performed%20in%20controlled%20conditions.

Hanaki, K., & Portugal-Pereira, J. (2018). *The Effect of Biofuel Production on Greenhouse Gas Emission Reductions.* In Biofuels and Sustainability (pp. 53–71). https://doi.org/10.1007/978-4-431-54895-9_6

Hydrogen Council. (2021). *Hydrogen for Net-Zero*. https://hydrogencouncil.com/wp-content/uploads/2021/11/Hydrogen-for-Net-Zero.pdf

Hydrogen Europe. (2024). *Long-term outlook on zero-emission mobility*. https://hydrogeneurope.eu/wp-content/uploads/2024/02/2024.02.14-Long-term-outlook-on-zero-emission-mobility_Report_14-02-2024_DIGITAL.pdf

ICCT (International Council on Clean Transportation). (2022). *Fuel-cell hydrogen long-haul trucks in Europe: A total cost of ownership analysis*. https://theicct.org/wp-content/uploads/2022/09/eu-hvs-fuels-evs-fuel-cell-hdvs-europe-sep22.pdf

IEA (International Energy Agency). (2024a). *Oil 2024*. https://www.iea.org/reports/oil-2024

IEA. (2024b). *The Role of E-fuels in Decarbonising Transport.* https://iea.blob.core.windows.net/assets/a24ed363-523f-421b-b34f-0df6a58b2e12/TheRoleofE-fuelsinDecarbonisingTransport.pdf

Industry Skills Australia. (2023). *Transport & Logistics Industry 2023 Initial Workforce Plan.* https://www.industryskillsaustralia.org.au/initial-workforce-plans

International Transport Forum. (2023). *How Improving Public Transport and Shared Mobility Can Reduce Urban Passenger Carbon Emissions.* https://www.itf-oecd.org/reduce-urban-passenger-emissions

Interreg. (2020). *Comparative report on alternative fuels for ship propulsion*. https://vb.nweurope.eu/media/14694/210225_h2ships_t232_compassesmtaltfuels-02.pdf

IRENA (International Renewable Energy Agency). (2019). *Advanced Biofuels, What holds them back?* https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Nov/IRENA_Advanced-biofuels_2019.pdf

IRENA. (2021). *A pathway to decarbonise the shipping sector by 2050*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Oct/IRENA_Decarbonising_Shipping_2021.pdf

JSA (Jobs and Skills Australia). (2023). *The Clean Energy Generation.* https://www.jobsandskills.gov.au/publications/the-clean-energy-generation

Leung, A., Burke, M., Akbar, D., & Kaufman, B. (2021). *Mobility as a Service Regional Research.* https://www.griffith.edu.au/__data/assets/pdf_file/0040/1379947/MaaS_Regional_Research_Report_FINALREPORT_Final1.pdf

McKinsey. (2023). *Powering the transition to zero-emission trucks through infrastructure.* https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/powering-the-transition-to-zero-emission-trucks-through-infrastructure

Methanol Institute. (2022). *Carbon footprint of methanol.* https://www.methanol.org/wp-content/uploads/2022/01/CARBON-FOOTPRINT-OF-METHANOL-PAPER_1-31-22.pdf

Mission Possible Partnership. (2022). *Making Net-Zero Aviation Possible*. https://www.mckinsey.com/~/media/mckinsey/industries/aerospace%20and%20defense/our%20insights/decarbonizing%20the%20aviation%20sector%20making%20net%20zero%20aviation%20possible/making-net-zero-aviation-possible-full-report.pdf

The National Farmers' Federation. (2024). *Farmers fear impacts of Federal 'ute tax.' National Farmers Federation.* https://nff.org.au/media-release/farmers-fear-impacts-of-federal-ute-tax/

National Heavy Vehicle Regulator. (2016). *National heavy vehicle mass and dimension limits.* Https://Www.Nhvr.Gov.Au/Files/201607-0116-Mass-and-Dimension-Limits.Pdf.

National Transport Commission. (2023). *Electric bus evaluation.* https://www.ntc.gov.au/sites/default/files/assets/files/Electric%20Bus%20Evaluation%20-%202023.pdf

NatRoad (National Road Transport Association). (2024). *Rule changes to better enable uptake of electric vehicles.* https://www.natroad.com.au/rule-changes-to-better-enable-uptake-of-electric-vehicles/#:~:text=NSW%20and%20South%20Australia%20have,powered%20models%20imported%20from%20Europe.

NCVER (National Centre for Vocational Education Research). (2024). *Driving towards a green economy.* https://www.ncver.edu.au/__data/assets/pdf_file/0042/9687156/Snapshot-electric-vehicles-FF.pdf

Norwegian Electric Vehicle Association. (2022). *Norwegian EV policy.* https://elbil.no/english/norwegian-ev-policy/

Norwegian Government. (2023). *National charging strategy.* https://www.regjeringen.no/en/dokumenter/national-charging-strategy/id2950371/?ch=6

NPROXX. (2024). *Growing demand in Europe for hydrogen bus systems.* https://www.nproxx.com/growing-demand-in-europe-for-hydrogen-bus-systems/#:~:text=Buses%20powered%20by%20hydrogen%2Dpowered,compared%20to%20battery%20electric%20buses.

NSW Government. (2023). *Biodiesel, renewable diesel and bioethanol.* https://www.dpi.nsw.gov.au/dpi/climate/energy/clean-energy/bioenergy/biofuels

Office of Energy Efficiency & Renewable Energy. (n.d.). *Biofuel Basics*. Retrieved July 12, 2024, from https://www.energy.gov/eere/bioenergy/biofuel-basics

Point Advisory. (2023). *ACT Greenhouse Gas Inventory for 2022-23.* https://www.climatechoices.act.gov.au/__data/assets/pdf_file/0003/2329824/ACT-Greenhouse-Gas-Inventory-Report-2022-23.pdf

Prussi, M., Lee, U., Wang, M., Malina, R., Valin, H., Taheripour, F., Velarde, C., Staples, M. D., Lonza, L., & Hileman, J. I. (2021). CORSIA: *The first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels.* Renewable and Sustainable Energy Reviews, 150, 111398. https://doi.org/10.1016/j.rser.2021.111398

Queensland Transport and Logistics Council. (2022). *Addressing barriers to zero emissions trucks in Queensland to 2025.* Https://Www.Qtlc.Com.Au/Wp-Content/Uploads/2022/02/QTLC-EV-Report-2022.Pdf. https://www.qtlc.com.au/wp-content/uploads/2022/02/QTLC-EV-Report-2022.pdf

Rosel, R. (2023). *Electric Car Survey and Statistics 2023.* Budget Direct. https://www.budgetdirect.com.au/car-insurance/research/electric-car-survey.html

Rural and Regional Affairs and Transport References Committee. (2014). *Role of public transport in delivering productivity outcomes*. https://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Rural_and_Regional_Affairs_and_Transport/Public_transport/Report

S&P Global. (2024). *E-fuels: A Challenging Journey To A Low-Carbon Future.* https://www.spglobal.com/_assets/documents/ratings/research/101595057.pdf

Strata Community Association. (2023). *Electric Vehicles in Strata Phase 2: Challenges. Strata Community Association.* https://www.strata.community/_files/d/5b1a8d_78e2afca3ece404daf3ad1e1be5053a2.pdf

The Australia Institute. (2023). *Community Attitudes to Home and Car Electrification.* https://australiainstitute.org.au/wp-content/uploads/2023/04/P1408-Household-Electrification-WEB.pdf

Transport and Environment. (2020). *Comparison of hydrogen and battery electric trucks*. https://www.transportenvironment.org/wp-content/uploads/2021/07/2020_06_TE_comparison_hydrogen_battery_electric_trucks_methodology.pdf

Transport Canberra. (2024). *Light Rail Five Years On: Benefits Realisation Report 2024.* https://www.transport.act.gov.au/__data/assets/pdf_file/0005/2442965/Light-Rail-Five-Years-On-Benefits-Realisation-of-Light-Rail-Stage-1-Report-2024-access-.pdf

Trucksales. (2024). Qld Government rolls out axle weight increase for electric trucks. https://www.trucksales.com.au/editorial/details/qld-government-rolls-out-axle-weight-increase-for-electric-trucks-144954/#:~:text=The%20Queensland%20Government%20has%20today,selected%20roads%20throughout%20the%20state.

US Energy Information Administration. (2024). Biomass explained. https://www.eia.gov/energyexplained/biomass/biomass-and-the-environment.php

van Dyk, S. (2022). Sustainable aviation fuels are not all the same and regular commercial use of 100% SAF is more complex. Greenair Communications. https://www.greenairnews.com/?p=2460

VicRoads. (2023). Low or Zero Emission Heavy Vehicles (LZEHVs). https://www.vicroads.vic.gov.au/business-and-industry/heavy-vehicle-industry/heavy-vehicle-map-networks--in-victoria/low-or-zero-emission-heavy-vehicles

Visontay, E. (2024, April 26). Australia's skilled mechanics shortage forcing insurers to write off electric vehicles after minor accidents. The Guardian. https://www.theguardian.com/environment/2024/apr/26/australias-skilled-mechanics-shortage-forcing-insurers-to-write-off-electric-vehicles-after-minor-accidents

Wood Mackenzie. (2022). Waste-based biofuels could be the key to unlocking the energy transition. https://www.woodmac.com/press-releases/waste-based-biofuels-could-be-the-key-to-unlocking-the-energy-transition/

Wood Mackenzie. (2024). E-fuels: frequently asked questions. https://www.woodmac.com/news/opinion/e-fuels-faq/

Industry and waste

INDUSTRY AND WASTE

Sector summary

Australia's industries can prosper in a low emissions world. Rapid decarbonisation, primarily through electrification, fuel switching and process changes, can contribute materially to meeting Australia's emissions reduction targets. There are opportunities for the sector to supply zero and low emissions materials (such as steel and ammonia) to the domestic economy and deliver low emissions exports (such as alumina and aluminium) to Australia's trading partners.

Emissions from the industry and waste sector were 64 Mt CO_2-e in 2022 (CCA, 2024a). The sector's emissions are concentrated at a small number of large facilities (over 50% of emissions emanate from just 20 major facilities). Reducing emissions at many major facilities hinges on replacing or retrofitting large industrial assets at a suitable time. Further significant emissions reductions in the sector could occur from the 2030s as new and emerging technologies become available. There may be residual emissions after all available technologies have been taken up.

For the industry and waste sector to decarbonise, a portfolio of solutions will be required:

- widespread deployment of energy efficiency and adoption of a circular economy approach
- electrification and fuel switching (including to hydrogen and biofuels) to decarbonise high temperature process heat to produce iron and steel, alumina, ammonia and cement
- substitution of feedstock materials, including using electrolytic hydrogen, to produce iron and ammonia, alternative materials for cement, and captured CO_2 for chemicals, plastics and building materials
- carbon capture use and storage (CCUS) to capture emissions not abatable through other measures.

Decarbonisation of the industry sector and unlocking associated opportunities is highly dependent on the availability of a reliable supply of sufficiently firmed decarbonised electricity, and new fuels where they are required.

Other barriers to decarbonisation include technological readiness of solutions for key processes and issues associated with access to sufficient raw, recycled or recovered material, as well as to infrastructure. Substantial new private investment will be required to replace or retrofit large assets, including in major facilities in trade exposed industries.

Addressing these issues will require improved planning and coordination within industries and government, and between them. Development of low emissions industrial precincts and improving materials circularity is likely to aid decarbonisation efforts.

IW.1 Sector state of play

The industry and waste sector processes, manufactures and produces goods, and disposes of materials that have reached their end of life. Australia's industry and waste sector's Gross Value Added contributed around 5% of Australia's total Gross Domestic Product in 2022-23 (Appendix B). In 2023, the export of manufactured goods from the sector generated over $140 billion, approximately 25% of Australia's exports for that year (ABS, 2024). The sector consumed 18% of Australia's energy in 2021-22, including from electricity, gas, liquid and solid fuels (DCCEEW, 2023).

The sector accounts for approximately 7% of total employment, employing more than 900,000 people, including more than 250,000 women (Appendix B).

As industry decarbonises, competition with other sectors for electricians and engineers could cause shortages, delays and increased costs. Further, ongoing and projected labour and skills shortages in manufacturing may hinder Australian ambitions for growth of low emissions industries (MISA 2023; Climate Council 2023).

Within the industry and waste sector, the authority considered the following sources of emissions (scope 1):

- production of alumina and aluminium, iron and steel, lime and cement and ammonia
- emissions from waste
- manufacturing (including chemicals and plastics other than ammonia, food and beverages, building materials, pulp and paper)
- some synthetic greenhouse gases.

Emissions from the five highest emitting subsectors (alumina and aluminium, iron and steel, lime and cement, ammonia, and waste) are responsible for over 80% of the industry and waste sector's total scope 1 emissions (Table IW.1). The authority focused its analysis on decarbonisation technologies for these five subsectors but has also considered decarbonisation opportunities in the sector more generally, especially in relation to process heat.

Table IW.1: Industry and waste emissions breakdown by subsector, 2021-22

Subsector	Mt CO_2-e	Subsector share (%)
Alumina and aluminium	15	24
Waste	12	19
Iron and steel	11	17
Lime and cement	9	13
Ammonia*	5	8
Other industry	13	19
Total	64	100

Note: (DCCEEW & DISR 2024; CER 2024; CCA 2024a)*includes the production of ammonia derivatives

Emissions in the industry and waste sector originate from combustion of fossil fuels for heat and on-site electricity generation, industrial process and product use (IPPU),[1] and methane produced in landfills. Emissions in the sector have decreased from 79 Mt CO_2-e in 2005 to 64 Mt CO_2-e in 2022 (CCA, 2024a), which reflects decreased emissions from:

- energy use for manufacturing, with metals manufacturing having the largest decrease.
- IPPU, due to decreased emissions across manufacturing. The largest decrease was from metals manufacturing due to lower emission rates of perflurocarbons (PFCs) in aluminium smelting. Small improvements in emissions intensity of cement production have also played a role.
- the waste sector, largely due to landfill gas capture, but this decline has slowed in the last decade.

1 Industrial Processes and Product Use (IPPU), covers greenhouse gas emissions occurring from industrial processes, from the use of greenhouse gases in products, and from non-energy uses of fossil fuel carbon.

IW.2 Existing and prospective technologies

Emissions reduction opportunities currently available for deployment in the industry and waste sector include:

- **energy efficiency** to provide incremental emissions reduction by reducing energy consumption (AIETI, 2021).
- **electrification** of low temperature process heat, which is likely to occur at the end of asset life, eliminating emissions from fuel combustion (AIETI 2021; RACE for 2030 2021; ARENA 2019; McKinsey 2020).
- **fuel substitution** for some industrial processes, including biofuels used in existing assets to decarbonise high temperature heat processes (AIETI 2021; MPP 2023).
- **scrap metal recycling** to reduce the amount of primary metal production (AIETI, 2021).
- **landfill diversion** to redirect organic waste.

Thermal storage may be deployed as part of electrification or energy efficiency upgrades, to reduce energy demands and support decarbonisation by easing use of variable renewable energy in steady industrial processes. These technologies are expected to become more widely available for higher temperature processes and may be particularly relevant for medium to high temperature heat processes.

While many emissions reduction opportunities are available to decarbonise the sector, technologies are not yet commercially available at industrial scale to fully decarbonise several key industrial processes, particularly alumina, iron and steel and cement production, which comprise approximately 50% of the sector's emissions footprint.

Major changes expected in the industry and waste sectors over time include:

- increasing demand for decarbonised electricity and alternative fuels, including hydrogen and biofuels
- changing consumer preferences, and policy preferences in major markets, for goods produced using low emissions processes
- increasing opportunities for exports of low emissions metals, materials, and manufactured goods
- increasing circularity in the economy.

IW.2.1 Decarbonising process heat

Process heat is the thermal energy used in the production of manufactured goods (US DoE, n.d.-a). It is a key source of emissions across industry, from small food manufacturing facilities to the large manufacturing facilities in the highest emitting subsectors (alumina and aluminium, iron and steel, cement and ammonia). Process heat typically accounts for over 50% of scope 1 energy use in industry (ARENA 2019; McKinsey 2020). Decarbonising these emissions sources will have impacts across the sector.

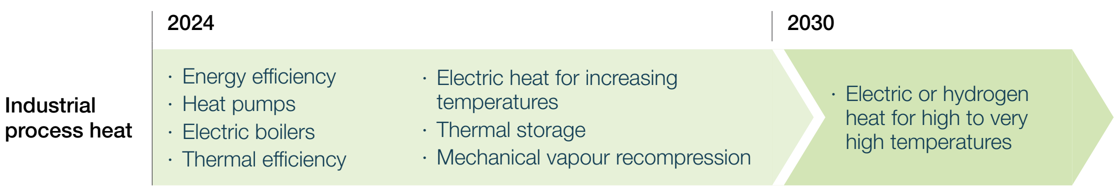
Decarbonising process heat focuses on changing how heat is generated and stored, right-sizing heat generation, improved heat recovery in systems, as well as research into lowering the temperature requirements for processes. Thermal storage may provide additional opportunities to reduce emissions or overall energy consumption.

The availability of decarbonisation solutions for the generation of process heat will depend on the temperature requirements for a given industrial process (Figure IW.1):

- Electrification of low (<100 °C) and medium temperature (100-400 °C) process heat is possible now through existing technologies (McKinsey, 2020). Heat pumps and electric boilers are commercially available and cost competitive for low temperature heat (AIETI, 2021).
- Electric furnaces for generation of high temperature (400-1,000 °C) process heat are being developed but are not yet commercially available at industrial scale for all processes (WBCSD 2021; McKinsey 2020). For some locations, solar thermal could be suitable for providing industrial heat, and is capable of heating to over 1,000 C (US DoE, n.d.-b).

Decarbonisation of very high temperature (>1,000 °C) process heat typically requires fuel switching to hydrogen or bioenergy (WBCSD, 2021; ARENA, 2019).

Figure IW.1: Prospective decarbonisation pathway for process heat



IW.2.2 Decarbonising the highest emitting subsectors within the industry and waste sector

A portfolio of technology solutions is required to decarbonise the highest emitting subsectors of industry and waste as shown in Table IW.2. The readiness of these technologies varies significantly, and there are various other barriers to their adoption (IEA 2023, 2019; AIETI 2021; MPP 2023).

Table IW.2: Priority abatement levers for key subsectors

Emissions subsector	Share of sector scope 1 emissions	Priority abatement lever	Readiness	Barriers to adoption
Alumina and aluminium	24%	Electric digestion for alumina refining (electric boilers or mechanical vapour recompression)	Range from demonstration to deployment, depending on temperature required (ARENA, 2022)	· High CAPEX · Lack of mature technologies (for medium temperature process heat at high pressure) · Insufficient supply of firmed renewable electricity
		Electric or hydrogen calcination for alumina refining	Demonstration (ARENA, 2022)	· Lack of mature technologies · High CAPEX and OPEX · Insufficient supply of firmed renewable electricity and electrolytic hydrogen
		Inert anodes for aluminium smelting	Demonstration (Rio Tinto, 2023)	· Lack of mature technologies · High CAPEX
		New cell design for aluminium smelting	Research and Development (AIETI, 2021)	· Lack of mature technologies · High CAPEX
		Secondary production	Commercial	· Limited to availability of scrap
Iron and steel	17%	Direct reduction of iron ore (DRI) in a direct reduction shaft furnace using hydrogen as a reducing agent (using natural gas before hydrogen becomes available)	Demonstration (IEA, 2023) (commercial using natural gas)	· High CAPEX and OPEX · Insufficient supply of firmed renewable electricity and electrolytic hydrogen
		Steelmaking with an electric arc furnace (EAF) powered by renewable energy	Commercial	· High CAPEX · Insufficient supply of firmed renewable electricity · Limited to ore containing high iron content
		Secondary production	Commercial	· Limited to availability of scrap
Lime and cement	13%	Electric or hydrogen kiln for clinker production	Research and Development (IEA 2023; MPP 2023)	· Lack of mature technologies · High CAPEX · Access to significant supply of renewable electricity or electrolytic hydrogen
		Material substitution	Commercial (VDZ 2021; MPP 2023)	· Limited by maximum substitution potential · Limited to availability of suitable materials
		Carbon Capture Use and Storage (CCUS)	Demonstration (IEA, 2023)	· High CAPEX and OPEX · Insufficient carbon storage or use opportunities

Emissions subsector	Share of sector scope 1 emissions	Priority abatement lever	Readiness	Barriers to adoption
Ammonia	8% for ammonia and derivatives	Green hydrogen for ammonia	First of a kind commercial stage	· Insufficient supply of electrolytic hydrogen or renewable electricity · High CAPEX and OPEX
		Steam methane reforming (SMR) with CCS to generate hydrogen for ammonia	Demonstration to commercial (depending on capture rate) (IEA 2023; IRENA 2022)	· High CAPEX and OPEX · Insufficient carbon storage or use opportunities
		Electric heat generation for ammonia	Demonstration (MPP, 2022)	· High CAPEX · Insufficient supply of renewable electricity
Waste	19%	Diversion of organic waste from landfills	Commercial	· High cost (in comparison to landfill) · Lack of market for products · Lack of reliable and consistent feedstock supply

IW.2.3 Alumina and aluminium

There are 6 alumina refineries and 4 aluminium smelters in Australia (AAC, 2024a, 2024b), all of which are covered under the Safeguard Mechanism (CER, 2024). These facilities are owned by Alcoa (3 refineries and one smelter), Rio Tinto (2 refineries and 3 smelters, including one jointly owned with CSR and Hydro Aluminium) and South32 (one refinery) (AAC, 2024a, 2024b; Rio Tinto n.d.). Alcoa announced the closure of their Kwinana facility early in 2024 (Alcoa, 2024).

Aluminium is produced in two main steps: the refining of bauxite into alumina, and the smelting of alumina into aluminium. Alumina refining and aluminium smelting were 80% and 20% of the scope 1 aluminium supply chain emissions in 2022, respectively (CER, 2024).

In alumina refining, digestion and calcination are the two most energy intensive steps, and together account for the largest portion of emissions associated with the refining process.

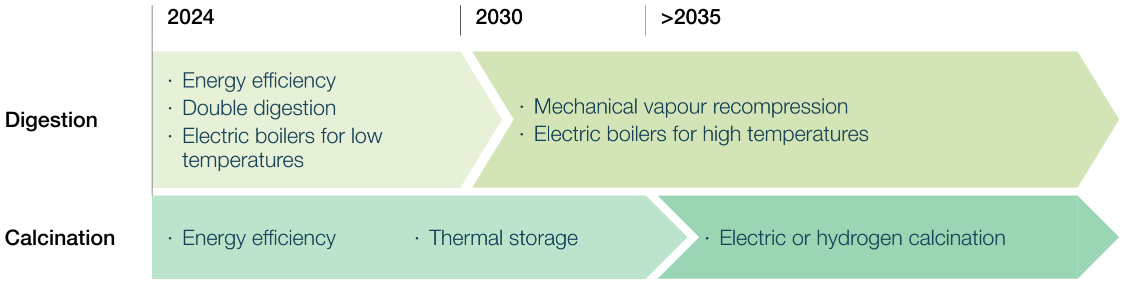
Digestion requires pressure and medium temperature heat ranging between 145-265 °C,[2] currently generated from steam from combustion of fossil fuels, and is responsible for 65% of the emissions from alumina refining (ARENA, 2022; AIETI, 2021). Electrification is the key pathway to decarbonising alumina digestion, with electric boiler technologies commercially available for the lower end of the digestion temperature range, but not yet proven at the higher pressures required for the higher end (ARENA, 2022).

Mechanical vapour recompression (MVR) is another electric digestion technology, requiring approximately one-third of the energy of electric boilers (ARENA, 2022). MVR is currently being tested at pilot scale for low temperature digestion at the Wagerup Alcoa facility (ARENA, 2023a). For bauxite ore that requires higher heat for digestion, double digestion of the ore may facilitate the use of MVR by enabling a second digestion stage to be conducted at lower temperature (ARENA, 2022; DCCEEW, 2024a).

Calcination requires high temperature heat over 800 °C, which is typically produced from natural gas, and produces 33% of the emissions for alumina refining (ARENA, 2022; AIETI, 2021). Both electric and hydrogen calcination technologies are being explored in Australia (ARENA, 2023b, 2023c). The pathway for decarbonising this step of alumina refining will be determined by availability and cost of electrolytic hydrogen and decarbonised electricity (AIETI, 2021; ARENA, 2022). Figure IW.2 details prospective decarbonisation pathways for alumina refining.

2 depending on the type of bauxite ore

Figure IW.2: Prospective decarbonisation pathway for alumina refining



Aluminium smelting is an energy intensive process that runs on electricity. Scope 2 emissions are responsible for 85% of combined scope 1 and 2 emissions from aluminium smelting. These electricity emissions will be abated through:

- energy efficiency, including through process improvements and equipment upgrades
- increasing use of scrap aluminium (known as secondary production)
- decarbonisation of Australia's electricity grids.

Box: IW.1 Aluminium smelting scope 2 emissions

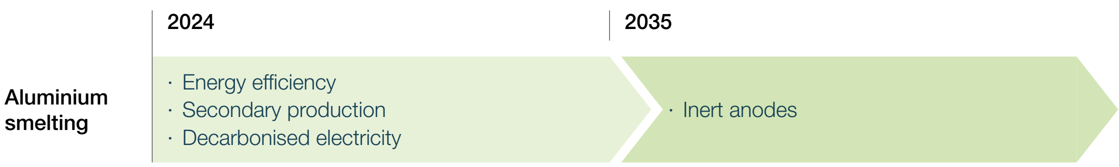
Aluminium smelting emissions are dominated by scope 2 emissions, due to the large amount of electricity required to convert alumina to aluminium via electrolysis. The 4 aluminium smelters in Australia are connected to the NEM and use approximately 10% of the NEM's electricity supply (AAC 2024b, 2024c).

These smelters have long term electricity contracts that expire between 2025 and 2029, and the owners have indicated they intend to contract renewable electricity when contracts end (AAC, 2024c).

In February 2024, Rio Tinto announced the signing of Australia's largest renewable power purchase agreement (PPA) to date to supply its Gladstone operations, including the aluminium smelter, with wind energy (Rio Tinto, 2024). This agreement to source electricity from Windlab's Bungaban project follows a PPA to source electricity from European Energy's Upper Calliope solar farm. These 2 projects (2.2 GW combined) are anticipated to meet half of its Gladstone operations' electricity needs (4 GW).

Direct emissions from aluminium smelting are dominated by process emissions, which are emissions generated from chemical and physical transformations, from the use of carbon anodes as they are consumed. These emissions account for 95% of scope 1 emissions (AAC, 2023), and 15% of combined scope 1 and 2 emissions for aluminium smelting (ARENA, 2022). Decarbonising the direct emissions from aluminium smelting will require the development of inert anodes to replace the carbon anodes currently used. Inert anodes are in the research and development stage (ELYSIS, n.d.).

Figure IW.3: Prospective decarbonisation pathway for aluminium smelting



IW.2.4 Iron and steel

In Australia, BlueScope and Liberty are the primary steel producers that manufacture steel from iron ore using the blast furnace and basic oxygen furnace (BF-BOF) process (ASI, 2023). Infrabuild and Molycop produce steel from scrap using electric arc furnaces (EAF). The largest source of emissions from iron and steel production is the use of coal in BF-BOF process. Coking coal is used to provide heat and as a reductant to remove oxygen from the iron ore, generating emissions from combustion and process emissions. The two primary steel production facilities in Australia that make steel from iron ore both use the BF-BOF process.

The most prospective pathway for decarbonising iron and steel production involves direct reduction of iron and an electric arc furnace (DRI-EAF) eliminating the need for coal (AIETI, 2021). The DRI process uses hydrogen or natural gas as a reductant to remove oxygen from the iron ore, and the EAF turns the resulting iron into steel using electricity. If the DRI-EAF is run using electrolytic hydrogen and decarbonised electricity, this process will avoid both combustion and process emissions. The technology and commercial readiness of the DRI-EAF steelmaking process varies depending on the fuel source and reductant being considered, and is:

- commercially available with the use of natural gas
- at the demonstration stage using electrolytic hydrogen blended with natural gas
- at the prototype stage for 100% electrolytic hydrogen (IEA, 2023).

An EAF requires high iron content materials, such as scrap steel or iron generated from the DRI processing of magnetite ore with low impurities (Shahabuddin et al., 2023). For lower grade hematite ores, electric smelter furnaces (ESF) are being piloted to remove impurities (BlueScope, 2024; Wood Mackenzie, 2024). ESF would make the DRI route applicable to a greater portion of the global supply of iron ore (76% for ESF compared to 8% EAF, (Wood Mackenzie, 2024)).

The DRI-EAF route could reduce emissions by 95%, while the DRI-ESF-BOF route could reduce emissions by 77%, when both are run on decarbonised electricity and electrolytic hydrogen (Wood Mackenzie, 2024). The use of biochar or carbon capture use and storage (CCUS) may enable deeper decarbonisation for the latter route. Figure IW.4 details prospective decarbonisation pathways for iron and steel production.

Figure IW.4: Prospective decarbonisation pathways for iron and steel production

	2024	2030	2035
Key pathway (lower emissions pathway)	· Energy efficiency · Secondary production	· Natural gas DRI-EAF	· Hydrogen DRI-EAF
Higher emissions pathway	· Energy efficiency · Secondary production	· Natural gas DRI with electric smelter and BOF	· Hydrogen DRI with electric smelter and BOF plus biochar or CCUS

IW.2.5 Lime and Cement

There are 7 lime and cement manufacturing facilities covered by the Safeguard Mechanism (CER 2024; CIF 2023). These facilities are owned by Adbri (4 facilities), Cement Australia (2 facilities), and Boral (1 facility).

The two main emissions sources in cement production are:

- CO_2 process emissions from the chemical reactions to produce clinker, a key component of cement
- combustion of fossil fuels for the generation of very high temperature heat (1,450 °C) to produce clinker.

Process emissions account for approximately two-thirds of emissions from cement production, and heat generation accounts for the remaining one-third (MPP, 2023).

Near-term opportunities to reduce emissions from cement production include:

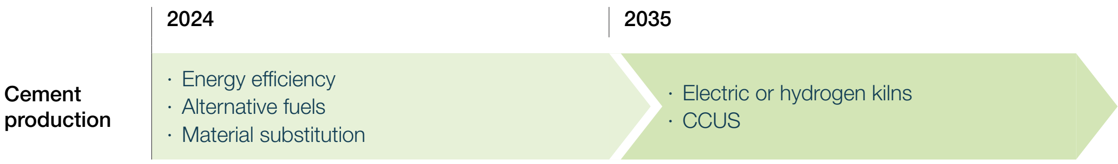
- energy efficiency, including through process improvements and waste heat recovery
- use of alternative fuels in place of fossil fuels in cement kilns
- material substitution to reduce the amount of clinker in cement.

Figure IW.5 outlines a prospective pathway for decarbonising cement production that results in maximum abatement through:

- electric or hydrogen powered kilns
- further material substitution to reduce the amount of clinker in cement
- CCUS to capture process emissions.

Process emissions associated with current cement production techniques cannot be abated without CO_2 capture, use or storage. CCS is unlikely to be used in the Australian cement industry, due to the distance from most existing cement facilities to appropriate CO_2 storage facilities (GA, 2023a). The Australian cement industry is exploring CCUS opportunities, including through a feasibility study for generating methanol from proposed captured CO_2 produced from Cement Australia's Gladstone facility (CSIRO, 2022).

Figure IW.5: Prospective decarbonisation pathway for cement production



Box: IW.2 Removal, capture, use and storage

Carbon dioxide removal

Engineered forms of carbon dioxide removal (CDR) include direct air capture (DAC), mineral carbonation, and biochar. These early-stage CDR technologies remove carbon from the atmosphere, and most also require the development of geological storage for the captured CO_2.

The quantity of CO_2 removed by these technologies remains small globally (Smith et al., 2024). Costs of capture remain high, in some cases around USD 700/tonne of CO_2 removed, e.g. for DAC (Smith et al., 2024). DAC also has high energy requirements (e.g. Casaban and Tsalaporta, 2023), and land requirements estimated at around 0.26 square meters per tonne CO_2 (Climeworks consultation, 2024).

With strong policy and financial support, novel CDR could reach the megatonne-per-year scale by the 2030s.[3] For that abatement to contribute to meeting Australia's targets, approaches such as biochar, DAC, enhanced weathering and mineral carbonation would need to be included in national greenhouse gas inventories.

Other technology options such as large-scale modifications of environments through ocean alkalinity enhancement and ocean fertilisation remain at early stages of R&D. However, they are of interest because of their global potential to reach gigatonne scale (Bach et al., 2024).

To achieve megatonne-scale uptake of novel engineered CDR in Australia, a rapid acceleration of funding support will be needed, both for basic research and for implementation of pilot projects, as recommended by the authority in previous reports (CCA, 2023a, CCA, 2023b).

3 This estimate derives from consultation for this report and from the CSIRO Report, 'Australia's carbon sequestration potential,' Australia's carbon sequestration potential - CSIRO

Carbon capture and storage

Point-source capture of CO_2, known as carbon capture and storage (CCS), could play an important role in reducing emissions.

Access to storage sites is critical to enable adoption of CCS. However, policies will be needed to ensure that CCS is deployed by industries that are critical for Australia's energy transition, rather than prolonging the life of fossil fuel-based equipment that could be transitioned to zero emissions alternatives.

At present, CCS remains expensive and at small-scale, but it has been deployed for decades and has potential to be scaled up. The Safeguard Mechanism is a key policy driver, requiring annual net emission reductions of 4.9% for covered facilities. Industries that emit a comparatively high concentration of CO_2, such as natural gas processing, hydrogen production (from gas) and cement, are most suited to implementation of CCS and should be prioritised by industry and government for assessment of the potential to adopt CCS at scale.

Carbon capture and use

Carbon capture and use (CCU) is another process expected to play a role in a future carbon removal industry. The capture of point source emissions can support scaling of CCU while atmospheric capture develops to be deployed economically at scale. The fact that some industries (e.g. aviation, cement, and chemicals) may not be able to fully decarbonise for some time gives rise to the possibility of new industries emerging, utilising captured CO_2 to make a range of products (Srinivasan et al., 2021). The use of CO_2 as a feedstock for manufacture of products such as synthetic gas, biomethane, and long-lived products such as bricks or cement is small today, but these uses may scale up as Australia approaches net zero emissions. As the ARC Research Hub for Carbon Utilisation and Recycling (2024) noted in its submission, new industries based on carbon capture will be necessary as the gradual phase out of fossil fuels removes them as critical feedstocks.

IW.2.6 Ammonia

There are 8 ammonia facilities in Australia, and they are covered by the Safeguard Mechanism (CER, 2024). These facilities are owned by Incitec Pivot (3 facilities), Orica (2 facilities), Yara (1 facility) and Wesfarmers (1 facility).

Ammonia is most commonly produced through a method known as the Haber-Bosch process which reacts nitrogen with hydrogen. The major sources of emissions in ammonia production are process emissions from making hydrogen using steam methane reforming (SMR), and generation of heat for the SMR and Haber-Bosch processes.

Hydrogen production through SMR separates hydrogen from methane, resulting in CO_2 process emissions. Process emissions account for approximately 65% of the emissions associated with ammonia production, and the combustion of fossil fuels for the generation of heat is responsible for approximately 33% (IRENA, 2022).

Figure IW.6 shows a prospective pathway to decarbonise ammonia production that involves the use of electrolytic hydrogen feedstock produced through electrolysis and electric heat generation (AIETI, 2021). An alternative production route with less abatement potential involves the use of CCUS (DCCEEW, 2022) with SMR hydrogen production and electric heat generation (AIETI, 2021).

To reduce emissions intensity of ammonia production, electrolytic hydrogen can be substituted into the existing processes up to 20% before any retrofitting or plant upgrades are required.

Figure IW.6: Prospective decarbonisation pathway for ammonia production

	2024	2035
Key pathway (lower emissions pathway)	· Energy efficiency · Substitution of grey hydrogen feedstock with green hydrogen	· 100% green hydrogen feedstock · Electric heat generation for Haber Bosch
Higher emissions pathway	· Energy efficiency · Increasing use of CCUS with SMR hydrogen production	· Electric steam generation for heat · CCUS with SMR for all hydrogen production

IW.2.7 Waste

There are approximately 1,200 landfills receiving waste in Australia (DCCEEW, 2024b, 2022). Waste management has become more concentrated over the last decade with the 21 largest landfills receiving approximately 50% of landfilled waste (DCCEEW, 2024b). The sector is dominated by several large companies, but there are also many smaller operators that specialise in specific markets (DCCEEW, 2022).

Methane is produced when organic waste is broken down by microorganisms in an anaerobic environment, such as in landfill. Methane from the decomposition of organic matter in landfill represents around three-quarters of the emissions from the waste sector. Other emissions from the waste sector include emissions from wastewater, which makes up about 20% of emissions, and biological and thermal waste treatment, which make up the remainder. Consequently, reducing methane emissions from landfill will have the largest impact on emissions in the waste sector.

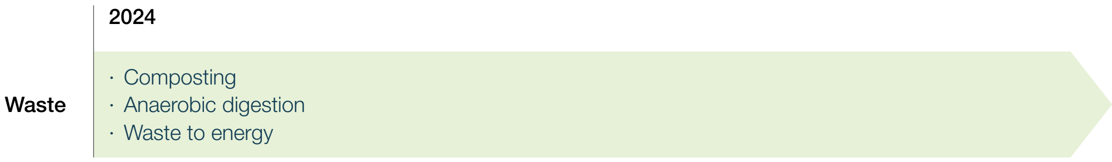
Diverting organic waste from landfill to low-emissions treatment options prevents the generation of methane and therefore remains the most effective pathway to decarbonise the sector. While landfill gas capture rates can reach 85-90% in a well-engineered, closed landfill, capture rates are much lower in open landfills. In Australia, landfill gas capture rates have plateaued in recent years even with current government incentives through the ACCU scheme (DCCEEW, 2024b). Landfill gas capture will remain an important part of the emissions reduction technology mix to reduce emissions of methane that cannot be abated by diversion in the short to medium term.

A mix of technologies for the processing of organic waste will be required, and these are likely to consist of composting, anaerobic digestion and combustion of waste to generate energy. These technologies are all available now.

From a circular economy perspective, composting and anaerobic digestion allow for the recovery of materials. Composting allows recovery of nutrients when the compost is applied to land. Anaerobic digestion is a process of microorganisms breaking down organic waste in the absence of oxygen to produce methane and organic byproducts. The methane can be captured and combusted to produce energy on-site or, where feasible, transported for use as energy in industrial processes. The byproducts of anaerobic digestion can be applied to land to recover their nutrients.

Processing organic waste through composting or anaerobic digestion can reduce emissions by over 90%, compared to landfill (NSW EPA, 2023). Further emissions reductions can be achieved through the use of composted products to displace other fertilisers and use of biomethane to produce low-emissions energy. Energy production from waste combustion could play a role where the waste cannot be used in one of these treatments, for example due to contamination.

Figure IW.7: Prospective decarbonisation pathway for organic waste



W.2.8 Other industry

Manufacturing and synthetic gases make up the bulk of the remaining emissions in the industry and waste sector. Emissions from the manufacturing sector are dominated by combustion of fossil fuels used to produce on-site electricity and process heat. Decarbonising process heat is temperature dependent. Electrification of low temperature heat is cost competitive with heat generated through combustion of fossil fuels (AIETI, 2021). A study on Australian industrial process heat indicated approximately 50% of the industrial heat requirement was 250 °C or below, and 40% was above 800 °C (ARENA, 2019). High temperature processes include the production of glass, bricks, sugar, and other chemicals.

Emissions from synthetic gases occur across a number of sectors including industry, the built environment, transport and electricity (DCCEEW, 2015). Synthetic gases include:

- hydrofluorocarbons (HFCs) used in refrigeration, air conditioning, aerosols, firefighting materials and medical inhalers
- sulfur hexafluoride (SF_6) used in electricity distribution
- nitrogen trifluoride (NF_3) used in the semiconductor industry, in chemical lasers and as high energy fuels
- perfluorocarbons (PFCs) produced as by-products from aluminium production.

HFCs comprise the largest portion of emissions from synthetic gases (96%), followed by PFCs (2%), and SF_6 (1%) (DCCEEW, 2024b).

As a party to the Kigali amendment, Australia began phasing down HFC imports in January 2018. The phase down of annual imports of bulk HFCs is due to reach an 85% reduction from baseline by 2036 (DCCEEW, 2021).

Box: IW.3 Hydrogen

Hydrogen, and its derivatives, can play a significant role in the net zero pathways of four sectors (see Table IW.3). For this to come to fruition, development of the hydrogen industry in Australia will need to be a high priority in the government's net zero plan. The government has already indicated this will be the case through its Future Made in Australia initiatives and the development of a new National Hydrogen Strategy.

Table IW.3: Uses for hydrogen and its derivatives across sectors

Sector	Uses for hydrogen and its derivatives	
Transport	Road	Hydrogen powered heavy trucks for long and heavy freight tasks
	Rail	Hydrogen powered rail in addition to electrification
	Shipping	Ammonia and methanol (derivatives of hydrogen) powered heavy shipping
	Aviation	Sustainable aviation fuel (which can be derived from either hydrogen, or biomass and waste) to decarbonise most of aviation
Electricity and energy	Hydrogen could be blended with, or replace, gas in peaking generators used to firm renewables	
Resources	Hydrogen could be used to decarbonise natural gas and LNG operations	
Industry	Hydrogen will be an important alternative to electrification of high to very high temperature process heat or to replace high emitting feedstocks	

Most hydrogen produced in Australia uses the steam methane reforming (SMR) process. Hydrogen is labelled blue when this CO_2 is captured and stored. Electrolytic hydrogen is produced using electrolysis powered by electricity.

The authority heard from industry stakeholders that many intend to use blue hydrogen to decarbonise their operations because it is currently lower cost and more readily available than electrolytic hydrogen. Several major natural gas and LNG producers told the authority they intend to use blue hydrogen as a key lever to decarbonise their operations, despite electric drives and boilers being commercially available. They cited a preference to run existing gas turbines on hydrogen rather than replacing them with electric drives and challenges in electrifying brownfield facilities as reasons for preferring hydrogen to electrification.

IW.3 Barriers, opportunities and enablers

IW.3.1 Technological constraints

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 cement production, and direct reduction of iron using hydrogen.

Depending on the technology and commercial readiness of each solution, targeted support is required to accelerate the demonstration, commercialisation and deployment of technologies, noting Australia will be a technology leader for some emissions reduction activities and a fast follower for others. Several submissions to the authority's issues paper noted the importance of technological advances and increasing the pace of deployment of key technologies:

> *'The challenges of availability and integration of abatement technology for some industrial activities is expected to be a relevant issue, at minimum, through the mid-2030s'*
>
> AIGN submission, 2024

> *'Investment in research and development, particularly pilots and demonstrations, could advance industry's ability to deploy technologies earlier and ensure Australia builds the capabilities, expertise and workforce it needs.'*
>
> Climateworks submission, 2024

IW.3.2 Green premium

> Significant investments are needed to replace and retrofit large industrial assets, power energy intensive processes, and replace high emitting feedstocks.

Continued technology advancement will contribute to lower costs. It is important investment decisions do not lock in emissions, result in stranded assets or add to the cost of decarbonisation.

Markets for low emissions products are still developing, lacking depth in demand and supply. Governments can boost demand through their own procurement activity and incentivise shifts in consumer preferences, and encourage supply through support for technology innovation, production and through regulatory measures. Efforts to reduce embodied emissions from buildings and infrastructure could drive demand for low emissions steel, cement and aluminium. Certification schemes will also support procurement for green metals and materials that use captured CO_2, while supporting international trade.

IW.3.3 Planning, approvals and coordination

> Low emissions industrial precincts could be a key enabler for decarbonisation of emissions intensive industries.

They can provide shared infrastructure, and help build economies of scale, including for:

- increased decarbonised energy generation, with transmission capacity of appropriate size to meet future energy demands from electrification
- hydrogen production and local distribution
- biofuel production, including biomethane generated from horticulture and other organic waste
- carbon management technologies, including CCUS and carbon dioxide removal (CDR)
- storage and reuse of heat.

The co-location of facilities can catalyse investment, foster innovation and increase export opportunities, collaboration, and job creation. Governments can play a coordinating role for planning and investment in shared infrastructure to enable the development of low emissions industrial precincts (CEDA, 2024).

> *'Shared infrastructure is recognised as a key enabler of private investment, and industrial hubs are being considered to support decarbonisation'.*
>
> AIGN submission, 2024

'Developing Renewable Energy Industrial Precincts to co-locate industrial activities with large-scale renewable electricity generation can minimise the need for new transmission and better streamline delivery of the large amounts of energy required for electrified mining and manufacturing'.

The Climate Council submission, 2024

IW.3.4 Supply chain constraints

> Coordination and planning are required to ensure availability of energy, and raw, recycled or recovered material, and access to infrastructure.

- **Decarbonised electricity** – Electrification of industrial processes and potential onsite production of hydrogen will lead to increased demand for decarbonised electricity. Information about expected and anticipated industrial loads and timing will be important to plan for electrification. For example, current alumina production consumes around 220 PJ of energy from gas and coal, which may require 3-5 GW of firmed electricity, depending on the technology (AAC, 2023).

'Government needs to ensure that throughout the transition all industry has firm, ongoing supply of high amounts of energy.'

Australian Steel Institute submission, 2024

'The biggest opportunity for industry is to expedite the scale and pace of Australia's electricity transition.'

Australian Aluminium Council submission, 2024

- **Electrolytic hydrogen** – Industrial facilities that require hydrogen as a feedstock or for high temperature heat will need a secure supply of hydrogen. Electrolytic hydrogen is currently not available at the scale or cost required for industrial use.
- **Alternative fuels** – Alternative fuels could be used for some industries, particularly for near-term emissions reductions while technologies for high temperature heat mature. There will be challenges in securing these fuels at the scale, cost, and consistency required. Biofuels could be used in industry, but there is competing demand for these fuels across the economy, and the supply is limited (MPP, 2024). Natural gas is likely to be used to reduce the emissions intensity of steel production and enable the investment in DRI-EAF assets until electrolytic hydrogen becomes available.
- **CO_2 transportation or storage infrastructure** – For facilities that could capture CO_2, there may be limited storage opportunities related to the facility location. This could include lack of pipelines for transporting CO_2, or no suitable storage sites in close proximity.
- **Iron ore type** – The lowest emissions route for iron and steel production, DRI-EAF, requires magnetite ores. However, approximately 96% of Australian iron ore exports are hematite, which is not currently suitable for this process (GA, 2023b). Research is being done to develop processes for these ores to be used in low emissions steel making (HILT CRC, 2024). Australia has magnetite deposits, which are suitable for DRI-EAF, but they require processing to reduce impurities before they can be used in steel making (GA, 2023b).
- **Scrap steel and aluminium** – The use of scrap metals for secondary production is dependent on its availability. Reducing the volume of scrap metals that are exported may facilitate higher domestic recycling. The total volume of local scrap metal is not sufficient to replace current domestic production volumes.
- **Supplementary cementitious materials (SCMs)** – The most common SCMs used to replace cement in concrete are fly ash and slag. These are produced from coal-fired power plants and steel production. Supply of these will reduce as these plants decarbonise.

Materials circularity in the industry sector can reduce the amount of new materials required for production processes and can reduce the emissions gap required, allowing more time to deploy more expensive technologies (Material Economics, 2018). In addition to reducing energy use and embedded emissions in products, a more circular industry sector would realise co-benefits such as reduced pollution and waste and reducing use of natural resources. Opportunities in the industry and waste sector include greater recycling of metals, cement, glass and organics. The transition to a more circular economy can be facilitated by investment in recycling infrastructure, building markets for recovered materials and increasing information on availability of supply of byproducts and waste materials.

IW.3.5 Information and data gaps

Decarbonisation roadmaps serve as a blueprint for adopting new technologies in emissions-intensive industries that require significant planning and investments, particularly for large scale assets. Given the small number of high emitting facilities within each subsector of industry, industry led roadmaps could facilitate collaboration and knowledge sharing between companies that would otherwise be competing, and enable facility owners to derisk investments by reducing uncertainty around timing and technology options to decarbonise.

Separate collection of organics from both households and commercial sources allows for greater diversion of organics from landfill and can reduce the risk of contamination in the organic waste stream. Although separate organics collection is being rolled out across most states, the authority heard from stakeholders that availability of food and garden organics collection remains uneven and contamination remains an issue. Education on the correct use of separate organics bins also remains important to reduce contamination.

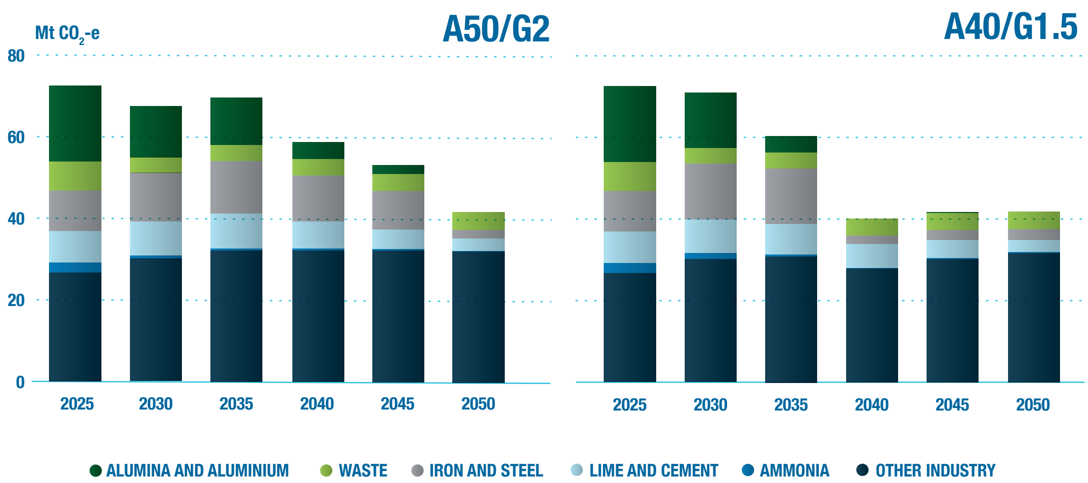
IW.4 Emissions pathways

Projected emissions from CSIRO's AusTIMES modelling (A50/G2 and A40/G1.5 scenarios) for the sector are shown in Figure IW.8.

In CSIRO's modelling of the industry sector the largest abatement came from the alumina and aluminium subsector, followed by iron and steel. Increased emissions from other industry could reflect increased production and less take up of abatement technologies applied for these emissions in the model.

In CSIRO's modelling final energy use for the sector shows no coal use, and almost 60% reduction in the use of natural gas from 2025 to 2050. Electricity demand approximately doubles in the A40/G1.5 scenario, and hydrogen demand grows from 0 PJ to over 250 PJ in both scenarios.

Figure IW.8: Modelled industry and waste sector emissions breakdown by subsector, under A50/G2 and A40/G1.5 AusTIMES modelling scenarios, 2025-2050



Source: CSIRO modelling in AusTIMES commissioned by the Climate Change Authority

A comparison between the authority's estimates of emissions in 2050 from the ground-up analysis and modelling are presented in Table IW.4. Based on the authority's internal analysis informed by Worley (CCA, 2024b), 44 Mt CO_2-e of emissions could be abated in the sector by 2050. In general, there is broad agreement between ground-up estimates and modelled results. The authority's ground-up estimates reflect potential emissions reduction pathways to net zero through implementation of priority technology levers. The analysis took into account estimated timing and emissions reduction potential for each decarbonisation lever.

Table IW.4: Projections of emissions reductions to 2050 using estimates from AusTIMES modelling and ground-up analysis

Reference: emissions in 2022 were 64 Mt CO_2-e	Projected emissions reductions to 2050 (Mt CO_2-e)*		
	AusTIMES modelling (A50/G2)	AusTIMES modelling (A40/G1.5)	Ground-up estimate**
Alumina and aluminium	19	19	15
Iron and steel	8	7	8
Lime and cement	5	5	5
Ammonia	2	2	5
Waste***	3	3	6
Other industry	-5	-5	5
Total	31	31	44

**Abatement was calculated as the difference between base year emissions and the projected 2050 emissions from each model. In AusTIMES the base year for the abatement calculation is 2025 and in ground-up estimates the base year for estimates was 2022. In both scenarios, the modelling results show higher emissions in 2025 compared to emissions reported in the 2022 inventory, partly due to differences in how the sector's emissions boundary was defined, as discussed in Appendix B.*

***Ground-up analysis assumes emissions from each subsector are due to material sources of emissions associated with production. For example, emissions from the iron and steel subsector are assumed to be from blast furnaces and basic oxygen furnaces used to produce primary steel. It does not reflect emissions from shaping steel or melting scrap steel. It also assumes production is constant.*

****Waste flows and stocks were not modelled. Modelled emissions reduction in the waste sector is primarily from change in energy use while the ground-up estimate only considers change in waste stock.*

The authority's ground-up analysis indicates there could be 20 Mt CO_2-e of remaining emissions in the industry and waste sector in 2050. In comparison, CSIRO's modelling results show 42 Mt CO_2-e remaining in 2050 under both A50/G2 and A40/G1.5 scenarios.

The amount of residual emissions in the sector is contingent on the abatement potential and the uptake rates of decarbonisation technologies. These uptake rates depend on technology and commercial readiness, cost and asset lifecycle.

Near-term emissions reduction opportunities exist for all subsectors. The authority has found that, in general, many owners of assets that are liable under the Safeguard Mechanism intend to pursue these near-term decarbonisation opportunities to meet their obligations. Asset owners are likely to pursue the most cost-effective direct emissions reduction opportunities, and more expensive options will be assessed against costs for purchasing offsets. Policy certainty for Safeguard obligations beyond 2030 could provide more guidance around expectations for industry in the 2030-40 decade.

If all available and expected key technologies are deployed by 2050, residual emissions in industry and waste are expected to be attributable to:

- cement production, due to incomplete capture of CO_2 from process emissions
- waste, due to the difficulty of achieving a 100% reduction in organic waste to landfill, and the complete capture of methane from landfills and wastewater.[4]

4 Emissions from the decomposition of waste can continue decades after it is deposited in landfill

IW.5 References

AAC (Australian Aluminium Council). (2023). *AAC Submission on Climate-related financial disclosure*. https://treasury.gov.au/sites/default/files/2023-04/c2022-314397-australian-aluminium-council.pdf

AAC. (2024a). *AAC Response to Electricity and Energy Sector Plan Discussion Paper*. https://aluminium.org.au/news/aac-response-to-electricity-and-energy-sector-plan-discussion-paper/

AAC. (2024b). *Australian Alumina*. https://aluminium.org.au/australian-industry/australian-alumina/

AAC. (2024c). *Australian Aluminium*. https://aluminium.org.au/australian-industry/australian-aluminium/

ABS (Australian Bureau of Statistics). (2024). *Table 32a. Merchandise exports, industry (ANZSIC 2006), FOB value*. https://www.abs.gov.au/statistics/economy/international-trade/international-trade-goods/latest-release

AIETI (Australian Industry Energy Transitions Initiative). (2021). *Australian Industry Energy Transitions Initiative – Phase 1 Technical Report*. https://www.climateworkscentre.org/resource/australian-industry-energy-transitions-initiative-phase-1-report/

Alcoa. (2024). *Alcoa announces curtailment of Kwinana Alumina Refinery in Western Australia*. https://news.alcoa.com/press-releases/press-release-details/2024/Alcoa-announces-curtailment-of-Kwinana-Alumina-Refinery-in-Western-Australia/default.aspx

ARENA (Australian Renewable Energy Agency). (2019). *Renewable Energy Options for Industrial Process Heat*. https://arena.gov.au/knowledge-bank/renewable-energy-options-for-industrial-process-heat/

ARENA. (2022). *A Roadmap for Decarbonising Australian Alumina Refining*. https://arena.gov.au/knowledge-bank/a-roadmap-for-decarbonising-australian-alumina-refining/

ARENA. (2023a). *Alcoa Renewable Powered Electric Calcination Pilot*. https://arena.gov.au/projects/alcoa-renewable-powered-electric-calcination-pilot/

ARENA. (2023b). *Mechanical Vapour Recompression for Low Carbon Alumina Refining*. https://arena.gov.au/projects/mechanical-vapour-recompression-for-low-carbon-alumina-refining/

ARENA. (2023c). *Yarwun Hydrogen Calcination Pilot Demonstration Program*. https://arena.gov.au/projects/yarwun-hydrogen-calcination-pilot-demonstration-program/

ASI (Australian Steel Institute). (2023). *Submission to the Future Gas Strategy consultation paper*. https://consult.industry.gov.au/future-gas-strategy/survey/view/59

Bach, L., Vaughan, N., Law, Cliff., Williamson, P. (2024). Implementation of marine CO_2 removal for climate mitigation: The challenges of additionality, predictability and governability. *Elementa: Science of the Anthropocene, 12* (1), 00034. https://doi.org/10.1525/elementa.2023.00034.

BlueScope. (2024). *Australia's leading iron ore producers partner with BlueScope on steel decarbonisation*. https://www.bluescope.com/news/australia-s-leading-iron-ore-producers-partner-with-bluescope-on

Casaban, D., Tsalaporta, E. (2023). Life cycle assessment of a direct air capture and storage plant in Ireland. *Scientific Reports, 13,* 18309. https://doi.org/10.1038/s41598-023-44709-z.

CCA. (2023a). *2023 Annual Progress Report*. https://www.climatechangeauthority.gov.au/annual-progress-advice-0

CCA. (2023b). *Reduce, remove and store: The role of carbon sequestration in accelerating Australia's decarbonisation.* https://www.climatechangeauthority.gov.au/publications/reduce-remove-and-store-role-carbon-sequestration-accelerating-australias-decarbonisation

CCA (Climate Change Authority). (2024a). *National Sectoral Pathways Emissions Mapping based on estimates published in Australia's National Greenhouse Accounts*. https://greenhouseaccounts.climatechange.gov.au/

CCA (Climate Change Authority). (2024b). *Internal analysis informed by Worley, literature review and stakeholder engagement*.

CEDA (Committee for Economic Development of Australia). (2024). *Clean energy precincts: How to seize the green export opportunity*. https://www.ceda.com.au/researchandpolicies/research/energy/clean-energy-precincts

CER (Clean Energy Regulator). (2024). *Safeguard facility reported emissions 2021-22*. https://cer.gov.au/markets/reports-and-data/safeguard-facility-reported-emissions-data/safeguard-facility-reported-4

CIF (Cement Industry Federation). (2023). *Decarbonisation Pathways for the Australian Lime Sector*. https://cement.org.au/wp-content/uploads/2023/06/Decarbonisastion_Pathways_Australian_Lime_Sector.pdf

Climate Council. (2023). *Australia's Clean Industry Future: Making Things Here In A Net Zero World*. https://www.climatecouncil.org.au/resources/australias-clean-industry-future-making-things-in-a-net-zero-world/

CSIRO (Commonwealth Scientific and Industrial Research Organisation). (2022). *Green Methanol Feasibility Study*. https://research.csiro.au/hyresource/green-methanol-feasibility-study/

DCCEEW (Department of Climate Change Energy the Environment and Water). (2015). *Australian and global HFC, PFC, Sulfur Hexafluoride, Nitrogen Trifluoride and Sulfuryl Fluoride Emissions - 2015*. https://www.dcceew.gov.au/environment/protection/ozone/publications/australian-hfc-pfc-sulfur-hexafluoride-nitrogen-trifluoride-sulfuryl-fluoride-emissions-2015

DCCEEW. (2021). *HFC phase-down – Frequently asked questions*. https://www.dcceew.gov.au/environment/protection/ozone/hfc-phase-down/hfc-phase-down-faqs

DCCEEW. (2022). *National Waste Report 2022*. https://www.dcceew.gov.au/environment/protection/waste/national-waste-reports/2022

DCCEEW. (2023). *Australian Energy Update 2023*. https://www.energy.gov.au/publications/australian-energy-update-2023

DCCEEW. (2024a). *Investing over $330m in lower emissions industry*. https://www.dcceew.gov.au/about/news/investing-over-330m-lower-emissions-industry

DCCEEW. (2024b). *Volume 1: National Inventory Report 2022*. https://www.dcceew.gov.au/climate-change/publications/national-inventory-report-2022

DCCEEW & DISR (Department of Industry Science and Resources). (2024). *National Sectoral Plan Emissions Mapping based on estimates published in Australia's National Greenhouse Accounts*. https://greenhouseaccounts.climatechange.gov.au/

ELYSIS. (n.d.). *What is Elysis?* Retrieved 6 May 2024, from https://www.elysis.com/en/what-is-elysis

GA (Geoscience Australia). (2023a). *Geological Storage Studies*. https://www.ga.gov.au/scientific-topics/energy/resources/carbon-capture-and-storage-ccs/geological-storage-studies

GA (Geoscience Australia). (2023b). *Iron Ore*. https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/iron-ore

HILT CRC (Heavy Industry Low-carbon Transition Cooperative Research Centre). (2024). *Research Programs*. https://hiltcrc.com.au/research-programs/

IEA (International Energy Agency). (2019). *Innovation Gaps*. https://www.iea.org/reports/innovation-gaps

IEA. (2023). *ETP Clean Energy Technology Guide*. https://www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide

IRENA (International Renewable Energy Agency). (2022). *Innovation Outlook: Renewable Ammonia*. https://www.irena.org/publications/2022/May/Innovation-Outlook-Renewable-Ammonia

Material Economics. (2018). *The Circular Economy – a Powerful Force for Climate Mitigation*. https://asbp.org.uk/resource-report/the-circular-economy-a-powerful-force-for-climate-mitigation

McKinsey. (2020). *Plugging in: What electrification can do for industry*. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/plugging-in-what-electrification-can-do-for-industry

MISA (Manufacturing Industry Skills Alliance). (2023). *Initial Workforce Plan*. https://manufacturingalliance.org.au/wp-content/uploads/2024/05/Initial_Workforce_Plan_2023_excerpt_OL.pdf

MPP (Mission Possible Partnership). (2022). *Making Net-Zero Ammonia Possible*. https://missionpossiblepartnership.org/ammonia-sts-press-release/

MPP. (2023). *Making Net-Zero Concrete and Cement Possible*. https://missionpossiblepartnership.org/action-sectors/concrete-cement/

MPP. (2024). *MPP Global Project Tracker – Insights*. https://missionpossiblepartnership.org/tracker/

NSW EPA (New South Wales Environment Protection Authority). (2023). *Organics processing technology assessment*. https://www.epa.nsw.gov.au/your-environment/recycling-and-reuse/business-government-recycling/food-organics-and-garden-organics/emissions-impacts-of-food-waste-recovery-technologies

RACE for 2030. (2021). *Electrification & renewables to displace fossil fuel process heating*. https://racefor2030.com.au/project/electrification-and-renewables-to-displace-fossil-fuel-process-heating/

Rio Tinto. (n.d.). *Non-managed operations*. Retrieved 5 July 2024, from https://www.riotinto.com/en/operations/non-managed-operations

Rio Tinto. (2023). *Carbon-free aluminium smelting is a step closer*. https://www.riotinto.com/en/can/news/stories/aluminium-emissions-free

Rio Tinto. (2024). *Rio Tinto signs Australia's biggest renewable power deal as it works to repower its Gladstone operations*. https://www.riotinto.com/en/news/releases/2024/rio-tinto-signs-australias-biggest-renewable-power-deal-as-it-works-to-repower-its-gladstone-operations

Shahabuddin, M., Brooks, G., & Rhamdhani, M. A. (2023). Decarbonisation and hydrogen integration of steel industries: Recent development, challenges and technoeconomic analysis. *Journal of Cleaner Production*, *395*, 136391. https://doi.org/10.1016/j.jclepro.2023.136391

Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., & Vaughan, N. E. (2024). *The State of Carbon Dioxide Removal - 2nd Edition.* The State of Carbon Dioxide Removal. https://osf.io/f85qj/

Srinivasan, V., Temminghoff, M., Charnock, S., Moisi, A., Palfreyman, D., Patel, J., Hornung, C., & Hortle, A. (2021). *CO_2 Utilisation Roadmap.* https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/energy-and-resources/co2-utilisation-roadmap

US DoE (United States Department of Energy). (n.d.-a). *Process Heat Basics*. Retrieved 7 May 2024, from https://www.energy.gov/eere/iedo/process-heat-basics

US DoE (United States Department of Energy). (n.d.-b). *Solar-Thermal Power and Industrial Processes Basics*. Retrieved 2 July 2024, from https://www.energy.gov/eere/solar/solar-thermal-power-and-industrial-processes-basics

VDZ. (2021). *Decarbonisation Pathways for the Australian Cement and Concrete Sector*. http://cement.org.au/australias-cement-industry/industry-report/

WBCSD (World Business Council for Sustainable Development). (2021). *Hot Spots for Renewable Heat (Decarbonizing Low- to Medium-Temperature Industrial Heat Across the G-20)*. https://www.wbcsd.org/Programs/Climate-and-Energy/Energy/New-Energy-Solutions/Resources/Hot-Spots-for-Renewable-Heat

Wood Mackenzie. (2024). *What's next for green steel technologies?* https://www.woodmac.com/news/opinion/whats-next-for-green-steel-technologies/

Agriculture and land

AGRICULTURE AND LAND

Sector summary

The agriculture and land sector is well placed to continue to grow and underpin Australia's food security, deliver significant economic value and support healthy ecosystems, while at the same time making a vital contribution to Australia's transition to net zero emissions by providing a significant source of carbon removals.

Agricultural emissions are expected to remain stable around current levels to 2035 and then reduce modestly to 2050. This trend would result from a scale up of existing practices and technologies and new low emissions technologies becoming commercially viable in the sector from the 2030's through the 2040's. Some of these technologies include:

- feed supplements
- slow-release or nitrification inhibiting coated fertilisers
- improved herd and pasture management
- manure management, and
- vehicles and machinery powered by renewable fuel sources or electricity.

Combined emissions of Australia's agriculture and land sector produced a net sink of 3 Mt CO_2-e in 2022, with agriculture contributing 85 Mt CO_2-e in emissions and land contributing an 88 Mt CO_2-e sink.

Emissions from enteric fermentation from livestock are the main source of sector emissions, and are expected to remain high until around 2035. In the absence of a technology breakthrough on livestock emissions, or a major shift in production due to changing dietary preferences, the sector will likely need to rely on continued improvements in farming practices (herd and pasture management), as well as sequestration through land-based carbon removals, to balance livestock emissions and thereby contribute to whole of economy net zero emissions by 2050.

Increased land-based removals, including through reforestation, will be needed if emissions do not reduce significantly in energy-intensive sectors elsewhere in the economy. There is an opportunity to increase these removals by:

- establishing new forests for timber, carbon sequestration, agroforestry and environmental plantings, and
- protecting existing forests and other native vegetation from deforestation and degradation.

The sector will need to reconcile multiple pressures on land resources to maintain food security, protect and conserve biodiversity, store carbon, support infrastructure and increasingly produce biofuel feedstock. Land-based removals are exposed to the risks of climate change and these risks are expected to increase in the future.

AL.1 Sector state of play

The agriculture and land sector produces most of the food and fibre consumed and used in Australia. The sector underpins Australia's food security, contributes to the economy and is critical to the management of natural resources.

The total value of agricultural, fisheries and forestry production grew by 46 per cent from 2003-04 to 2022-23, reaching $100 billion in real terms (ABARES, 2024b) across the three industries. The agriculture industry is highly export-oriented, with 72 per cent of the total value of agricultural production, and 78 per cent of beef and veal production, being exported (ABARES, 2024b). Grains, meats and industrial crops (i.e. crops not for direct consumption or requiring further processing like oilseeds and fibres) made up 28 per cent, 20 per cent and 12 per cent of Australia's total agricultural exports respectively (ABARES, 2024a). The sector produces 90 per cent of food and beverages consumed domestically (ABARES, 2020).

The Australian agriculture industry is aiming to grow its economic value, with a target of reaching $100 billion by 2030 (NFF, 2019). Favourable growing conditions saw agricultural production reach $71 billion in value in 2021-22 (ABS, 2022). The sector accounted for 2 per cent of Australia's value-added GDP in 2022-23 (see Appendix B).

In 2022-23, the agriculture and land sector employed 299,000 workers (see Appendix B) with 81 per cent of workers living in regional or rural areas (ABARES, 2023). Across the workforce, 31 per cent of workers identified as female (Appendix B), 1.8 per cent as Indigenous and 13 per cent as culturally and linguistically diverse (ABARES, 2023). It is an aging workforce with a median age of 50 years (compared to 40 years for the general Australian workforce), with only 25 per cent of the workforce being under 35 years old (ABARES, 2023). Existing challenges for the workforce include labour shortages across most occupations, for both unskilled and skilled work (requiring post-school qualifications) (Skills Insight, 2023). Agriculture's peak food industries bodies calculated a labour shortage of at least 172,000 workers across the agriculture and food supply chain during 2022 and 2023 (NFF, 2023a). According to these peak bodies, labour shortages are increasing the costs of production, leading to higher prices for consumers (NFF, 2023a).

The agriculture and land sector contributes both significant sources and sinks of greenhouse gas emissions. The biggest sources of the sector's emissions are associated with livestock production through enteric fermentation and manure, and deforestation to maintain pastures (Table AL.1). Agricultural soils are the second largest source of emissions in the agriculture sector. Emissions from agricultural soils include those from fertiliser, crop residues, animal wastes deposited by grazing animals on pasture and mineralisation due to loss of soil carbon. Other sources of emissions stem from fuel use in agricultural vehicles and machinery. The storage of carbon in woody biomass and vegetation, and in soils, represents a substantial carbon sink in the sector.

Climate change impacts on the agriculture and land sector are already being experienced and are projected to increase, presenting a growing challenge for the sector. Changes in climate have impacted the productivity and profitability of Australian cropping farms, particularly in south-western Australia and south-eastern Australia from higher temperatures and lower winter rainfall (Hughes et al., 2017, 2019, 2022). Increased heat stress can reduce the milk yield, milking frequency and rumination time in dairy cows (Talukder et al., 2023), and in livestock heat stress can reduce feed intake, growth, weight gain, and reproduction (Lees et al., 2019). Droughts result in increased costs, decreased production and lower income for livestock producers (MLA, 2024a). ABARES' modelling shows that hotter and drier conditions in northern Australia are projected to impact livestock profitability through reduced herd numbers and increased fodder expenses (Hughes et al., 2022). As climate impacts are projected to increase over time, farmers will require significant adaptation responses to maintain productivity and profitability (Hughes & Gooday, 2021).

Table AL.1: Emissions and sinks in the agriculture and land sector (2022)

	Mt CO_2-e	Subsector share (%)
Agriculture		
Enteric fermentation[a]	55	64%
Agricultural soils (including fertiliser and urea application)	13	16%
Manure management	7	8%
Fuel use and other	10	11%
Net total – Agriculture	85	
Land		
Deforestation[b]	8	8%
Existing forests	-15	-14%
Reforestation	-50	-48%
Croplands	-12	-11%
Grasslands	-17	-16%
Other land use, land-use change and forestry (LULUCF)	-3	-3%
Net total – Land	-88	
Net total – Agriculture and land	-3	

[a] Subsectoral agriculture emissions proportions are expressed as a percentage of total agriculture emissions for 2021-22.
[b] Subsectoral land emissions proportions are expressed as a percentage of land sector carbon stocks (sources and sinks) for 2021-22. A negative emissions value indicates a carbon sink. A negative subsector share indicates the proportion of the associated emissions value relative to the total land sector carbon stocks.

Net emissions from the agriculture and land sector have steadily decreased since 2005. This has been driven by declines in sheep and dairy cattle numbers and reductions in deforestation (ABARES, 2024a; DCCEEW, 2023). More recently, net emissions decreases have been influenced by recent La Niña conditions that caused vegetation to rapidly grow and recover from drought impacts in preceding years (DCCEEW, 2023).

AL.2 Existing and prospective technologies

Safeguarding Australia's food and fibre production is critical for food security and economic growth. Technologies that reduce agricultural emissions and simultaneously achieve productivity benefits are a priority for the sector. Food production and land management is interlinked with many other societal and environmental issues, beyond productivity. This includes competing demands on land and the potential for flow-on impacts for people, communities and ecosystems (see AL.3 Barriers, opportunities and enablers). As such, careful planning by communities, businesses and government is essential to realise the full potential of benefits and avoid unintended consequences within the Australian agriculture and land sector.

Within existing production systems, there are limited existing technology solutions to reduce agricultural emissions in large volumes. The land component of the sector is currently a net sink with significant potential for additional land-based carbon removal (CSIRO, 2022a). Emissions reductions and long-term decarbonising of the agriculture and land sector will require a suite of technologies.

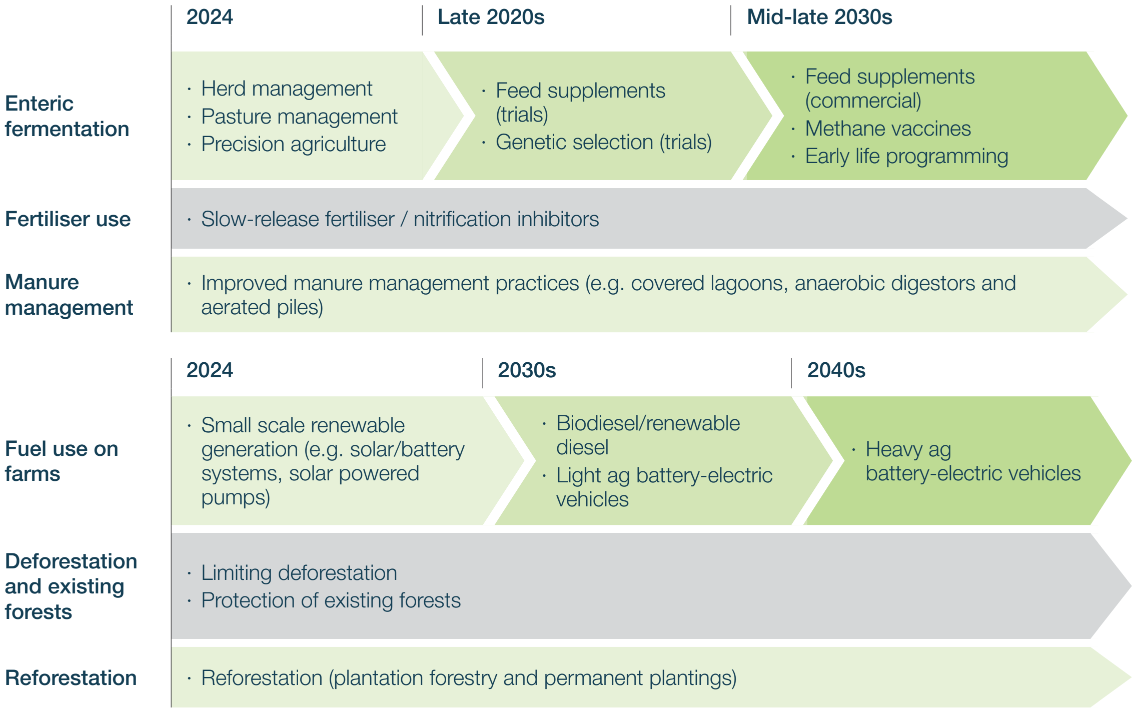
Key technologies are identified in Table AL.2 below and a possible technology deployment pathway is shown in Figure AL.1. These are presented in order of abatement potential for agriculture and land, respectively and are discussed further below.

Table AL.2: Key technologies and practices

Emissions subsector	Percent of sector emissions	Technology	Readiness	Barriers to adoption
Enteric fermentation	64% of agriculture emissions	Feed supplements	· Commercially available but further R&D required. Scale up of production of *Asparagopsis* would be required to allow for widespread adoption. · 3-NOP is commercially available and research suggests no negative effects on animal productivity (Alemu et al., 2021; De Almeida et al., 2022).	· Cost · Tech maturity · Uncertainty of productivity benefits · Scale of production · Current lack of effective delivery mechanism for pasture-based cattle and sheep
Fertiliser	7% of agriculture emissions	Slow-release and nitrification inhibitor coated fertilisers	· Commercially available	· Cost
Manure management	8% of agriculture emissions	Improved manure management practices	· Commercially available	· Cost · Awareness and capacity
Fuel use on farms	7% of agriculture emissions	Replacement of fossil fuels with renewable fuel sources or renewable electricity	· Various (commercial to developing)	· Cost · Availability · Lack of awareness of benefits · Slow equipment turnover
Deforestation[a]	2% of national emissions	Limiting deforestation / Protection of existing forests	· Well-established	· Competing land uses · Limited financial incentives
Existing forests	-3% of national emissions			
Reforestation	-10% of national emissions	Reforestation: Plantation forestry and permanent plantings	· Well-established	· Cost · Competing land uses · Land and water requirements · Supply chain limitations · Social impact · Regulatory burden

[a] Subsectoral land sector emissions proportions are a percentage of Australia's total emissions for 2021-22 (excluding LULUCF).

Figure AL.1: Prospective decarbonisation pathways for agriculture and land sector activities



AL.2.1 Feed supplements

Feed supplements can reduce emissions from enteric fermentation and show strong potential for abatement in the medium to long term. However, more research is required to firm up technical efficacy, and further efforts are needed to resolve commercialisation and implementation barriers. With the need to address supply, cost and delivery mechanisms to livestock, the authority's research indicates the technology is currently not likely to achieve extensive commercial use until the mid-to late 2030's.

The effectiveness of feed supplements can be variable, depending on dosage rates and delivery approaches. A recent study from Meat and Livestock Australia found that the inclusion of Asparagopsis-oil in cattle diets did not result in declines in methane emissions intensity when considered with declines in liveweight that counter-balanced emissions reductions (Cowley et al., 2023). Other studies have shown more promising results, with methane reduction potentials ranging from 59 to 98 per cent (Ridoutt et al., 2022). 3-NOP feed supplements have been shown to reduce emissions by 8 to 30 per cent (Black et al., 2021).

Feed supplements can reduce emissions from enteric fermentation and show strong potential for abatement in the medium to long term. However, more research is required to firm up technical efficacy, and further efforts are needed to resolve commercialisation and implementation barriers.

The effective mitigation potential of feed supplements is currently limited. Most supplements are required to be delivered with feed on a regular basis, applicable in feedlot and dairy cattle production (Ridoutt et al., 2022). As a point of comparison, Australian cattle only spend a relatively short portion of their lifespan in feedlots compared to intensive cattle production systems in the US (Drouillard, 2018).

Cattle raised in pasture-based grazing systems for beef contribute approximately 60 per cent of the total emissions from enteric fermentation. The majority of grazing cattle production is located in large open rangelands in northern Australia (McGowan et al., 2020). Feed supplements can be delivered to feedlot and dairy cattle on a regular basis, however this is not currently possible in rangeland pasture systems where individual animals may not be seen for multiple years. There are currently no commercially viable solutions in the near to medium term to reduce emissions from grazing cattle herds. This is a key barrier to widespread uptake of this technology in Australian beef production (Ridoutt et al., 2022).

The estimated marginal abatement cost for delivery of feed supplements to beef cattle in feedlots, sheep on pasture and pasture fed cattle is estimated to be \$57/t CO_2-e, \$121/t CO_2-e and \$188/t CO_2-e respectively (EY, 2021). While feedlot and dairy production can feasibly adopt feed additives to reduce emissions, there remains significant uncertainty on the efficacy and cost. The authority has heard from stakeholders that the current cost of feed supplements can be up to \$2 per animal per day. At lower costs, uptake of supplements, and therefore reduction in emissions, is likely to occur sooner. New ACCU scheme methodologies could be used to encourage adoption of feed supplements.

Changes in domestic consumption towards lower emissions protein sources, including chicken and pork, may have limited impact on total beef production in Australia in the near term, with approximately 78 per cent of beef meat produced being exported (ABARES, 2024b). However, access to and the requirements of international markets and supply chains will continue to strongly influence production systems in Australia. Tools such as the EU's Carbon Border Adjustment Mechanism (CBAM) could introduce requirements for lower emissions products and may influence the requirements of other trading markets in the future. However, agricultural commodities are not currently included in the products required to buy carbon certificates under the CBAM. The shifts in food consumption and alternative, lower emissions protein sources are discussed further below.

AL.2.2 Slow-release or nitrification inhibitor coated fertilisers

Use of nitrification inhibitors can more than halve the nitrous oxide emissions produced by fertiliser applied to land (Grace et al., 2023; Meng et al., 2021). Fertilisers coated in nitrification inhibitors are commercially available but are more expensive than conventional fertilisers (Fertilizer Australia, 2023). This is likely limiting widespread adoption. The near-term marginal abatement cost of these stabilised fertilisers is estimated to be \$37/t CO_2-e (Energetics, 2019). Fertiliser coatings based on biopolymers are available that also limit risks associated with microplastics in agricultural soils and waterways (Islam et al., 2023; Witt et al., 2024).

Continued efforts to improve fertiliser use efficiency, such as through precision agriculture, could help to achieve further emission reductions, positive environmental outcomes and cost savings for farmers.

AL.2.3 Manure management practices

There are commercially available options for managing emissions from livestock manure such as anaerobic digesters, covered lagoons, aerated stockpiles and composting. These treatments directly reduce methane emissions and can enable the production of by-products that can substitute for energy from fossil fuels and chemical fertilisers.

Manure management technologies that contain and capture methane and use it as a fuel are reported to be cost negative when factoring in revenue from energy and other products (Energetics, 2019). Near-term marginal abatement costs for manure management are estimated to provide a net economic gain ranging from \$12/t CO_2-e for composting to \$250/t CO_2-e for large-scale production of biogas (Energetics, 2019; EY, 2021). Uptake of these technologies is limited by capital costs, space, the availability of concentrated, collectable manure and the relatively small size of Australia's biogas industry (Energetics, 2019). Recycling manure and other on-farm residues has the added benefit of reducing on-farm loss and waste, a key feature of a lower emission circular economy production system (Energetics, 2019).

AL.2.4 Replacement of fossil fuels in agricultural vehicles and machinery

Fossil fuel emissions from the use of diesel in agricultural vehicles and machinery comprise 7 per cent of agricultural emissions. Renewable fuels like biofuels and renewable diesel are commercially available and can replace diesel in existing vehicles but can cost 1.5 to 3 times more than petroleum fuels (Acclimate Partners, 2022). Renewable fuels will likely be the only significant option for near term decarbonisation of agricultural vehicles and machinery (Acclimate Partners, 2022; Gjerek et al., 2021). Uptake of these fuels in Australia is limited as domestic production and availability is modest and costs are high (Acclimate Partners, 2022; Gjerek et al., 2021).

The near-term marginal abatement cost for electric tractors and heavy vehicles is estimated to be \$113 and \$222/t CO_2-e, respectively (EY, 2021). It is possible that the uptake of electrified agricultural machinery may increase following the transport and mining sectors' overall trends toward the development and deployment of electrified heavy vehicles around the mid-2030s. The marginal cost of hydrogen farm vehicles in 2030 is estimated to be above \$370/t CO_2-e (Energetics, 2019).

The use of solar PV systems on farms is reported to have a near-term marginal abatement cost of -\$42/t CO_2-e (EY, 2021). There are also other existing opportunities to reduce fuel use on farms, such as through replacement of diesel water pumps with solar powered pumps. Solar powered pumps produce no emissions and have low operational and maintenance costs (Aliyu et al., 2018), with an estimated marginal abatement cost of -\$27/t CO_2-e (Energetics, 2019).

AL.2.5 Additional agriculture technologies

Beyond the key technologies listed above, there are other opportunities to reduce emissions from agriculture and store carbon in the land.

Technologies that address ruminant methane emissions are unlikely to be ready for extensive commercial use in the near term, but commercial readiness in dairy and feedlot applications is progressing. To achieve near term emissions reductions, agricultural producers may need to focus primarily on pursuing the broadest and most efficient uptake of current technologies and practices to increase productivity for given inputs (e.g. fuel and fertiliser) and therefore reduce the emissions intensity of production.

Herd management practices could yield significant emission reductions within current farming approaches and result in productivity gains. These practices include improved health management, optimised joining strategies, removal of unproductive livestock, and improved genetics among other strategies (Almeida et al., 2021; Harrison et al., 2016).

Current practices in pasture management, such as selecting specific legume or grass species for pastures, can reduce livestock emissions by improving feed quality and the presence of anti-methanogenic compounds such as fats, oils and condensed tannins (Badgery et al., 2023). However, selecting pasture species with greater emissions reduction properties may also affect productivity (Badgery et al., 2023). The authority heard from stakeholders that improving pasture species is an effective near-term opportunity to reduce emissions and is likely to be lower cost and significantly easier to deliver to livestock than currently available feed additive strategies. Vaccines targeting ruminant methanogens or methane oxidising microorganisms could become viable technologies in the future (Finn et al., 2012; Jeyanathan et al., 2014; Soder & Brito, 2023).

Precision agriculture techniques that harness new developments in agricultural equipment, spatial mapping and measurement (e.g. nutrients, soil carbon, water or salinity) technologies can optimise productivity and sustainability (Shafi et al., 2019). The purpose of precision agriculture is to provide farmers with a better means to observe, understand and manage variability in their production systems. This can be done by tailoring inputs to optimise efficiency and yield and applying enhanced land management techniques, such as limiting soil compaction through controlled traffic farming for cropping production (GRDC, 2013). Further uptake of precision agriculture techniques can be realised across areas such as viticulture, broadacre cropping, dairy and sugar cane farming (CSIRO, 2021).

Increased uptake of intensive horticultural practices and technology can also improve the efficiency of production and use of inputs such as water and fertiliser (Zhou et al., 2021). These technologies can include controlled environment greenhouses, sunlight spectrum modification and artificial lighting, arid land glasshouses and vertical farming systems (Goddek et al., 2023; Goodman & Minner, 2019; QFF, 2015). Intensive agricultural production systems have the potential to reduce land use demand and consequently rates of land clearing and associated carbon emissions (Tollefson, 2010).

Farmers and other land managers are already undertaking activities to increase carbon drawdown and storage on their land. This includes through reforestation and retaining existing vegetation, which is discussed further below. There are also other agricultural practices already used by farmers that can be scaled up to increase the storage of carbon in soils and vegetation. These include low- or no-till cropping, stubble retention, adaptive multi-paddock grazing or the application of compost and manure (Biala et al., 2021; Jayaraman & Dalal, 2022; McDonald et al., 2023; Page et al., 2020). Application of biochar to soils also has the potential to improve soil carbon storage (Woolf et al., 2010).

Increasing soil carbon can also have important productivity, soil structure and water retention benefits (Soussana et al. 2019). However, soil carbon is highly influenced by soil type, season, weather and climate (Luo et al., 2019). Some studies have also found variable or negligible long-term impacts of some agricultural practices on soil carbon stocks (Luo et al. 2010; McDonald et al. 2023). Therefore, while increasing soil carbon is an opportunity to achieve carbon and non-carbon benefits, the scale and permanence of its potential impact as a climate solution is less certain than many other land-based carbon removal opportunities.

The use of fencing around farm dams can also reduce emissions and improve water quality by reducing the production of methane from organic decomposition from manure contamination (Malerba et al., 2022).

AL.2.6 Limiting deforestation and increasing reforestation

A critical aspect of decarbonising the agriculture and land sector is scaling up nature-based solutions that store biological carbon, particularly through limiting deforestation and increasing reforestation. Beyond forests, native vegetation more broadly provides land-based carbon removal as well as valuable habitat for biodiversity. While the data and analysis presented for the sector has a primary focus on forests, the authority considers that protecting native vegetation that falls outside the government's formal definition of forests is also a critical opportunity.

A critical aspect of decarbonising the agriculture and land sector is scaling up nature-based solutions that store biological carbon, particularly through limiting deforestation and increasing reforestation. Beyond forests, native vegetation more broadly provides land-based carbon removal as well as valuable habitat for biodiversity.

Limiting deforestation is a readily available opportunity to avoid emissions in the landscape. Australia's forests currently play a critical role in storing carbon, protecting biodiversity and providing a range of other ecosystem services (ABARES, 2018a). Limiting clearing of forests involves avoiding conversion of forests and other native vegetation into other uses. This can include forestry and land management practices that prevent degradation of carbon stocks and biodiversity in existing forests or land cleared of native vegetation. Analysis by CSIRO found that human induced regeneration of forests costs around $5/t CO_2-e and the cost of avoided deforestation is between $5 and $10/t CO_2-e (CSIRO, 2022a). More broadly, avoiding clearing of native vegetation, both within and outside forested landscapes, is an opportunity to increase land-based carbon removal.

Box AL.1: What are nature-based solutions?

Nature-based solutions are 'actions to protect, sustainably manage and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human wellbeing and biodiversity benefits' (IUCN, 2020). These solutions target challenges such as climate change, biodiversity loss, and water and food security, and are an opportunity to remove carbon from the atmosphere and store it in the landscape using natural sinks.

Submissions to the authority's Issues Paper supported a focus on nature-based solutions to achieve carbon removal as well as broader outcomes, such as biodiversity conservation, improved water quality and climate resilience (The Nature Conservancy, Better Futures Australia, Queensland Conservation Council submissions, 2024).

Increasing reforestation[1] is central to increasing Australia's land-based carbon removal. This can involve activities that establish large areas of new tree plantings, such as plantation forestry, agroforestry or farm forestry, and permanent plantings like carbon forestry and environmental plantings. CSIRO assessed the cost of plantation forestry is currently around $10 to $30/t CO_2-e and the cost of permanent plantings are currently around $20 to $30/t CO_2-e (CSIRO, 2022a). These costs are likely to be higher in the future as Australia is expected to require more abatement to achieve its net zero target. Reforestation can also include smaller scale revegetation projects, such as planting shelterbelts or restoring vegetation in marginal areas of agricultural land. Another practice involves allowing natural regeneration of ecosystems, though this has lower abatement potential in the near term than active planting (UNEP & IUCN, 2021). The vast majority of reforestation in Australia involves the conversion of grasslands to forest land (DCCEEW, 2024b). Other conversions such as croplands converted to forest land is a rare occurrence. It is likely that this is because the intensive management of croplands and improved pastures makes them valuable for agricultural production. This trend will likely continue and discussion of reforestation over the period to 2050 in this chapter should be read as the conversion of less intensively managed grasslands to forest.

How Australia meets demand for food, fibres and wood products while achieving climate and nature goals is an important consideration in informing land use choices. Balancing outcomes like carbon and biodiversity could involve balancing approaches that prioritise carbon through monoculture plantings and instead establishing mixed species plantings (Paul et al., 2016). It is also important to consider the water impacts of land use decisions, given current and growing pressures on water resources.

1 The Intergovernmental Panel on Climate Change describes reforestation as human-induced plantings on land that was previously forested, whereas afforestation involves planting on land that has not been previously forested for at least 50 years (Penman, 2003).

Competition for land and water resources and the potential to achieve multiple outcomes is discussed further in section AL.3 Barriers, opportunities and enablers.

Carbon stored in vegetation and soils via land-based removal is at risk of being released due to seasonal or climatic conditions, such as rainfall. This risk is exacerbated by the impacts of climate change, with the potential for more frequent and extreme bushfires, droughts and extreme weather events likely to impact the agriculture and land sector's rate of carbon removal and storage (Luo et al., 2019; Roxburgh, 2020; Viscarra Rossel et al., 2024).

AL.2.7 Expanding First Nations land management activities

First Nations people have been sustainably managing Australia's land, water and food resources through caring for Country for millennia (Janke et al., 2021). First Nations rights and interests in land are formally recognised over around 50 per cent of Australia's land mass – collectively referred to as the First Nations Estate (ABARES, 2022b). The activities of First Nations people in caring for Country currently takes many forms, including pastoral management, weed and feral animal control, cultural burning practices, threatened species management and revegetation (CSIRO, n.d.). These practices and activities positively contribute by reducing emissions and increasing land-based removal across First Nations lands. Opportunities to increase First Nations participation in the sector's workforce are discussed further in section AL.3 Barriers, opportunities and enablers. Much of Australia's renewable energy infrastructure will be located on lands where First Nations people have a legal right or interest (AEMO, 2024), presenting an opportunity for partnerships with First Nations communities (see section EE.3.4 on the electricity and energy sector pathway to net zero).

Demand for carbon dioxide removal is forecast to accelerate rapidly as Australia transitions to net zero (RepuTex Energy, 2023). Analysis in this report projects some sectors will have residual emissions by 2050 and may require offsets from sources of removal, including land-based removal, to achieve net zero emissions across the economy (see section NP.1). As identified in the authority's 2023 review of the ACCU scheme (CCA, 2023b), this represents a significant opportunity for First Nations individuals, businesses and communities to participate in and benefit from growing carbon markets.

The First Nations carbon farming industry has developed rapidly since 2006, to more than 39 First Nations-owned ACCU scheme projects generating 1.2 million tonnes of carbon equivalent abatement and $59 million in value each year (ICIN, 2024).

Savanna fire management currently represents the most significant share of First Nations-led ACCU scheme projects (ICIN, 2024). It is also a critical activity for reducing bushfire emissions, maintaining biodiversity, and storing carbon across Northern Australia (Gebbie et al., 2021). There are also a small number of First Nations-owned vegetation regeneration projects registered with the CER (ICIN, 2024).

The Indigenous Carbon Industry Network has highlighted opportunities to expand the scope of ACCU methods and projects available to First Nations peoples to practice on their lands (ICIN, 2022). There are opportunities to support greater access to caring for Country activities by First Nations people, which in turn can have positive social, cultural, economic and environmental outcomes.

AL.2.8 Other technologies and practices

AL.2.8.1 Blue carbon

Blue Carbon is the carbon captured by the world's ocean and coastal ecosystems. Coastal ecosystems generally store more carbon per hectare on average and remove carbon at a faster rate than terrestrial ecosystems (CSIRO, 2022a; UNEP & IUCN, 2021). Australia has relatively large volumes of blue carbon stocks and there are significant opportunities to restore blue carbon ecosystems that have been lost or degraded (Macreadie et al., 2021; Serrano et al., 2019). Actions such as the protection and restoration of mangrove, seagrass, saltmarsh and tidal ecosystems are an opportunity to increase blue carbon storage (McKinsey, 2022) while delivering a range of ecosystem services, such as enhancement of fisheries, water purification and coastal protection (Schindler Murray, 2023). First Nations peoples have legal or consent rights for over two thirds of Australia's coasts, presenting an opportunity for expanding First Nations leadership on blue carbon projects (ICIN, 2024).

AL.2.8.2 Shifts in food consumption patterns

Dietary preferences and consumption patterns in Australia and overseas are influenced by a range of factors, including economic conditions, culture, personal preference and health concerns (Australian Institute of Health and Welfare, 2012). The emissions impact of diets depends on a range of variables, including the type of protein consumed as well as food production and transport methods (Candy et al., 2019).

Shifts in consumption patterns that include lower emissions protein sources could represent another pathway to reducing emissions from meat production. Alternative proteins are plant-based and food-technology alternatives to animal protein.

They include food products made from plants (for example, grains, legumes and nuts), fungus (mushrooms), algae, insects, cell-cultured meat or protein from precision fermentation using yeast and other micro-organisms. Alternative proteins can be supplementary to red meat, particularly to ensure food security as global demand for protein grows (CSIRO, 2022b).

Cell-cultured protein is an emerging opportunity and currently expensive to produce in comparison to meat from livestock (Garrison et al., 2022; Specht, 2020). Costs are likely to reduce as production reaches industrial scale (Specht, 2020). Producing cultured protein may have environmental and biodiversity benefits (Treich, 2021). Cultured protein production is independent of climate and seasonal and climatic variations and can be decoupled from other risks to traditional production methods (Bajic et al., 2022). However, cultured protein requires significant amounts of electricity, and emissions benefits from switching to cultured proteins are maximised when renewable electricity is used for its production (CE Delft, 2021).

These emerging technologies require more R&D. Precision fermentation requires further development of microorganism engineering and strain development and optimisation and improvements in feedstock selection and processes (CSIRO, 2023). Cell-based agriculture requires further R&D to optimise cell culture media and identifying appropriate and sustainable cell source (CSIRO, 2023).

An emissions reduction contribution could be achieved through switching preferences away from higher-emissions products, such as beef and lamb, towards animal meats with a lower emissions intensity, such as chicken, pork and kangaroo. Australia has already seen a dietary shift towards pork and chicken and away from beef and lamb in recent decades, potentially driven by shifting consumer preferences and price (ABARES, 2019; Wong et al., 2015). Plant-based proteins, such as those in legumes, are also available now and options for plant-based 'meat' are increasing (CSIRO, 2022b).

The average Australian diet has a climate footprint of approximately 3.4 kg CO_2-e per person per day (CSIRO, 2023). Although younger Australians are likely to give more consideration to sustainability when making choices on their food, confusing options and information can present barriers (CSIRO, 2022b).

Consumption of red meat in Australia has been relatively stable, with a slight decline since 2014 (MLA, 2023). Cost is the predominant reason people reduce red meat consumption, with health and environmental concerns less significant drivers (MLA, 2023). The majority (65 per cent) of red meat grown in Australia is exported (ABARES, 2022a). Therefore, behavioural drivers and other influences on the food choices of individuals, both in Australia and overseas, are important considerations when determining potential emissions impacts of shifts in food consumption patterns. Certification of products and improved consumer information on sustainability of food can aid consumer decision-making (CSIRO, 2023).

AL.3 Barriers, opportunities and enablers

There are a range of barriers and opportunities facing the agriculture and land sector's transition to a net zero economy. These include financial, workforce, data and information, and supply chain barriers.

In considering these barriers and opportunities, it is important to acknowledge the multi-faceted task facing farmers and other land managers in the transition. This includes adapting to the impacts of climate change, evolving farming practices to improve sustainability and maintain productivity, and balance demands on their land for other uses, such as accommodating infrastructure, carbon and biodiversity sequestration. Therefore, it is important to consider the sector's unique context and develop approaches that enable farmers to adopt solutions that suit their individual circumstances.

AL.3.1 Technical constraints

There are technical and logistical barriers associated with some agricultural abatement activities, such as delivering feed supplements to cattle outside of dairy and feedlot farming systems. New solutions to ensure cattle are administered with correct dosages at required frequencies are needed to scale the use of feed additives in pasture and extensive systems.

Manure management practices are applicable to confined or semi-confined farming where manure can be stored and processed. These technologies are not viable for reducing methane emissions from pastured livestock manure where the manure is deposited directly onto pasture (Herrero et al., 2016; Rivera & Chará, 2021). Although there are options to reduce methane emissions from pasture cattle, these are likely to be impractical in the large area of pasture-based systems in Australia.

AL.3.2 Green premiums

Economically affordable emissions reductions are limited in the agriculture industry and cost is a common barrier to uptake of nearly all technologies.

Uptake of emissions reduction technologies in the agriculture industry will generally lead to increased costs to agri-businesses as most of the proposed solutions do not yet deliver consistent and significant productivity benefits. Agri-businesses are usually small to medium sized and typically have modest profit margins. Agri-business is the commercial side of agriculture, its pursuit of sustainability and the value chain that links producers and consumers (UQ, 2023). They are therefore unlikely to take on additional cost in their operations without an associated increase to productivity.

> Uptake of emissions reduction technologies in the agriculture industry will generally lead to increased costs to agri-businesses as most of the proposed solutions do not yet deliver consistent and significant productivity benefits.

High costs are limiting farmers' use of feed supplements in dairies and feedlots. The authority has heard from stakeholders that the current cost of delivering feed supplements to cattle is up to $2 per animal per day. The authority also heard the cost would need to decline to 20 cents per animal per day, or alternatively ACCU prices increase to around $130/t CO_2-e, for the technology to become commercially viable at the current cost of feed additives. The National Farmers' Federation suggests this cost barrier can be overcome through an increase in the price of animal products produced with a lower carbon footprint, enhanced productivity through supplement use and/or a carbon mitigation payment (NFF, 2023b). It is likely that the limited availability of feed supplements currently in supply chains are also contributing to relatively high prices (NSW Government, 2023b).

Fertilisers coated in nitrification inhibitors are more expensive than conventional fertilisers (Fertilizer Australia, 2023) and this is preventing their widespread uptake (Folina et al., 2021).

Targeted funding for research and early-stage commercialisation of technologies could help address these challenges. In the 2023 Annual Progress Report, the authority recommended that the Australian Government fund an extensive challenge-based program of research and early-stage commercialisation of agriculture emissions reduction technologies (CCA, 2023a). This program could help to reduce cost barriers, quantify potential productivity benefits and increase uptake of emerging technologies in the sector. New ACCU scheme methodologies can also play a role in addressing cost barriers to adoption of emerging emissions reduction technologies (DCCEEW, 2024a). However, the development of new methodologies must be underpinned by robust and comprehensive research and data. Government initiatives that continue to build this evidence base, such as the MERiL Program (Minister for Agriculture, 2022), have proven to be highly effective and welcomed by stakeholders.

Other financing instruments, such as the existing research and development tax incentive, can encourage further research and development efforts (ATO, 2024). Looking beyond domestic investment, there could be opportunities to attract international research and development investment, such as from institutions like the Global Methane Hub (see more detail below). Australia could also leverage domestic public spending on agriculture mitigation solutions by connecting with similar international research initiatives.

The Global Methane Hub aims to provide $200 million in investment into research on reducing livestock methane emissions (Global Methane Hub, 2023). The research focus is on a range of topics including: exploring alternative livestock feed additives, breeding low-methane livestock, and developing a methane vaccine. This is an important suite of research which could directly benefit Australian beef producers and highlights the importance of participation in international research partnerships.

Establishment of new tree plantings can have high upfront costs and opportunity costs associated with shifting from agricultural production to timber, carbon or environmental plantings (CSIRO, 2022a). High land prices in productive agricultural areas and relatively low carbon prices are a barrier to landholders from establishing forest projects (CSIRO, 2022a), due to the potential opportunity cost of switching from one type of production to another.

Potential barriers to limiting deforestation and protection of existing forests are the limited financial and regulatory requirements to assign an economic value and factor carbon and biodiversity impacts into decision making.

Carbon and environmental markets are an opportunity to harness investment to achieve land-based carbon removal and other environmental and social outcomes. The authority has heard from stakeholders that the restoration of degraded agricultural areas could provide near-term emissions reductions, restore endangered habitats and simultaneously enhance biodiversity.

Trends in nature-related risk disclosure are following those in climate-related disclosure, with a number of food, agriculture and forestry companies committing to the Taskforce for Nature-related Financial Disclosures (TNFD, 2024). Increasing measurement and disclosure of the risks and dependencies on nature by businesses and institutions is also likely to support appropriate valuing of natural capital and biological sequestration. Other supply chain trends are also likely to influence the sector, such as new EU legislation preventing deforestation in the supply chain of key commodities, including cattle and beef products, and paper and wood products (European Commission, 2023).

Beyond preparing for these trends and the potential income gained through participation in markets, there are broader benefits of building and maintaining natural capital on farms. These include improved agricultural productivity and resilience to climate impacts and market shocks (MLA, 2024b). Continuing to grow the evidence base for these benefits can support the sector to prioritise activities that store carbon and protect nature alongside food and fibre production.

AL.3.3 Supply chain constraints

There may be logistical and supply chain barriers to establishing new forest projects at large scales. These include the cost and access to suitable land areas, and the availability of labour, skills and knowledge (CSIRO, 2022a; Whittle et al., 2019). Another key barrier is water availability, with some jurisdictions either regulating or considering water use in decision-making for new plantations, and the majority of commercial plantations being restricted to high or medium rainfall regions (ABARES, 2018a; Greenwood Strategy, 2021). These barriers may negatively impact the potential pace and scale of land-based removal achievable through reforestation.

There are potential limitations on the supply of equipment and appropriate seeds and tube-stock in large volumes for new plantings (CSIRO, 2022a). Access to timber milling is also a consideration for scaling up plantation forestry activities, as distance to mills and processing is a significant contributor to costs and consequently financial viability (CSIRO, 2022a). There is also the risk of social impacts if there are large-scale shifts in land use from agriculture to carbon farming, as highlighted in the authority's 2023 review of the ACCU scheme (CCA, 2023b).

> Balancing competing land uses is key to not only avoiding unintended consequences but also to earn social license. Stakeholders highlighted that it will be important that actions to increase land-based removal also achieve multiple benefits, like biodiversity, social and cultural outcomes.

Stakeholders have suggested that a barrier for many landholders in participating in reforestation activities and carbon markets is the complexity of the ACCU scheme and the challenge to navigate the regulatory processes (The Next Economy, 2023).

Land-based removals are likely to play a major role in Australia's pathway to net zero emissions by 2050. This, along with production of renewable fuel feedstocks, has the potential to add to the growing pressures on the land and water resources that provide food, fibre, biodiversity and cultural value. The establishment of new infrastructure to decarbonise the energy sector is also an increasingly important consideration for landholders and broader rural and regional communities, whose land or productivity may be impacted (AEIC, 2023).

Balancing competing land uses is key to not only avoiding unintended consequences but also to earn social license. Stakeholders highlighted that it will be important that actions to increase land-based removal also achieve multiple benefits, like biodiversity, social and cultural outcomes. Multiple stakeholders also raised concerns that the agriculture and land sector may not have the available carbon dioxide removal capacity to provide a low-cost source of abatement for other sectors (GrainGrowers and National Farmers' Federation submissions, 2024).

AL.3.4 Benefit sharing

Registered First Nations employment is concentrated within a small number of industries. Ninety per cent of agricultural workers who self-identify as First Nations are currently employed in regional or remote areas, primarily in sheep, cattle and grain farming (ABARES, 2023). The native food and botanicals industry as well as the carbon farming industry are already significant employers of First Nations people (Federation of Victorian Traditional Owner Corporations & Victorian State Government, 2021; Gebbie et al., 2021). Anticipated growth of these industries to support the transition to net zero has the potential to provide additional workforce and economic opportunities First Nations communities, provided benefits are shared equitably.

Acknowledgement of the non-carbon benefits of First Nations-led carbon farming projects has historically been limited to price premiums in the voluntary market (ILSC, 2022b). Sale of carbon credits generated by First Nations owned and operated projects receive a premium from buyers seeking to increase investment in businesses operating with strong 'Environmental, social, and governance (ESG)' values (ILSC, 2022a; NSW Government, 2023a). In previous submissions to the authority's 2023 ACCU scheme review, stakeholders highlighted concerns that these financial benefits do not always flow directly back to the First Nations communities (Kimberley Land Council and Wilinggin Aboriginal Corporation submissions, 2023).

The emergence of government initiatives which explicitly recognise non-carbon benefits, such as the Queensland Land Restoration Fund and the federal government's Nature Repair Market have the potential to improve the financial viability of First Nations carbon industry projects by formally rewarding caring for Country practices (DCCEEW, 2024c; Queensland Government, 2024). Associated compensation could assist projects to attract equity and diversify revenue streams, buffering against variability in carbon credit spot prices. Historically, difficulty in accessing equity has resulted in under-capitalisation of First Nations businesses, which can have flow-on effects including limiting potential for growth (Australian Government, 2018). Limited equity can also place small businesses at higher risk in the event of significant market shocks, such as the COVID-19 pandemic (Katare et al., 2021).

The benefits of growth in the First Nations carbon farming industry extend far beyond the production and sale of carbon credits. These additional benefits often referred to as 'core benefits' because of their equivalent, if not greater value to First Nations compared to carbon sequestration (Aboriginal Carbon Foundation, 2024). The financial resources generated through First Nations ownership in the growing carbon market have assisted in bringing First Nations peoples back to Country and supported the handing down of Traditional Knowledge from Elders to future generations (ILSC, 2022b). Projects can facilitate First Nations peoples to fulfil cultural obligations to look after Country. The carbon farming industry also provides meaningful and ongoing employment opportunities in very remote areas (ILSC, 2022a) where First Nations employment is as low as 51 per cent, well below the national average (Jobs and Skills Australia, n.d.).

There are also important benefits for Australia's environmental conservation and land management practices. Savanna fire management projects through the ACCU scheme have had a significant impact on the prevention of higher emissions late dry-season wildfires (Edwards et al., 2021). Environmental benefits of the broader First Nations carbon farming industry can include increased carbon storage, greater structural diversity and water yield, and increased habitat diversity and biodiversity (Gebbie et al., 2021). Incorporating First Nations cultural practices and Traditional Knowledge alongside western science can improve future land management initiatives undertaken by government and landholders (Kimberley Land Council, 2024).

AL.3.5 Information and data gaps

First Nations workers have played an important historical role in Australian agriculture, but this role has often been underacknowledged due to persistent data gaps (KPMG & NFF, 2023). According to ABARES analysis of 2021 census data, 1.8 per cent of the agricultural workforce identifies as First Nations. This represents an 80 per cent increase on the number of workers identifying as First Nations in 2016 (ABARES, 2018b). While these figures are encouraging, a proportion of this growth may be due to more accurate capture of existing workforce participants rather than onboarding of new workers. Given that the census only provides five-yearly data on First Nations participation, there is value in the agriculture and land sector considering opportunities for more frequent reporting on workforce demographics. This would assist in ensuring that First Nations contributions to the agriculture and land sector are adequately recognised and that the success of strategies to increase workforce participation can be evaluated.

Farmers are increasingly required to understand their on-farm emissions whilst managing risks to their businesses (DAFF 2023). Global and domestic agricultural markets are shifting, with increased interest in and expectations for environmental sustainability. Woolworths and McDonalds each have Science-Based Targets Initiative commitments (SBTi, 2024) and Australia's big four banks have signed the Net-Zero Banking Alliance (UNEP, n.d., 2021).

Land managers are also faced with decisions about whether to sell the carbon stored on their land into carbon offsets market or retain it for their own use. The authority has recommended landholders are provided with impartial, practical guidance and support to enable them to make informed decisions on retaining carbon for their own business, supplying the ACCU scheme offsets market, or undertaking farm forestry or other activities (CCA, 2023a). Stakeholders have welcomed funding into the Carbon Farming Outreach Program and have suggested that upskilling trusted professionals (e.g. agronomists, business and legal advisors) could enhance emissions reduction efforts as these are the experts that farmers look to for credible information and advice.

AL.4 Emissions pathways

Modelling by the CSIRO undertaken on behalf of the authority provides an indicative, least-cost pathway for the agriculture and land sector's decarbonisation based on assumed technology costs and uptake over the period to 2050 (Figure AL.2).

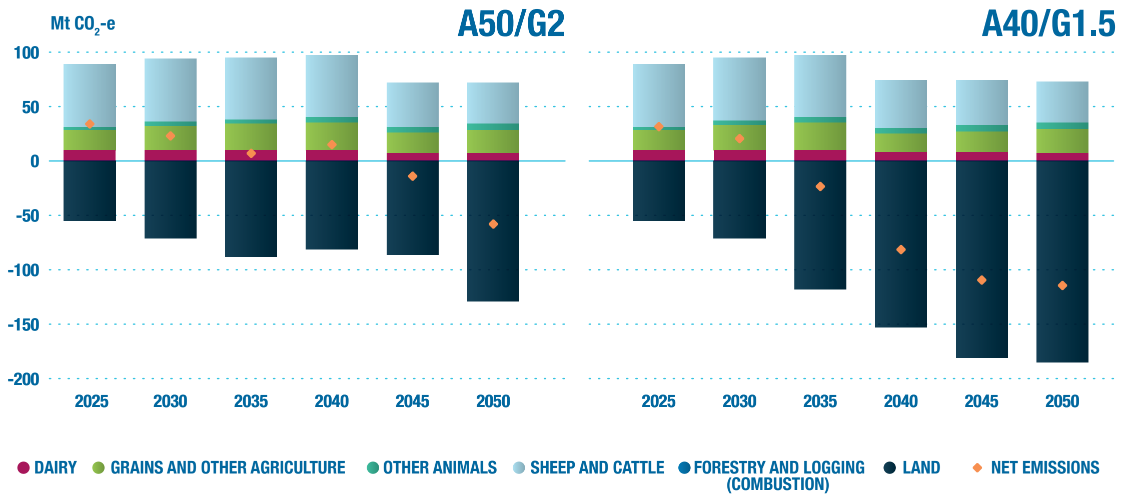
This modelling and additional analysis undertaken by the authority for this report defines agriculture and land as a single sector. This is based on the delineation of sectors by the Australian Parliament, in its referral of the sectoral pathways review to the authority (CCA, 2024). As such, net emissions for the sector are reported as combined agriculture and land emissions.

Under CSIRO's modelling, the agriculture subsector's emissions are projected to remain stable through the 2030s followed by a modest decrease to 2050 (A50/G2). Total agriculture emissions are projected to decrease by 20 per cent on current levels to 71 Mt CO_2-e by 2050.

Agricultural abatement options with significant potential are generally expensive in comparison to many other industries. The CSIRO's modelling results indicate that agriculture is slower to decarbonise and could contribute 47 per cent of Australia's gross emissions in 2050 in a net zero by 2050 scenario (A50/G2).

The land sink is projected to increase modestly (becomes more negative) to 2040 and then more than doubles by 2050, reaching approximately 129 Mt CO_2-e sink in 2050 (A50/G2). This increase is driven by the implied abatement incentive of our chosen carbon emissions trajectories. Under this scenario approximately 3 M ha of land is converted to forest to provide these projected levels of sequestration (see Table AL.4).

Figure AL.2: CSIRO's modelling projections of sources and sinks for agriculture and land sector for A50/G2 and A40/G1.5 scenarios



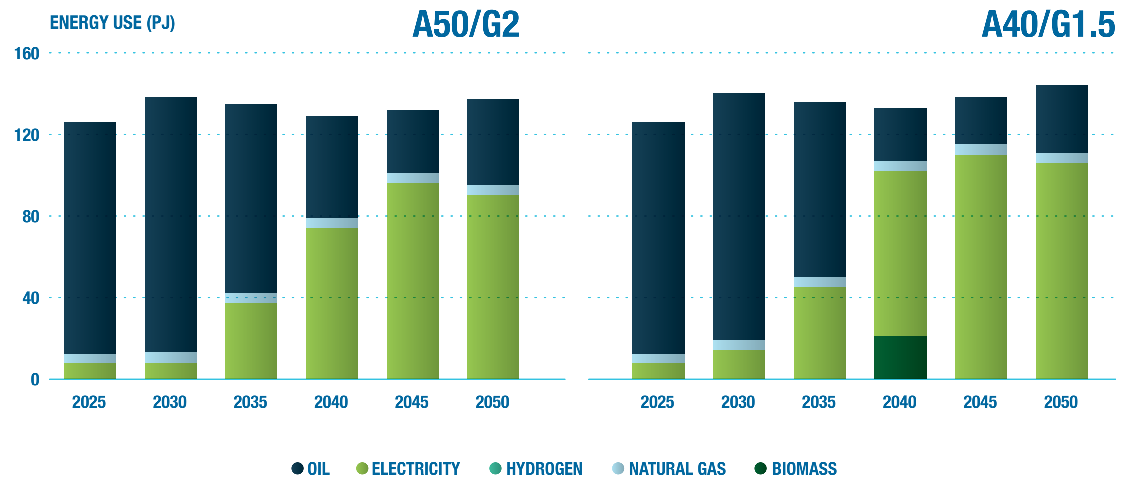
Source: CSIRO modelling in AusTIMES commissioned by the Climate Change Authority

The CSIRO modelling commissioned by the authority indicates that agriculture emissions reduce modestly to 2050, reaching 73 Mt CO_2-e. A downward trend in livestock emissions is the primary driver of these projected emission reductions, driven by the assumed deployment of technologies, such as feed supplements. Emissions from other sources remain relatively stable.

The land sink is projected to increase significantly (become more negative) through to 2050 in the A40/G1.5 scenario, providing a carbon sink of approximately 185 Mt CO_2-e. Under this scenario approximately 5.9 M ha of land is converted to forest to provide these project levels of sequestration (see Table AL.4).

Achieving the projected emission reductions in both CSIRO modelling scenarios relies heavily on the availability and uptake of feed supplements. Improvements in the emissions intensity of crop production are also assumed in this scenario through uptake of low-emissions fertilisers. However, these emissions reductions are largely offset by increased crop production from increasing crop productivity.

Figure AL.3: Energy use for the agriculture and land sector for A50/G2 and A40/G1.5 scenarios



Source: CSIRO modelling in AusTIMES commissioned by the Climate Change Authority

Oil, in the form of diesel, is projected to remain the primary source of energy in the agriculture industry across the period to 2035, with an increasing role for electric agricultural vehicles and machinery from 2040 onwards. In CSIRO's modelling of the A40/G1.5 scenario biomass pays a role as fuel in the period 2035-2040 as the model simulates the whole economy reaching net zero emissions in 2040, and draws on the necessary least-cost low emissions fuels that are assumed to be available during that period (see Figure AL.3).

The authority also undertook a ground-up analysis to estimate the abatement potential of individual technologies. The authority employed desktop research and discussion with stakeholders, including relevant experts, to identify key information and inform the analysis.

The ground-up analysis of the agriculture sector consisted of assessment of potential technology uptake rates and emissions abatement potential for priority technologies. The ground-up analysis of land-based carbon removals was based on assumptions regarding realisable planting rates, type and growth rate of plantings to calculate the potential carbon abatement. The ground-up estimates are conservative and drawn from a range of available evidence.

The ground-up analysis was limited in the number of technologies and emissions sources and did not account for complex economic or environmental interactions and processes, such as the cost implications of mitigation on competitiveness and production. Table AL.3 shows the abatement to 2050 of agriculture and land subsectors as calculated through both the ground-up and modelling approaches.

The results of CSIRO's modelling and the authority's ground-up analysis are broadly aligned on the estimated abatement potential within the sector. However, there are areas where the estimates generated by the two approaches do deviate significantly from each other.

The Grains and Other Agriculture subsector emissions increased by 3 Mt CO_2-e to 2050 in CSIRO's modelling scenarios and decreased by 2 to 4 Mt CO_2-e in the authority's ground-up estimates. This difference is due to the modelling scenarios incorporating an increase in agricultural production, which was not included in the ground-up analysis. Both the CSIRO's modelling and the authority's ground-up analysis include the assumption that cattle and sheep numbers remain around current levels out to 2050.

Projections of the existing land sink were based on the government's emissions projections in both the CSIRO's modelling and the authority's ground-up analyses. Additional environmental and carbon plantings are projected by CSIRO's model to deliver between 74 and 130 Mt CO_2-e of land-based removal in the year 2050. The authority's ground-up analysis estimates additional environmental and carbon plantings could deliver between 32 and 39 Mt CO_2-e based on lower planted area assumptions (Table AL.4).

Table AL.3: Projections of emissions reductions to 2050 using estimates from AusTIMES modelling and ground-up analysis

	Projected emissions reductions to 2050 (Mt CO_2-e)[a]		
Reference: Emissions were -3 Mt CO_2-e in 2022	**AusTIMES and LUTO modelling (A50/G2 scenario)**	**AusTIMES and LUTO modelling (A40/G1.5 scenario)**	**Ground-up estimate**
Sheep and cattle	19	19	7 to 23
Dairy	3	2	2 to 6
Fuel use	5	5	5
Other animals	-3	-3	2
Grains and other agriculture	-6	-7	2 to 4
Agriculture total	18	16	18 to 40
Management of existing land and forests	1	1	-8
Additional Environmental and carbon plantings	74	130	32 to 39
Land total	75	130	24 to 31
Agriculture and land total	92	146	42 to 71

[a] Abatement was calculated as the difference between base year emissions and the projected 2050 emissions from each model. In AusTIMES the base year for the abatement calculation is 2025 and in the ground-up estimates the base year is 2022.

Table AL.4: Area of additional planted forests in CSIRO modelling and ground-up analysis

	Projected area of additional environmental and carbon plantings (million hectares, M ha) in 2050
CSIRO for CCA – A50/G2	3.0
CSIRO for CCA – A40/G1.5	5.9
Ground-up	2.6
Reference point – area of planted forests in Australia in 2023*	2.1

**Source: State of the Forests Report 2023*

AL4.1 Residual emissions

CSIRO modelling commissioned by the authority indicates that by 2050 there are residual agriculture emissions remaining in even the most ambitious scenarios. There could between around 71-73 Mt CO_2-e of residual emissions from agriculture in 2050 under the A50/G2 and A40/G1.5 scenarios respectively. The CSIRO's modelling scenarios indicate that the largest sources of residual emissions in 2050 would be from enteric fermentation, grains and other agriculture. The authority's ground-up analysis indicated residual emissions from enteric fermentation in the range 26 Mt CO_2-e to 46 Mt CO_2-e in 2050.

AL.5 References

ABARES (Australian Bureau of Agricultural and Resource Economics and Sciences). (2018a). *Australia's State of the Forests Report 2018*. https://www.agriculture.gov.au/sites/default/files/abares/forestsaustralia/documents/sofr_2018/web%20accessible%20pdfs/SOFR_2018_web.pdf

ABARES. (2018b). *Snapshot of Australia's Agricultural Workforce*. https://daff.ent.sirsidynix.net.au/client/en_AU/search/asset/1027073/0

ABARES. (2019). *Global trends in meat consumption*. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/meat-consumption

ABARES. (2020). *Analysis of Australian food security and the COVID-19 pandemic*. https://daff.ent.sirsidynix.net.au/client/en_AU/search/asset/1030201/0

ABARES. (2022a). *Agricultural commodities and trade data: Rural commodities - meat - general*. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data#_2022

ABARES. (2022b, August 3). *Australia's Indigenous land and forest estate (2020)*.

ABARES. (2023). *Snapshot of Australia's agricultural workforce*. https://daff.ent.sirsidynix.net.au/client/en_AU/search/asset/1035161/0

ABARES. (2024a). *Agricultural commodities and trade data*. https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data#agricultural-commodities

ABARES. (2024b). *Snapshot of Australian Agriculture 2024*. https://daff.ent.sirsidynix.net.au/client/en_AU/search/asset/1035603/0

Aboriginal Carbon Foundation. (2024). *Carbon farming: Core benefits*. https://www.abcfoundation.org.au/carbon-farming/core-benefits

ABS (Australian Bureau of Statistics). (2022). *Value of Aussie Agriculture hits $71 billion in 2020-21*. https://www.abs.gov.au/articles/value-aussie-agriculture-hits-71-billion-2020-21#:~:text=The%20total%20value%20of%20Australian,%2471%20billion%20in%202020%2D21&text=Infographic%20showing%20total%20value%20of,%2471%20billion%20in%202020%2D21.

Acclimate Partners. (2022). *The Diesel Transition: Petroleum diesel alternatives for the Australian agriculture, fisheries and forestry sector*. https://agrifutures.com.au/product/the-diesel-transition-petroleum-diesel-alternatives-for-the-australian-agriculture-fisheries-and-forestry-sector/

AEIC (Australian Energy Infrastructure Commissioner). (2023). *Annual Report to the Parliament of Australia*. Australian Government. https://www.aeic.gov.au/sites/default/files/documents/2023-06/aeic-2022-annual-report.pdf

AEMO (Australian Energy Market Operator). (2024). *Appendix 3. Renewable Energy Zones*. https://aemo.com.au/-/media/files/major-publications/isp/2024/appendices/a3-renewable-energy-zones.pdf?la=en

Alemu, A. W., Pekrul, L. K. D., Shreck, A. L., Booker, C. W., McGinn, S. M., Kindermann, M., & Beauchemin, K. A. (2021). 3-Nitrooxypropanol Decreased Enteric Methane Production From Growing Beef Cattle in a Commercial Feedlot: Implications for Sustainable Beef Cattle Production. *Frontiers in Animal Science*, *2*. https://doi.org/10.3389/fanim.2021.641590

Aliyu, M., Hassan, G., Said, S. A., Siddiqui, M. U., Alawami, A. T., & Elamin, I. M. (2018). A review of solar-powered water pumping systems. *Renewable and Sustainable Energy Reviews*, *87*, 61–76. https://doi.org/10.1016/j.rser.2018.02.010

Almeida, A. K., Hegarty, R. S., Waters, C., Oddy, H., Greenwood, P., Eckard, R., & Jewell, M. (2021). *Managing livestock to reduce methane emissions: Assessment of strategies for abatement of enteric methane*. https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0005/1383494/UNE-DPI_Final_report_enteric_methane_management_journal_ref_added_alc2_20220111_accessible.pdf

ATO (Australian Tax Office). (2024). *About the R&D program*. https://www.ato.gov.au/businesses-and-organisations/income-deductions-and-concessions/incentives-and-concessions/research-and-development-tax-incentive-and-concessions/research-and-development-tax-incentive/about-the-r-d-program

Australian Government. (2018). *Indigenous Business Sector Strategy 2018-2028*. https://www.niaa.gov.au/resource-centre/indigenous-business-sector-strategy

Australian Institute of Health and Welfare. (2012). *Australia's food & nutrition 2012 : in brief*. Australian Institute of Health and Welfare. https://www.aihw.gov.au/reports/food-nutrition/australias-food-nutrition-2012-in-brief/summary

Badgery, W., Li, G., Simmons, A., Wood, J., Smith, R., Peck, D., Ingram, L., Durmic, Z., Cowie, A., Humphries, A., Hutton, P., Winslow, E., Vercoe, P., & Eckard, R. (2023). Reducing enteric methane of ruminants in Australian grazing systems – a review of the role for temperate legumes and herbs. *Crop and Pasture Science*, *74*(8), 661–679. https://doi.org/10.1071/CP22299

Bajić, B., Vučurović, D., Vasić, Đ., Jevtić-Mučibabić, R., & Dodić, S. (2022). Biotechnological Production of Sustainable Microbial Proteins from Agro-Industrial Residues and By-Products. *Foods*, *12*(1), 107. https://doi.org/10.3390/foods12010107

Biala, J., Wilkinson, K., Henry, B., Singh, S., Bennett-Jones, J., & De Rosa, D. (2021). The potential for enhancing soil carbon levels through the use of organic soil amendments in Queensland, Australia. *Regional Environmental Change*, *21*(4), 95. https://doi.org/10.1007/s10113-021-01813-y

Black, J. L., Davison, T. M., & Box, I. (2021). Methane emissions from ruminants in Australia: Mitigation potential and applicability of mitigation strategies. In *Animals* (Vol. 11, Issue 4). MDPI AG. https://doi.org/10.3390/ani11040951

Candy, S., Turner, G., Larsen, K., Wingrove, K., Steenkamp, J., Friel, S., & Lawrence, M. (2019). Modelling the Food Availability and Environmental Impacts of a Shift Towards Consumption of Healthy Dietary Patterns in Australia. *Sustainability*, *11*(24), 7124. https://doi.org/10.3390/su11247124

CCA (Climate Change Authority). (2023a). *2023 Annual Progress Report*. https://www.climatechangeauthority.gov.au/sites/default/files/documents/2023-11/2023%20AnnualProgressReport_0.pdf

CCA. (2023b). *2023 review of the Carbon Credits (Carbon Farming Initiative) Act 2011*. Climate Change Authority. https://www.climatechangeauthority.gov.au/accu-scheme-reviews

CCA. (2024, May 21). *Sector pathways review*. https://www.climatechangeauthority.gov.au/sector-pathways-review

CE Delft. (2021). *TEA of cultivated meat: Future projections of different scenarios-corrigendum*. https://gfi.org/blog/cultivated-meat-lca-tea/#:~:text=If%20renewable%20energy%20is%20used%20throughout%20the%20supply%20chain%2C%20cultivated,about%20the%20same%20as%20chicken.

Cowley, F., Simanunkalit, G., Kelly, M., & Gray, E. (2023). *Final report Effect of Asparagopsis extract in a canola oil carrier for long-fed Wagyu cattle*. https://www.mla.com.au/contentassets/e4ce8f8ddb2743f38ac0f6e83a0724a3/p.psh.1353-mla-final-report-100723.pdf

CSIRO (Commonwealth Scientific and Industrial Research Organisation). (n.d.). *Indigenous Land Management in Australia*. www.daff.gov.au/natural-resources/landcare/council/

CSIRO. (2021, March 29). *Precision Agriculture*. https://www.csiro.au/en/research/plants/crops/farming-systems/precision-agriculture

CSIRO. (2022a). *Australia's carbon sequestration potential*. https://www.csiro.au/en/research/environmental-impacts/emissions/carbon-sequestration-potential

CSIRO. (2022b). *Protein: A roadmap for unlocking technology-led growth opportunities for Australia*. https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/agriculture-and-food/australias-protein-roadmap

CSIRO. (2023). *Reshaping Australian Food Systems*. https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/CSIRO-futures/Agriculture-and-Food/Reshaping-Australian-Food-Systems

DAFF (Department of Agriculture, Fisheries and Forestry). (2023). *National Statement on Climate Change and Agriculture*. https://www.agriculture.gov.au/agriculture-land/farm-food-drought/climatechange/national-statement-on-climate-change-and-agriculture

DCCEEW (Department of Climate Change, Energy, the Environment and Water). (2023). *Quarterly Update of Australia's National Greenhouse Gas Inventory: December 2022*. https://www.dcceew.gov.au/sites/default/files/documents/nggi-quarterly-update-dec-2022.pdf

DCCEEW. (2024a). *Developing new ACCU Scheme methods*. https://www.dcceew.gov.au/climate-change/emissions-reduction/accu-scheme/developing-new-methods

DCCEEW. (2024b). *National Inventory Report 2022, Volume I*. https://www.dcceew.gov.au/sites/default/files/documents/national-inventory-report-2022-volume-1.pdf

DCCEEW. (2024c). *Nature Repair Market*. https://www.dcceew.gov.au/environment/environmental-markets/nature-repair-market

De Almeida, A., Cowley, F., & Hegarty, R. (2022). *Final report Methane emissions of Australian feedlot cattle as influenced by 3-Nitrooxypropanol (Bovaer 10®)*.

Drouillard, J. S. (2018). Current situation and future trends for beef production in the United States of America — A review. *Asian-Australasian Journal of Animal Sciences*, *31*(7), 1007–1016. https://doi.org/10.5713/ajas.18.0428

Edwards, A., Archer, R., De Bruyn, P., Evans, J., Lewis, B., Vigilante, T., Whyte, S., & Russell-Smith, J. (2021). Transforming fire management in northern Australia through successful implementation of savanna burning emissions reductions projects. *Journal of Environmental Management*, *290*, 112568. https://doi.org/https://doi.org/10.1016/j.jenvman.2021.112568

Energetics. (2019). *Marginal abatement cost curve (MACC): Queensland agriculture and land use*. https://documents.parliament.qld.gov.au/com/SDRIC-F506/IQ-81CF/TP%20-%20Marginal%20abatement%20cost%20curve%20(MACC)%20Queensland%20agriculture%20and%20land%20use.pdf

European Commission. (2023). *Regulation on deforestation-free products*. https://environment.ec.europa.eu/topics/forests/deforestation/regulation-deforestation-free-products_en

EY (Ernst & Young). (2021). *How can Australia's agriculture sector realise opportunity in a low emissions future?* https://farmersforclimateaction.org.au/wp-content/uploads/2021/09/FCA-EY-FINAL-Report-Low-emissions-future-for-Agriculture.pdf

Federation of Victorian Traditional Owner Corporations, & Victorian State Government. (2021). *Victorian Traditional Owner Native Food and Botanicals Strategy*. https://gunaikurnai.org/wp-content/uploads/2021/07/Victorian-Traditional-Owner-Native-Foods-and-Botanicals-Strategy-ONLINE.pdf

Fertilizer Australia. (2023). *Nitrogen Fertiliser Use and Greenhouse Gases An Australian Assessment: Challenges and Opportunities*. https://fertilizer.org.au/Portals/0/Documents/Publications/Fertilizer%20Australia%20-%20Full%20Whitepaper%20Document.pdf?ver=2023-12-18-010557-300

Finn, D., Ouwerkerk, D., & Klieve, A. (2012). *Methanotrophs from natural ecosystems as biocontrol agents for ruminant methane emissions final report*. https://www.mla.com.au/contentassets/30f30d40f3e041f7b2206cb502f24446/b.cch.1013_final_report.pdf

Folina, A., Tataridas, A., Mavroeidis, A., Kousta, A., Katsenios, N., Efthimiadou, A., Travlos, I. S., Roussis, I., Darawsheh, M. K., Papastylianou, P., & Kakabouki, I. (2021). Evaluation of Various Nitrogen Indices in N-Fertilizers with Inhibitors in Field Crops: A Review. *Agronomy*, *11*(3), 418. https://doi.org/10.3390/agronomy11030418

Garrison, G. L., Biermacher, J. T., & Brorsen, B. W. (2022). How much will large-scale production of cell-cultured meat cost? *Journal of Agriculture and Food Research*, *10*. https://doi.org/10.1016/j.jafr.2022.100358

Gebbie, L., Miller, D., & Keenan, R. (2021). *Opportunities for Traditional Owners in the Carbon Economy*. Pursuit, University of Melbourne. https://pursuit.unimelb.edu.au/articles/opportunities-for-traditional-owners-in-the-carbon-economy

Gjerek, M., Morgan, A., Gore-Brown, N., & Womersley, G. (2021). *Diesel use in NSW agriculture and opportunities to support net zero emissions*. https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0011/1321796/mov3ment-diesel-use-in-ag.pdf

Global Methane Hub. (2023, December 2). *Enteric Fermentation Research & Development Accelerator, a $200M Agricultural Methane Mitigation Funding Initiative*. https://www.globalmethanehub.org/2023/12/02/enteric-fermentation-research-development-accelerator-a-200m-agricultural-methane-mitigation-funding-initiative/

Goddek, S., Körner, O., Keesman, K. J., Tester, M. A., Lefers, R., Fleskens, L., Joyce, A., van Os, E., Gross, A., & Leemans, R. (2023). How greenhouse horticulture in arid regions can contribute to climate-resilient and sustainable food security. *Global Food Security*, *38*, 100701. https://doi.org/https://doi.org/10.1016/j.gfs.2023.100701

Goodman, W., & Minner, J. (2019). Will the urban agricultural revolution be vertical and soilless? A case study of controlled environment agriculture in New York City. *Land Use Policy*, *83*, 160–173. https://doi.org/https://doi.org/10.1016/j.landusepol.2018.12.038

Grace, P., De Rosa, D., Shcherbak, I., Strazzabosco, A., Rowlings, D., Scheer, C., Barton, L., Wang, W., Schwenke, G., Armstrong, R., Porter, I., & Bell, M. (2023). Revised emission factors for estimating direct nitrous oxide emissions from nitrogen inputs in Australia's agricultural production systems: a meta-analysis. *Soil Research*, *62*(1). https://doi.org/10.1071/SR23070

Grains Research & Development Corporation (GRDC). (2013). *Controlled traffic farming: Fact sheet*. https://grdc.com.au/__data/assets/pdf_file/0028/83872/Controlled-Traffic-Farming-GRDC-Fact-sheet-2013.pdf

Greenwood Strategy. (2021). *Planning and approvals requirements for new plantations in Australia*. https://ausfpa.com.au/wp-content/uploads/2021/09/Planning-and-approvals-requirements-for-new-plantations-in-Australia.pdf

Harrison, M. T., Cullen, B. R., Tomkins, N. W., McSweeney, C., Cohn, P., & Eckard, R. J. (2016). The concordance between greenhouse gas emissions, livestock production and profitability of extensive beef farming systems. *Animal Production Science*, *56*(3), 370–384. https://doi.org/10.1071/AN15515

Herrero, M., Henderson, B., Havlík, P., Thornton, P. K., Conant, R. T., Smith, P., Wirsenius, S., Hristov, A. N., Gerber, P., Gill, M., Butterbach-Bahl, K., Valin, H., Garnett, T., & Stehfest, E. (2016). Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*, *6*(5), 452–461. https://doi.org/10.1038/nclimate2925

Hughes, N., Galeano, D., & Hatfield-Dodds, S. (2019). *The effects of drought and climate variability on Australian farms*. https://www.agriculture.gov.au/abares/products/insights/effects-of-drought-and-climate-variability-on-Australian-farms

Hughes, N., & Gooday, P. (2021). *Climate change impacts and adaptation on Australian farms*. https://daff.ent.sirsidynix.net.au/client/en_AU/search/asset/1032401/0

Hughes, N., Lawson, K., & Valle, H. (2017). *Farm performance and climate: Climate-adjust-*

ed productivity for broadacre cropping farms. https://china.elgaronline.com/edcollchap/edcoll/9781786432414/9781786432414.00012.xml

Hughes, N., Lu, M., Soh, W. Y., & Lawson, K. (2022). Modelling the effects of climate change on the profitability of Australian farms. *Climatic Change*, *172*(1), 12. https://doi.org/10.1007/s10584-022-03356-5

ICIN (Indigenous Carbon Industry Network). (2022). *Mapping the Opportunities for Indigenous Carbon in Australia*. https://assets.nationbuilder.com/icin/pages/182/attachments/original/1664240300/Mapping_the_opportunities_ABRIDGED_WEB.pdf?1664240300

ICIN. (2024). *Industry Snapshot*. https://www.icin.org.au/latest_industry_snapshot.

ILSC (Indigenous Land and Sea Corporation). (2022a). *Carbon Factsheet*. https://www.ilsc.gov.au/wp-content/uploads/2022/05/Carbon-Factsheet.pdf

ILSC. (2022b). *Discussion paper: Indigenous participation in the carbon industry*. https://www.ilsc.gov.au/wp-content/uploads/2022/05/Indigenous-participation-in-the-carbon-industry.pdf

Islam, Z. F., Cherepanov, P. V., & Hu, H.-W. (2023). Engineering biodegradable coatings for sustainable fertilisers. *Microbiology Australia*, *44*(1), 9–12. https://doi.org/10.1071/MA23003

IUCN (International Union for Conservation of Nature). (2020). *IUCN Global Standard for Nature-based Solutions: a user-friendly framework for the verification, design and scaling up of NbS: first edition*. IUCN, International Union for Conservation of Nature. https://doi.org/10.2305/IUCN.CH.2020.08.en

Janke, T., Cumpston, Z., Hill, R., Woodward, E., Harkness, P., S, von G., & Morrison, J. (2021). Indigenous: Caring for Country. In *Australia State of the environment 2021*. Australian Government Department of Agriculture, Water and the Environment. https://doi.org/10.26194/3JDV-NH67

Jayaraman, S., & Dalal, R. C. (2022). No-till farming: prospects, challenges – productivity, soil health, and ecosystem services. *Soil Research*, *60*(6), 435–441. https://doi.org/10.1071/SR22119

Jeyanathan, J., Martin, C., & Morgavi, D. P. (2014). The use of direct-fed microbials for mitigation of ruminant methane emissions: a review. *Animal*, *8*(2), 250–261. https://doi.org/10.1017/S1751731113002085

Jobs and Skills Australia. (n.d.). *First Nations People Workforce Analysis*. Retrieved 7 June 2024, from https://www.jobsandskills.gov.au/studies/first-nations-people-workforce-analysis

Katare, B., Marshall, M. I., & Valdivia, C. B. (2021). Bend or break? Small business survival and strategies during the COVID-19 shock. *International Journal of Disaster Risk Reduction*, *61*, 102332. https://doi.org/10.1016/j.ijdrr.2021.102332

Kimberley Land Council. (2024). *Indigenous Fire Management*. https://www.klc.org.au/indigenous-fire-management

KPMG & NFF (National Farmers Federation). (2023). *Realising the Opportunity.* NFF-Realising-the-Opportunity-Final-Report_25.5.2023.pdf

Lees, A. M., Sejian, V., Wallage, A. L., Steel, C. C., Mader, T. L., Lees, J. C., & Gaughan, J. B. (2019). The Impact of Heat Load on Cattle. *Animals*, *9*(6), 322. https://doi.org/10.3390/ani9060322

Luo, Z., Eady, S., Sharma, B., Grant, T., Liu, D. L., Cowie, A., Farquharson, R., Simmons, A., Crawford, D., Searle, R., & Moore, A. (2019). Mapping future soil carbon change and its uncertainty in croplands using simple surrogates of a complex farming system model. *Geoderma*, *337*, 311–321. https://doi.org/https://doi.org/10.1016/j.geoderma.2018.09.041

Macreadie, P. I., Costa, M. D. P., Atwood, T. B., Friess, D. A., Kelleway, J. J., Kennedy, H., Lovelock, C. E., Serrano, O., & Duarte, C. M. (2021). Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment*, *2*(12), 826–839. https://doi.org/10.1038/s43017-021-00224-1

Malerba, M. E., Lindenmayer, D. B., Scheele, B. C., Waryszak, P., Yilmaz, I. N., Schuster, L., & Macreadie, P. I. (2022). Fencing farm dams to exclude livestock halves methane emissions and improves water quality. *Global Change Biology*, *28*(15), 4701–4712. https://doi.org/10.1111/gcb.16237

McDonald, S. E., Badgery, W., Clarendon, S., Orgill, S., Sinclair, K., Meyer, R., Butchart, D. B., Eckard, R., Rowlings, D., Grace, P., Doran-Browne, N., Harden, S., Macdonald, A., Wellington, M., Pachas, A. N. A., Eisner, R., Amidy, M., & Harrison, M. T. (2023). Grazing management for soil carbon in Australia: A review. *Journal of Environmental Management*, *347*, 119146. https://doi.org/https://doi.org/10.1016/j.jenvman.2023.119146

McGowan, M., McCosker, K., Fordyce, G., & Kirkland, P. (2020). Epidemiology and Management of BVDV in Rangeland Beef Breeding Herds in Northern Australia. *Viruses*, *12*(10), 1063. https://doi.org/10.3390/v12101063

McKinsey. (2022). *Blue carbon: The potential of coastal oceanic climate action*. https://www.mckinsey.com/capabilities/sustainability/our-insights/blue-carbon-the-potential-of-coastal-and-oceanic-climate-action#/

Meng, Y., Wang, J. J., Wei, Z., Dodla, S. K., Fultz, L. M., Gaston, L. A., Xiao, R., Park, J., & Scaglia, G. (2021). Nitrification inhibitors reduce nitrogen losses and improve soil health in a subtropical pastureland. *Geoderma*, *388*, 114947. https://doi.org/10.1016/j.geoderma.2021.114947

Minister for Agriculture, Fisheries and Forestry. (2022, October 23). *Joint media release: Methane Emissions Reduction in Livestock (MERiL) Program*. https://minister.agriculture.gov.au/watt/media-releases/joint-media-release-methane-emissions-reduction-livestock-meril-program

MLA (Meat and Livestock Australia). (2023). *Community Sentiment Research*. https://www.mla.com.au/globalassets/mla-corporate/marketing-beef-and-lamb/documents/mla-community-sentiment-research---mla-website-summary-2023.pdf

MLA. (2024a). *Drought feeding*. https://www.mla.com.au/research-and-development/livestock-production/livestock-nutrition/drought-feeding/

MLA. (2024b). *Farming for the Future: An impact focussed research and change program for Australian producers*. https://www.mla.com.au/globalassets/mla-corporate/research-and-development/final-reports/2024/mla_fftf_project-final-report_updated.pdf

NFF (National Farmers Federation). (2019). *2030 Roadmap*. https://nff.org.au/policies/roadmap/

NFF (2023a). *Significant labour shortages across food supply chain weighing on growth, cost of living*. https://nff.org.au/media-release/significant-labour-shortages-across-food-supply-chain-weighing-on-growth-cost-of-living/

NFF. (2023b). *Agriculture Land and Emissions Discussion Paper Submission*. https://nff.org.au/wp-content/uploads/2024/02/20-12-2023-NFF-Agriculture-Land-and-Emissions-Discussion-Paper-Submission.pdf

NSW Government. (2023a). *Carbon on Country: A guide for NSW Aboriginal landholders and managers*. https://www.energy.nsw.gov.au/sites/default/files/2023-02/202301-Carbon-on-Country-Guidelines.pdf

NSW Government. (2023b). *Supplementary feed options update July 2023*. https://www.lls.nsw.gov.au/__data/assets/pdf_file/0010/1469530/NC-feed-prices-July2023.pdf

Page, K. L., Dalal, R. C., Reeves, S. H., Wang, W. J., Jayaraman, S., & Dang, Y. P. (2020). Changes in soil organic carbon and nitrogen after 47 years with different tillage, stubble and fertiliser management in a Vertisol of north-eastern Australia. *Soil Research*, *58*(4), 346. https://doi.org/10.1071/SR19314

Paul, K. I., Cunningham, S. C., England, J. R., Roxburgh, S. H., Preece, N. D., Lewis, T., Brooksbank, K., Crawford, D. F., & Polglase, P. J. (2016). Managing reforestation to sequester carbon, increase biodiversity potential and minimize loss of agricultural land. *Land Use Policy*, *51*, 135–149. https://doi.org/10.1016/j.landusepol.2015.10.027

Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., & Wagner, F. (2003). *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* https://www.ipcc.ch/site/assets/uploads/2018/03/GPG_LULUCF_FULLEN.pdf

QFF (Queensland Farmers' Federation). (2015). *Planning Guideline for Intensive Horticulture and Production Nurseries*. https://www.qff.org.au/wp-content/uploads/2016/11/QFF-Guide-to-Planning-Intensive-Hort-Prod.pdf

Queensland Government. (2024). *The Land Restoration Fund and Australia's carbon market*. https://www.qld.gov.au/environment/climate/climate-change/land-restoration-fund/about/australian-market

RepuTex Energy. (2023). *ACCU Market Analysis - Final Report For Publication*. https://www.climatechangeauthority.gov.au/sites/default/files/documents/2023-12/ACCU%20Market%20Analysis%20-%20Final%20Report%20For%20Publication.pdf

Ridoutt, B., Lehnert, S. A., Denman, S., Charmley, E., Kinley, R., & Dominik, S. (2022). Potential GHG emission benefits of Asparagopsis taxiformis feed supplement in Australian beef cattle feedlots. *Journal of Cleaner Production*, *337*, 130499. https://doi.org/10.1016/j.jclepro.2022.130499

Rivera, J. E., & Chará, J. (2021). CH4 and N2O Emissions From Cattle Excreta: A Review of Main Drivers and Mitigation Strategies in Grazing Systems. *Frontiers in Sustainable Food Systems*, *5*. https://www.frontiersin.org/articles/10.3389/fsufs.2021.657936

Roxburgh, S. K. P. P. L. (2020). *Technical review of physical risks to carbon sequestration under the Emissions Reduction Fund (ERF)*. https://www.climatechangeauthority.gov.au/sites/default/files/ERF%20Review%20-%20CSIRO%20Technical%20Report%20on%20Climate%20Risk%20-%20Final%20pdf.pdf

Science Based Targets Initiative (SBTi). (2024). *Companies taking action*. https://sciencebasedtargets.org/companies-taking-action#dashboard

Schindler Murray, L. M. Ben. (2023). *The blue carbon handbook: Blue carbon as a nature-based solution for climate action and sustainable development*. https://oceanpanel.org/publication/blue-carbon/

Serrano, O., Lovelock, C., Atwood, T., Macreadie, P., Canto, R. F., Phinn, S., Arias-Ortiz, A., Bai, L., Baldock, J., Bedulli, C., Carnell, P., Connolly, R., Donaldson, P., Esteban, A., Ewers Lewis, C., Eyre, B., Hayes, M., Horwitz, P., Hutley, L., & Duarte, C. (2019). Australian vegetated coastal ecosystems as global hotspots for climate change mitigation. *Nature Communications*, *10*. https://doi.org/10.1038/s41467-019-12176-8

Shafi, U., Mumtaz, R., García-Nieto, J., Hassan, S. A., Zaidi, S. A. R., & Iqbal, N. (2019). Precision agriculture techniques and practices: From considerations to applications. In *Sensors (Switzerland)* (Vol. 19, Issue 17). MDPI AG. https://doi.org/10.3390/s19173796

Skills Insight. (2023). *Skills Insight Jobs and Skills Council Initial Workforce Plan*. https://skillsinsight.com.au/wordpress/wp-content/uploads/2023/11/Skills-Insight-Initial-Workforce-Plan-2023.pdf

Soder, K. J., & Brito, A. F. (2023). Enteric methane emissions in grazing dairy systems. *JDS Communications*, *4*(4), 324–328. https://doi.org/10.3168/jdsc.2022-0297

Soussana, J.-F., Lutfalla, S., Ehrhardt, F., Rosenstock, T., Lamanna, C., Havlík, P., Richards, M., Wollenberg, E. (Lini), Chotte, J.-L., Torquebiau, E., Ciais, P., Smith, P., & Lal, R. (2019). Matching policy and science: Rationale for the '4 per 1000 - soils for food security and climate' initiative. *Soil and Tillage Research*, *188*, 3–15. https://doi.org/10.1016/j.still.2017.12.002

Specht, L. (2020). *An analysis of culture medium costs and production volumes for cultivated meat*. https://gfi.org/wp-content/uploads/2021/01/clean-meat-production-volume-and-medium-cost.pdf

Talukder, S., Qiu, D., Thomson, P. C., Cheng, L., & Cullen, B. R. (2023). Impact of heat stress on dairy cow rumination, milking frequency, milk yield and quality in a pasture-based automatic milking system. *Animal Production Science*, *64*(1). https://doi.org/10.1071/AN22334

TNFD (Taskforce on Nature-related Financial Disclosures). (2024). *TNFD adopters list*. https://tnfd.global/engage/tnfd-adopters-list/

Tollefson, J. (2010). Intensive farming may ease climate change. *Nature*, *465*(7300), 853. https://doi.org/10.1038/465853a

The Next Economy. (2023). *Submission to Agriculture and Land Sectoral Plan Discussion Paper*. https://haveyoursay.agriculture.gov.au/agriculture-and-land-sectoral-plan

Treich, N. (2021). Cultured Meat: Promises and Challenges. *Environmental and Resource Economics*, *79*(1), 33–61. https://doi.org/10.1007/s10640-021-00551-3

UNEP (United Nations Environment Programme). (n.d.). *Our members: Net-Zero Banking Alliance*. Retrieved 15 July 2024, from https://www.unepfi.org/net-zero-banking/members/

UNEP. (2021). *Guidelines for Climate Target Setting for Banks*. https://www.unepfi.org/wordpress/wp-content/uploads/2021/04/UNEP-FI-Guidelines-for-Climate-Change-Target-Setting.pdf

United Nations Environment Programme (UNEP), Nairobi and International Union for Conservation of Nature (IUCN). (2021). *Nature-based solutions for climate change mitigation*. https://www.unep.org/resources/report/nature-based-solutions-climate-change-mitigation

UQ (University of Queensland). (2023). *Agriculture vs agribusiness*. https://study.uq.edu.au/stories/agriculture-vs-agribusiness

Viscarra Rossel, R. A., Zhang, M., Behrens, T., & Webster, R. (2024). A warming climate will make Australian soil a net emitter of atmospheric CO_2. *Npj Climate and Atmospheric Science*, *7*(1), 79. https://doi.org/10.1038/s41612-024-00619-z

Whittle, L., Lock, P., & Hug, B. (2019). *Economic potential for new plantation establishment in Australia Economic potential for new plantation establishment in Australia Department of Agriculture and Water Resources ii Economic potential for new plantation establishment in Australia Department of Agriculture and Water Resources iii Contents*. https://doi.org/10.25814/5c6e1da578f9a

Witt, T., Robinson, N., Palma, A. C., Cernusak, L. A., Pratt, S., Redding, M., Batstone, D. J., Schmidt, S., & Laycock, B. (2024). Evaluating novel biodegradable polymer matrix fertilizers for nitrogen- efficient agriculture. *Journal of Environmental Quality*, *53*(3), 287–299. https://doi.org/10.1002/jeq2.20552

Wong, L., Selvanathan, E. A., & Selvanathan, S. (2015). Modelling the meat consumption patterns in Australia. *Economic Modelling*, *49*, 1–10. https://doi.org/https://doi.org/10.1016/j.econmod.2015.03.002

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*(1), 56. https://doi.org/10.1038/ncomms1053

Zhou, D., Meinke, H., Wilson, M., Marcelis, L. F. M., & Heuvelink, E. (2021). Towards delivering on the sustainable development goals in greenhouse production systems. *Resources, Conservation and Recycling*, *169*, 105379. https://doi.org/https://doi.org/10.1016/j.resconrec.2020.105379

Resources

Sector summary

As the world decarbonises, Australia can continue as a world leading resource provider with a prosperous resources sector. The production of fossil fuels will decline in response to falling domestic and international demand. However, the sector can grow and diversify by expanding metals and minerals extraction and leveraging Australia's renewables comparative advantage to increase value-added processing onshore.

Australia can be a major exporter of critical minerals required for the clean energy transition. New and growing industries can create economic opportunities for affected workers and regional communities, with support from governments including for re-training and upskilling of workers and the provision of public infrastructure.

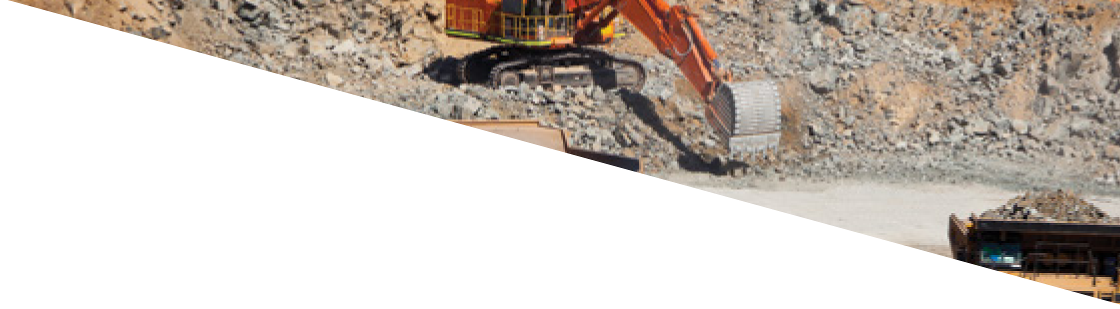
Emissions from the resources sector were 99 Mt CO_2-e in 2022, contributing to 23% of national emissions (CCA, 2024c). These were dominated by fossil fuel combustion and fugitive emissions from the mining, oil and gas subsectors. Decarbonisation of the sector requires widespread electrification, and deployment of fugitive abatement technologies in oil, gas and coal mining operations.

Electrification can play a significant role in reducing emissions from fuel combustion in the sector. Electric mining haulage and equipment is at pilot scale, with widespread adoption expected after 2030. In contrast, technologies to electrify gas and LNG operations, such as electric drives, are available now but require access to an abundant supply of firmed, cost-competitive renewable electricity through connection to the grid or off-grid generation.

Reducing fugitive emissions across oil and gas operations is also needed. This requires further development and widespread deployment of reservoir carbon capture and storage (CCS), and other abatement measures such as leak detection and repair programs and gas recovery systems. Deployment of methane mitigation technologies in underground coal mines, such as ventilation air methane (VAM) abatement technologies and gas drainage and utilisation, will be needed. Implementation of VAM abatement technologies is more nascent, with hurdles needing to be overcome before there is commercial-scale demonstration within Australia's coal mining regulatory environment.

Based on available technologies, several sources of emissions across the sector are expected to remain largely unabated while the activities continue. There are few opportunities to significantly reduce fugitive emissions from surface coal mines. For existing offshore oil and gas facilities, space constraints and difficulties accessing renewable electricity limit the opportunity to decarbonise.

Barriers to electrification and deployment of fugitive abatement measures across the sector include high upfront capital costs, integration challenges within existing facilities and the lack of access to a sufficient firmed supply of renewable electricity. Decarbonisation of the sector can be accelerated in the near to medium term with the right incentives in place to direct investment towards the long-lasting transformations required for onsite abatement, along with measures to improve emissions measurement, monitoring, reporting and verification. Timely development of shared infrastructure, such as renewable electricity generation and transmission, will be critical to this and require large-scale investment, coordination and planning.



R.1 Sector state of play

The resources sector comprises the mining, and oil and gas extraction and processing (including LNG production) subsectors. The resources sector contributes to approximately 13% of GDP (Appendix B) and accounts for more than two-thirds of Australia's total merchandise exports (DISR, 2024a). The sector employs more than 288,000 people, including 56,000 women (Appendix B).

R.1.1 Emissions profile of resources sector

In 2021-22, the resources sector was responsible for 99 Mt CO_2-e of emissions, which accounted for 23% of Australia's emissions (CCA, 2024c). As shown in Table R.1, there are five key emissions sources within the resources sector.

Table R.1: Resources sector emissions breakdown by key emissions source, 2021-22

Emissions source	Mt CO_2-e	Subsector share (%)
Fugitive emissions from coal mining	25	25
Fugitive emissions from oil and gas	20	21
Fuel combustion in mining	20	20
Fuel combustion in oil and gas	22	22
Onsite electricity generation (across all resources subsectors)	11	11
Other	1	1
Total	99	100

R.1.1.1 Fugitive emissions

Fugitive emissions are the intentional or unintentional release of greenhouse gases that occur during the extraction, processing and delivery of fossil fuels to the point of final use. Fugitive emissions from solid fuels arise from the production of coal, and emissions from decommissioned mines and coal mine waste gas flaring. Fugitive emissions from oil and gas extraction, production and transport involve venting, flaring, leakage, evaporation and storage losses (DCCEEW, 2023). Fugitive emissions account for almost half of the resources sector's emissions, with 25% from coal mining and 21% from oil and gas operations (CCA, 2024c).

Underground coal mines are responsible for 63% of coal mine fugitive emissions. Fugitive emissions from coal mining are predominantly methane emissions (95%). In oil and gas operations, 74% of fugitive emissions are carbon dioxide and 26% are methane (CCA, 2024c). For gas processing and LNG plants, the reservoir carbon dioxide that is vented after it has been removed from the gas during processing represents a large portion of reported fugitive emissions. The remaining fugitives result from flaring, venting of gas from equipment and general leaks from equipment onsite.

The reporting of fugitive emissions at the facility level has come under scrutiny in recent years due to reported discrepancies arising from comparisons with new sources of data, including from satellites. Australia's emission estimation methods, including facility-level methods under the NGER scheme, are subject to annual review and update (DCCEEW, 2024). In its 2023 Review of the National Greenhouse and Energy Reporting Legislation, the authority considered this issue and made several recommendations to improve the accuracy of fugitive methane emissions estimates in Australia through the use of higher order methods and independent verification of facility-level emissions estimates using top-down measurements (CCA, 2023).

R.1.1.2 Fuel combustion

Fuel combustion accounts for 43% of the sector's emissions, with 22% from oil and gas operations and 20% from all mining operations. The authority estimates that around 91% of these emissions are from the combustion of gaseous fuels within gas processing and LNG production facilities (CCA, 2024a), which are typically used to drive the turbines for compression or liquefaction of the gas. Within mining facilities, the authority estimates around 68% of fuel combustion emissions are from the combustion of diesel fuel (CCA, 2024a), which is used to power the mining haulage fleet and equipment.

R.1.1.3 Onsite electricity generation

The remaining 11% of the resources sector's emissions are due to the combustion of fuel to generate electricity for use onsite. The authority estimates at least 50% of Safeguard facilities within the resources sector (excluding coal mines) are not grid-connected[1] (CCA, 2024a). Many of these facilities are in remote areas including the Pilbara, central WA, northern QLD and the NT (CCA, 2024a).

1 Based on the authority's analysis of facilities under the Safeguard Mechanism.

In contrast to the rest of the sector, most coal mines are grid-connected (CCA, 2024a).

R.1.2 Decarbonisation of the resources sector is underway

The authority found various emissions reductions activities are already being implemented across the resources sector. Within the oil and gas subsector, this includes:

- energy efficiency such as more efficient turbines, waste heat recovery units, air and water chilling systems and the use of activated-methyldiethanolamine (aMDEA) for the removal of reservoir CO_2 (APPEA, 2020; Woodside, 2021; WorleyParsons & Australia Pacific LNG, 2014)
- fugitive abatement measures including replacement of existing devices with lower emitting alternatives (such as air-driven pneumatic devices), installation of new devices (such as boil-off gas compressors) and leak detection and repair programs (APPEA, 2020)
- hybrid electric-gas turbine drives or electrification of smaller compressors (APPEA, 2020; Woodside, 2021)
- sequestration of reservoir CO_2 at the Gorgon LNG facility (APPEA, 2020; Woodside, 2018, 2021)[2]

Electrification of the LNG facilities on Curtis Island near Gladstone has been investigated. A pre-feasibility study supported by the federal and Queensland governments was conducted in 2022 (Commonwealth of Australia, 2022). Santos also completed a feasibility study assessing the partial electrification of the Gladstone LNG facility and has commenced pre- front-end engineering design activities. Their project aims to replace gas-fired power generation units with grid-connected electricity and is also considering electrifying some of the gas-fired refrigerant compression (Santos, 2023a).

Within the mining subsector, current emissions reduction activities include:

- energy efficiency such as haul automation and mine plan optimisation (BHP, 2022; Fortescue, 2020; Rio Tinto, 2024)
- trials of battery electric and hydrogen fuel cell electric haulage trucks, trains and equipment (First Mode, 2023; Fortescue, 2024; Rio Tinto, 2022; South32, 2024)
- pre- and post-mining drainage in underground coal mines.

More broadly across the resources sector, smaller scale off-grid renewable electricity generation is beginning to come online or being actively explored (Fortescue, 2023; Rio Tinto, 2023; Whitehaven Coal, n.d.). This is not only to address emissions associated with current onsite fossil fuel-based electricity generation, but also to ensure facilities have access to sufficient electricity as they electrify.

Declining domestic production of coal and gas will contribute to a reduction in Australia's emissions. In the IEA's NZE Scenario[3], by 2030 global coal demand declines by 45%, and oil and gas demand declines by around 20%. By 2050, the share of fossil fuels in the total energy supply drops to less than 20% compared to around 80% of global total energy supply in 2022 (IEA, 2023c).

> Major changes to Australia's resources sector are expected as Australia and the world decarbonises.

This includes:

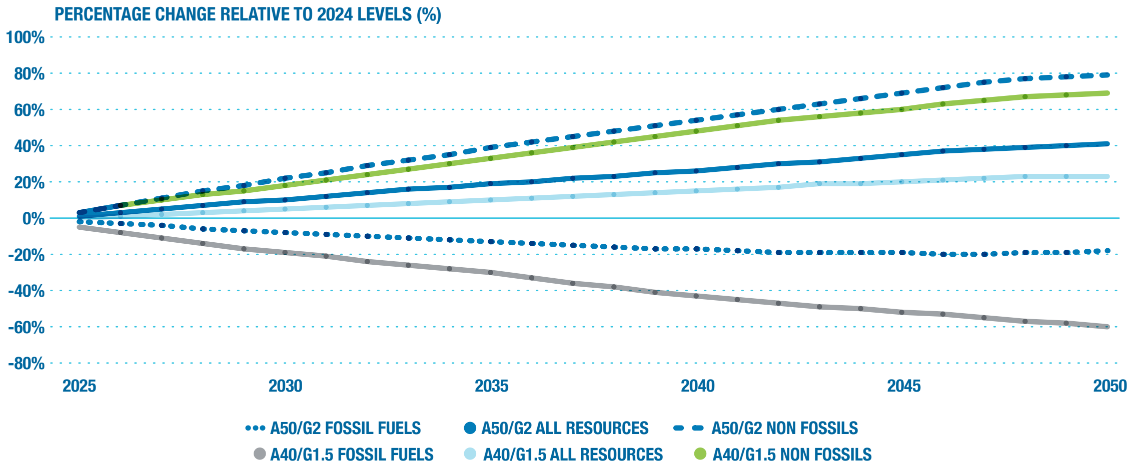
- a reduction in production of fossil fuels as domestic and international demand declines
- ramping up of emerging industries, including the extraction and processing of critical minerals, and production of green metals such as green iron.

In modelling by CSIRO, commissioned by the authority, the output from the fossil fuels subsector declines steadily to 2050, whereas the non-fossil fuels subsector continues to grow (Figure R.1). However, global market volatility and geopolitical influences will impact the opportunity for the Australian resources sector.

2 At the time of publication Santos' Moomba CCS facility had not commenced operations, updated as of 15/07.

3 The IEA's Net Zero Emissions Scenario (NZE Scenario) shows a pathway for the global energy sector to achieve net zero emissions by 2050 (IEA, 2023a).

Figure R.1: Modelled resources sector output as a percentage change relative to 2024 levels, under A50/G2 and A40/G1.5 modelling scenarios, 2025-2050



Source: CSIRO modelling in GTEM commissioned by the Climate Change Authority

The authority also notes that various companies, such as Woodside, ExxonMobil and Santos, are investing in new carbon management services including Carbon Capture and Storage (CCS) and hydrogen production with CCS (ExxonMobil, 2024; Santos, n.d.; Woodside, 2024).

R.2 Existing and prospective technologies

The authority focused its analysis of the opportunities to achieve emissions reductions in the mining, gas extraction and processing, and LNG production subsectors, which account for around 90% of emissions from the Australian resources sector (CCA, 2024a). The authority's analysis was informed by published literature where available, and views expressed during stakeholder engagement.

R.2.1 Decarbonising onsite electricity generation

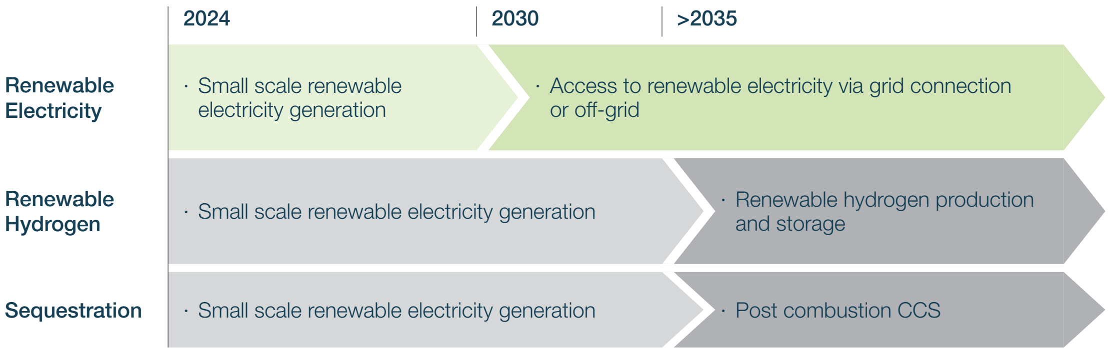
Onsite power generation from the combustion of fuels is responsible for 11% of emissions across the resources sector, predominantly at facilities that are not connected to the grid (CCA, 2024a). The oil and gas subsector (including gas processing and LNG production) accounts for 60% of the emissions from onsite electricity generation, and the mining subsector accounts for the remaining 40%.

Table R.2 outlines the key levers identified by the authority to decarbonise onsite electricity generation across the entire resources sector. Figure R.2 details the prospective decarbonisation pathways for each lever.

Table R.2: Key emissions reduction levers for reducing emissions from onsite electricity generation

Emissions reduction opportunity		Readiness	Barriers to adoption
Renewable electricity	Access to renewable electricity through grid connection or off-grid generation.	Commercial	· Lack of supporting infrastructure · High CAPEX · Obtaining land access and environmental approvals · Limited incentive under the Safeguard Mechanism
Renewable hydrogen production and storage	Access to renewable hydrogen or onsite renewable hydrogen production and storage.	R&D	· High CAPEX · Low technology maturity
Post combustion CCS	Capture and sequestration of CO^2 in the flue gas from the power generators.	R&D	· Low technology maturity · High CAPEX · Obtaining land access and environmental approvals

Figure R.2: Prospective decarbonisation pathways to reduce onsite electricity generation through renewable electricity, renewable hydrogen or sequestration



> Access to a sufficient supply of firmed renewable electricity is a key enabler to decarbonise other key sources of emissions across the Australian resources sector through electrification.

Facilities across the sector are already accessing smaller scale renewable electricity through onsite generation or power purchase agreements (PPAs) with independent power producers (IPPs) (Fortescue, 2023; Rio Tinto, 2023; Whitehaven Coal, n.d.). Future larger scale renewable electricity generation will be realised through similar approaches or by connecting to the grid.

The authority heard from industry of several key challenges in switching from onsite electricity generation using fuel combustion to renewable electricity, as described below.

Accessing a firmed supply of electricity

Most facilities require a reliable source of electricity to run their operations day and night. Options for firming include gas back-up or energy storage technologies such as batteries. Batteries with the required energy storage to provide the firming capability do exist, but the authority heard that they are typically cost prohibitive.

Accessing a sufficient and flexible supply of electricity

Significantly higher electricity demand and increased variability of demand loads are expected as facilities electrify. Industry has identified the ability to provide sufficient power to support the electrification of the sector as a key concern.

'…increasing the supply of low emission, affordable and reliable electricity is critical for decarbonisation of the resources sector. Many members advise that facility decarbonisation pathways to the mid-2030's predominantly involve process electrification, which is reflected in the significant increase in forecast industry electricity demand over the next decade. CME recommends that increasing low emission generation capacity should be prioritised, with improved co-ordination across Australia required to accelerate the transition.'

The Chamber of Minerals and Energy of Western Australia submission, 2024

Some grid-connected mines are establishing additional onsite electricity generation capability to ensure sufficient electricity supply due to concerns regarding the capacity of the grid. The authority is of the view that the expected electricity demand from the sector as it decarbonises and how this will be met is a notable current information gap, also noted in Minerals Council of Australia's submission to the authority's 2024 Issues paper.

'Delivery of renewable energy projects and transmission infrastructure within a limited timeframe is a critical enabler…..

There is little information available on additional electricity demand estimates coming from electrification of mining fleets, and potential additional electricity demand from an expansion in critical minerals processing.'

Minerals Council of Australia submission, 2024

Limited incentives under the Safeguard Mechanism

The authority heard from industry that there are limited incentives to replace electricity generated onsite through combustion of fuels with imported renewable electricity (either from the grid or off-grid but not co-located within the facility). As only scope 1 emissions generated within a facility boundary are included within the baseline, importing renewable electricity would result in a facility's gross emissions and baseline both reducing. Woodside Energy's submission to the authority's 2024 Issues paper identified this as a disincentive towards importing lower carbon electricity from a separate facility (not sited within facility boundaries as defined for reporting under the National Greenhouse and Energy Reporting (NGER) framework).

'The current Safeguard Mechanism (SGM) production variables disincentivise opportunities to drive emissions reductions through import of renewable or lower-carbon electricity from a separate facility. This disincentive occurs because these opportunities reduce emissions as well as the facility's baseline, due to a reduction in electricity production at the facility.'

Woodside submission, 2024

Cost of connection to the grid or local networks, and/or required upgrades to electricity infrastructure can be inefficient for some facilities.

Many of the facilities across the resources sector are not connected to the grid and are located in remote areas making connection to the grid prohibitively expensive. Additionally, upgrades to electricity infrastructure necessary to supply increased power demands can also be prohibitively expensive.

R.2.2 Decarbonising mining

Key subsectors within mining include coal mining, iron ore mining, and all other metals and minerals mining. In addition to the emissions from onsite electricity generation, the main sources of emissions across mining are fugitive emissions from coal mining and the combustion of diesel from mining haulage and equipment.

R.2.2.1 Emissions reduction levers for fugitive emissions from coal mining

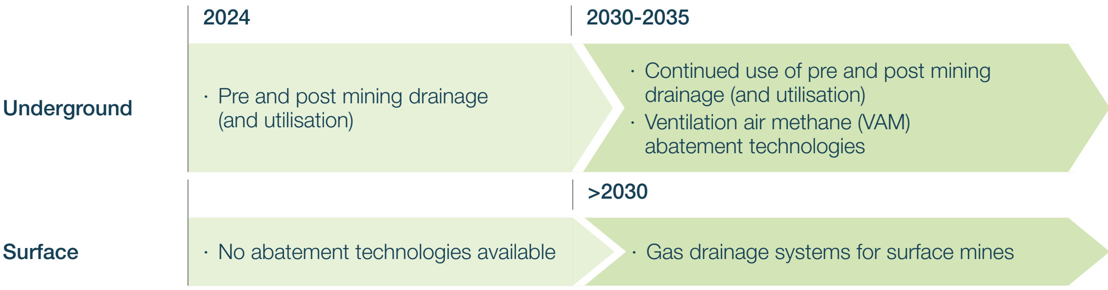
Fugitive emissions from surface and underground coal mines account for 25% of emissions from Australia's resources sector, and account for the majority 74% of emissions from Australia's coal mines (CCA, 2024c). These emissions are the result of the fracturing of gas-bearing strata when coal is extracted (Clean Energy Regulator, 2023). The amount of gas released varies considerably across different sites due to variations in the gas content and composition across coal basins.

The key levers identified by the authority for reducing these emissions are outlined in Table R.3. The technologies applicable to a particular mine depend on its characteristics, including whether it is a surface or underground mine, the gassiness of the mine and the gas composition of the fugitive emissions (e.g. methane or carbon dioxide). Figure R.3 outlines the prospective decarbonisation pathways for underground and surface mines.

Table R.3: Key emissions reduction levers for fugitive emissions from coal mining

Emissions reduction levers		Readiness	Barriers to adoption
Ventilation air methane (VAM) abatement technologies	Destruction or utilisation of the captured ventilation air methane from underground mines through thermal or catalytic oxidation, or concentration.	R&D to Commercial	· Low technology maturity · Safety risk · Safety regulation and approvals process · Difficulty integrating within existing facility
Gas drainage systems (and utilisation) for surface mines	Capture of gas from the coal seam, through bore holes into a pipeline collection system, and utilisation (such as electricity generation, pipeline injection or flaring).	R&D	· Low technology maturity · Lack of enabling regulatory environment · Lead time required to drain gas ahead of mining operations
Gas drainage systems (and utilisation) for underground mines	Capture of gas from the coal seam, through bore holes into a pipeline collection system, and utilisation (such as electricity generation, pipeline injection or flaring).	Commercial	· Cost to purify gas for utilisation · Lack of supporting infrastructure for utilisation

Figure R.3: Prospective decarbonisation pathways for fugitive emissions from underground and surface coal mines



In addition to the above key levers in Table R.3, the authority also heard of the potential use of CCS to abate fugitive emissions from coal mines.

Underground coal mines

Both gas drainage systems and VAM abatement technologies can be applied to underground mines. Gas drainage systems are already implemented at underground coal mines. Safety regulations across Australian jurisdictions require the methane concentration within the ventilated air of an underground coal mine to remain below a safe operating limit (NSW Government, 2014; Queensland Government, 2022). The introduction of gas drainage techniques in Australian gassy mines was necessary to complement ventilation systems to satisfy these requirements (KPMG, 2021). The cost of drilling additional bore holes and longer lead times ahead of mining are the barriers to further uptake of gas drainage systems in underground mines. Barriers to further utilisation of the drained gas through electricity generation or pipeline injection include cost, low or fluctuating methane concentrations and access to pipeline infrastructure.

In contrast, the implementation of VAM abatement technologies in Australia is more nascent and has significant uncertainties around its effectiveness, cost, commercial readiness, and deployment timeframes. While commercial-scale deployment of this technology has been demonstrated with multiple commercial VAM projects currently in operation, mostly in China and the US (CSIRO & Global Methane Initiative, 2018; U.S. Environmental Protection Agency, 2018), the authority heard that safety considerations remain a significant barrier to deployment within the Australian coal mining regulatory environment.

> *'The only currently available technologies to abate VAM involve a high-temperature, regenerative thermal oxidisation (RTO) system (~1000C). This is yet to be widely implemented due to concerns with meeting Australian mine safety requirements.'*
>
> Mineral Council of Australia submission, 2024

It is important to note that the regulatory environments in which these systems have been deployed overseas are very different to that of Australia, but the authority observed a knowledge gap of how these systems could be safely deployed domestically.

The authority also notes that deployment of these systems at even only a small portion of coal mines could result in meaningful emissions reduction. Approximately 60% of the fugitive methane emissions from underground coal mines are from ventilation air methane systems (EY Port Jackson Partners (internal assessment, unpublished), 2024). Anglo American have recently undertaken initial concept studies and are working to progress from a pre-feasibility to feasibility stage in VAM abatement with the design and construction of an industrial unit at its Moranbah North mine in Queensland (AngloAmerican, 2023).

Surface coal mines

There are limited opportunities to reduce fugitive emissions from surface coal mines due to their diffuse nature. It is possible to apply gas drainage techniques to surface mines, but few commercially viable applications have been reported globally (United Nations Economic Commission for Europe, 2021). The authority heard from mining companies that technical challenges remain. These include lower gas concentrations, draining multiple seams and longer drainage times required ahead of mining compared with underground coal mines. The authority observed that there is limited understanding of the potential application of gas drainage systems to surface coal mines in Australia, including the efficacy, cost, and realistic timeline of implementing such systems.

> *'While methane drainage is a mature technology for underground mining, it is novel for open-cut mining. This is especially the case at established mines where the integration of gas drainage and handling is likely to lead to mine planning and other operational challenges. These interactions need to be better understood, as do the geological conditions that are favourable (or otherwise) for effective gas drainage in this new and untested open-cut mining context.'*
>
> BHP submission, 2024

R.2.2.2 Emissions reduction levers for mining haulage and equipment

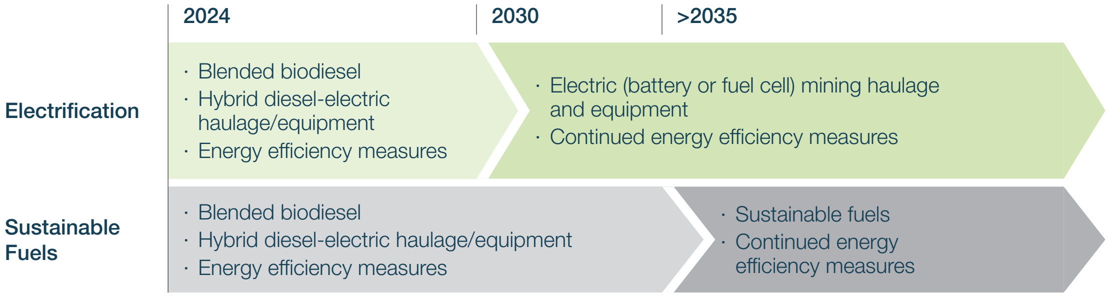
Combustion of diesel fuel to power the mining haulage fleet and equipment (e.g. dump trucks, diggers, loaders, excavators, drills and shovels) is responsible for around 14% of the resources sector's emissions (CCA, 2024a). The key levers for decarbonising mining haulage and equipment identified by the authority are outlined in Table R.4. Figure R.4 outlines the prospective decarbonisation pathways for mining haulage.

Table R.4: Key emissions reduction levers for reducing emissions from mining haulage and equipment

Emissions reduction levers		Readiness	Barriers to adoption
Electrification of haulage and equipment	Battery and tethered electric trucks and mining equipment. Trolley assist systems where haul trucks are connected to an overhead cable to power the electric drive.	Demonstration	· Low technology maturity · High CAPEX · Integration of the required supporting infrastructure to existing mines · Lack of supply of electric haulage and equipment · Lack of supply of firmed renewable electricity
Fuel cell electric trucks	Hydrogen fuel cell-powered haulage trucks and mining equipment.	Demonstration	· Low technology maturity · High CAPEX · Lack of supply of renewable hydrogen
Sustainable fuels	Fuel switching to more lower carbon fuels such as biodiesel or renewable diesel.	Commercial	· High OPEX · Lack of supply of sustainable fuels

In addition to the above key levers in Table R.4, the authority also heard the potential to use in pit crushing and conveying to reduce emissions from mining haulage and equipment.

Figure R.4: Prospective decarbonisation pathways for battery and fuel-cell electric mining haulage and equipment and sustainable fuels



Nearer term opportunities expected to be deployed ahead of the key abatement levers include continued energy efficiency improvement (such as haul automation and mine plan optimisation), the use of blended biodiesel as a drop-in fuel and hybrid diesel-electric haulage and equipment (Clean Energy Finance Corporation & Minerals Research Institute of Western Australia, 2022).

While the authority heard that battery-electric or tethered-electric haulage and equipment is the technology pathway most companies anticipate following, hydrogen fuel cell electric haulage is still being actively pursued by some. Both these technologies are at the R&D or demonstration phase, with various trials underway or announced (BHP, 2023). Partnerships and initiatives between industry and the original equipment manufacturers (OEMs) have been identified as an essential driver to accelerate technology development (BHP, 2023; ICMM, 2022). Widespread electrification of mining haulage is not expected to begin until 2030-2035 (BHP, 2023; KPMG, 2023), with the larger mining companies being the likely first adopters. It is also expected that underground mines will electrify first due to the enabling regulatory environment, co-benefits of switching from diesel to electric equipment in terms of noise and emissions reduction, and the commercial availability of electric equipment for underground operations.

A key prerequisite for mine site electrification is access to a sufficient supply of flexible but firmed electricity. Significantly higher electricity demand and increased variability of demand loads are expected as mines electrify. The ability to provide sufficient electricity, either from onsite generation or the grid, to support the electrification of mines has been identified as a key concern by industry. Electrification of a mine site also requires significant enabling infrastructure, including: charging stations, transmission lines and overhead power lines for trolley assist systems. The dynamic nature of some mining operations presents a challenge for the installation of such semi-permanent infrastructure due to continually evolving mine plans.

Various mining companies have proposed the use of sustainable fuels as a long-term decarbonisation strategy due to their benefits as drop-in fuels and the operational flexibility they offer. However limited supply of sustainable fuels (and no current domestic supply chain) and expected competition from other sectors with limited alternatives, such as aviation, introduce uncertainty around the viability of this pathway to decarbonise mining haulage.

> *'We would also observe that some existing solutions such as biofuels are currently cost prohibitive, are supply constrained and have a range of issues in relation to ethical providence which may make them unsuited for large scale deployment and use.'*
>
> Glencore submission, 2024

The authority observed there is an information gap relating to the future production, use and import of biofuels in Australia.

R.2.2.3 Emissions pathways for the mining subsector

Based on the analysis of the key levers to decarbonise mining discussed in the previous sections, the authority has developed the following possible emissions pathways for the coal mining, iron ore mining and all other mining subsectors that could be achieved through implementation of particular decarbonisation levers (CCA, 2024b). This ground up analysis considered several factors including estimated timing of implementation, barriers to implementation and emissions reduction potential for each decarbonisation lever.

Table R.5: Possible decarbonisation pathway for the coal mining subsector, showing the relevant emissions reduction levers and corresponding reduction in emissions

	Emissions reduction opportunity (as % of total subsector emissions)	Estimated start of implementation
Battery or tethered electric ancillary fleet	10	2025
Battery electric haul trucks	13	2030
VAM and gas drainage	29	2030
Open cut drainage	5	2035

Table R.6: Possible decarbonisation pathway for all other mining, showing the relevant emissions reduction levers and corresponding reduction in emissions

	Emissions reduction opportunity (as % of total subsector emissions)	Estimated start of implementation
Battery or tethered electric ancillary fleet	23	2025
Source renewable energy via Independent Power Provider	26	2028
Battery electric haul trucks	31	2030
Not considered	12	N/A

The emission sources from all other mining that the authority did not consider in this analysis largely relate to the processing and refining of metals and minerals within the mine sites.

R.2.3 Decarbonising gas processing and LNG

The key sources of emissions for gas processing and LNG production (in addition to the emissions from onsite electricity generation) are from the compression and liquefaction of gas, vented reservoir CO_2, and all other fugitive emissions from flaring, venting from other equipment and general leaks.

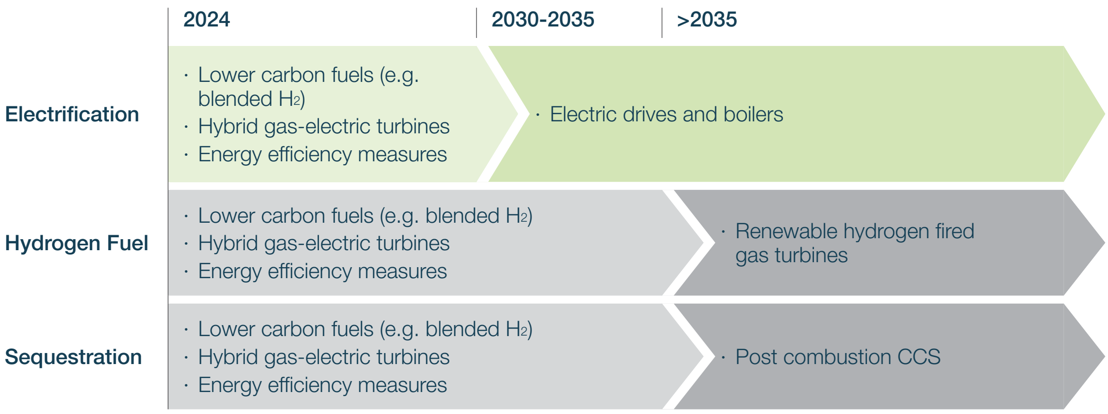
R.2.3.1 Emissions reduction levers for the compression and liquefaction of natural gas in gas and LNG production

Combustion of gaseous fuels, predominantly consumed to drive turbines for the compression and liquefaction of natural gas, is responsible for around 20% of emissions from the Australian resources sector (Advisian, 2022; CCA, 2024a). Table R.7 outlines the key levers identified by the authority to decarbonise this process. Figure R.5 outlines the prospective decarbonisation pathways for each key lever.

Table R.7: Key emissions reduction levers for decarbonising the compression and liquefaction of natural gas

Emissions reduction opportunity		Readiness	Barriers to adoption
Electrification	Installation of electric drives or boilers.	Commercial	· High CAPEX · Difficulty integrating within existing facilities · Lack of supply of firmed renewable electricity · Production downtime
Hydrogen fired gas turbines	Replacement of natural gas with hydrogen to fuel the turbines.	R&D	· Low technology maturity · Lack of supply of renewable hydrogen
Post combustion CCS	Capture and sequestration of CO^2 in the flue gas from gas-fired turbines.	R&D	· Low technology maturity · High CAPEX · Obtaining land access and environmental approvals · Difficulty integrating within existing facilities · Lack of supporting infrastructure

Figure R.5: Prospective decarbonisation pathways for decarbonising the compression and liquefaction of natural gas through electrification, hydrogen fuel and sequestration



Near term opportunities include energy efficiency (such as more efficient gas turbines), use of lower carbon alternative fuels such as blended hydrogen, and hybrid electric-gas turbine drives (APPEA, 2020; Woodside, 2021).

Electric drives and boilers are already commercially available. However, retrofitting such equipment within an existing facility is challenging. This is due to the large land requirements to build electric equipment alongside existing assets, or the long periods of shutdown to replace existing equipment with the associated cost of production downtime being a barrier to uptake. Operators would also need to consider alternative uses for the end flash gas following electrification of the assets. Additionally, if a facility does not have access to a firmed supply of renewable electricity, there can be limited emissions reductions when electrifying these processes. This is due to the electricity being otherwise generated onsite through fuel combustion. An Advisian study examining opportunities for reducing fuel combustion emissions in the mining and energy sector forecast zero uptake for electrification of refrigerant compressors and boilers at LNG facilities under a BAU scenario. Under a more optimistic 'high technology scenario', the study forecast that electrification of refrigerant compressors may be implemented at Curtis Island LNG plants.

The use of hydrogen fuel for gas turbines is a less proven technology. However, the authority heard from several major industry companies of their intended use of hydrogen as a key lever to decarbonise their operations.

Post-combustion CCS is a demonstrated technology. However, it is yet to be deployed at a commercial scale for natural gas processing[4]. Integration challenges within existing facilities are expected to be the main barriers to deployment.

The authority heard there are very limited opportunities to electrify or deploy post combustion CCS at offshore facilities due to the difficulty in accessing renewable electricity and space constraints.

R.2.3.2 Emissions reduction levers for reservoir CO_2 in gas and LNG production

Carbon dioxide that is removed from gas during processing (known as reservoir CO_2) and then vented to the atmosphere often contributes to a large portion of fugitive emissions for gas processing and LNG production facilities (Chevron, 2024b; Shell, 2020; Woodside, 2021). Capture and sequestration of the reservoir CO_2, known as reservoir CCS, is the only available technology to abate these emissions (see in Table R.8). It is important to note that reservoir CCS is a different approach to post-combustion CCS (which instead is targeting the CO_2 from a flue gas stream). Reservoir CCS is used to abate the reservoir CO_2 emissions that would otherwise be vented to the atmosphere and has significant cost advantages (Wood Mackenzie, 2021).

4 Based on a review of Global CCS Institute's Facilities database for 'Commercial CCS facilities' in 'operation', as at 15/06/2024

Table R.8: Key emissions reduction lever to abate reservoir CO^2 emissions

Emissions reduction opportunity		Readiness	Barriers to adoption
Reservoir CCS	Capture and sequestration of the CO_2 that is removed during the processing of the natural gas.	Commercial	· High CAPEX · Obtaining land access and environmental approvals · Difficulty integrating within existing facilities · Lack of supporting infrastructure

This technology has been in use at Chevron's Gorgon facility since 2019 (Chevron, 2024a) but has experienced technical challenges since commencement (CSIRO, 2023). Under the terms of the environmental approval from the WA government, Chevron is required to sequester 80% of the CO_2 emissions extracted from the Gorgon reservoir (WA Government, 2009). This CCS facility was designed to capture and inject 4 Mt of CO_2 each year (Chevron, 2021). Chevron reported that in the 2022-2023 financial year, 5.0 Mt CO_2-e of reservoir CO_2 was removed from the incoming natural gas stream, and 1.7 Mt CO_2-e of the reservoir CO_2 was injected. Chevron cites the key reason for the shortfall between the volume of reservoir CO_2 extracted and injected is the management of injection rates to ensure reservoir pressure remains within an acceptable range (Chevron, 2023).

Santos' reservoir CCS project at the Moomba gas processing facility is expected to commence in 2024 (Santos, 2023b). Inpex's Ichthys LNG facility was designed to be able to retrofit the facility with CCS capability in the future (APPEA, 2020). Inpex was awarded the greenhouse gas assessment permit in the offshore Petrel sub-basin in 2022 and is exploring the development of a large-scale CCS facility (Inpex, n.d.).

In relation to the deployment of reservoir CCS in Australia, the authority heard from industry that:

- Deployment is more likely at onshore gas and LNG processing facilities that are extracting gas from reservoirs with higher CO_2 concentration (due to the space constraints at offshore gas and LNG processing facilities and low CO_2 concentration reservoirs being less suitable due to the increased cost associated with concentration and compression of the gas).
- Cost and approvals processes are significant barriers.
- Purchasing offsets may be more cost effective in the longer term for facilities with shorter lifespans if abatement using reservoir CCS is not available in the near term.

R.2.3.3 Emissions reduction levers for all other fugitive emissions in gas and LNG production

All other fugitive emissions in the gas and LNG subsectors result from flaring, venting from other equipment and general leaks. There are a range of measures and technologies currently available to reduce these fugitive emissions shown in Table R.9.

Table R.9: Key emissions reduction levers to reduce fugitive emissions in gas and LNG subsectors

Emissions reduction opportunity		Readiness	Barriers to adoption
Fugitive abatement measures	Range of measures including: · replacing existing devices with lower-emitting versions, · installing new devices that can reduce or avoid vented emissions, · leak detection and repair programs, · more stringent regulations around non-emergency venting and flaring, and · equipment standards.	Commercial	· High CAPEX · Difficulty integrating within existing facilities

There are a range of measures and technologies commercially available to reduce fugitive emissions within oil and gas operations. Replacement of existing devices with lower-emitting versions include replacing pneumatic pumps with air instruments or electric pumps, replacing fuel motors with electric motors and converting wet seals to dry seals. Installation of new devices that can avoid or reduce emissions include boil off gas compressors and flare gas recovery systems. Leak detection and repair programs aid in the location and repair of fugitive leaks and can be applied across the supply chain. In addition to these technologies, other abatement measures include regulation of non-emergency venting and flaring, and equipment standards (APPEA, 2020; IEA, 2023b; Rystad Energy, 2023). The IEA estimates that many of these measures could be deployed in Australia at no net cost (IEA, 2024).

R.2.3.4 Emissions pathways for the gas processing and LNG subsectors

Based on the analysis of the key decarbonisation levers in the previous sections, the authority has developed the following possible emissions reduction pathways for gas processing and LNG subsectors that could be achieved through implementation of particular decarbonisation levers (CCA, 2024b). This ground up analysis considered factors including estimated timing of implementation, barriers to implementation and emissions reduction potential for each decarbonisation lever.

Table R.10: Possible decarbonisation pathway for the onshore gas processing and LNG subsectors, showing the relevant emissions reduction levers and corresponding reduction in emissions

	Emissions reduction opportunity (as % of total subsector emissions)	Estimated commencement
Leak detection and repair	2	2025
Flare and boil off gas recovery	7	2028
Connect to grid for auxiliary power	14	2030
Compressor electrification	48	2030-2035
CCS of reservoir CO_2	26	2030

R.3 Barriers, opportunities and enablers

R.3.1 Think global, act local

With significant reserves of critical metals and minerals required for the global energy transition, Australia is well placed to seize the opportunities, and leverage its competitive strengths, to grow and diversify metals and minerals extraction and increase value added processing onshore. This will help Australia improve resilience of supply chains while increasing sovereign critical minerals processing capacity.

R.3.2 Technical constraints

Some technologies to decarbonise the sector are not yet mature. Trials of electric mining haulage are currently being conducted, with widespread deployment not expected until after 2030. Drainage systems for surface coal mines and VAM abatement technologies for underground coal mines have not been widely demonstrated within Australia with technical hurdles still to be overcome.

The ability to retrofit or integrate new assets or infrastructure within an existing facility is a significant barrier for the deployment of technologies including electric drives or CCS within gas and LNG facilities, or the supporting infrastructure required to electrify a mine site. The associated production downtime to integrate new assets or equipment into an existing facility can also be a significant barrier to deployment.

R.3.3 Green premiums

The high cost of implementing most emissions reduction levers is a significant barrier across the resources sector. These technology deployment opportunities are typically capital intensive, and for some technologies that are more nascent there is also significant uncertainty around the cost of deployment.

The limited remaining lifespan of facilities reduces the incentive to invest in decarbonisation technologies, with viable business cases being difficult to develop when the payback period exceeds the life of the facility.

Allocating public capital expenditure committed to developing common infrastructure in parallel with significant development planning can act as a key enabler to kickstart the private finance necessary to build out the sector.

> The high cost of implementing most emissions reduction levers is a significant barrier across the resources sector.

Accelerated innovation and RD&D for nascent and less mature technologies through partnerships between industry, manufacturers and researchers, and access to funding mechanisms such as grants and concessional loans.

Accelerated uptake of reservoir CCS through the development of common use CCS infrastructure, including pipelines and storage, signalling from government on the role of CCS to decarbonise the sector, and improved regulation for the sequestration of reservoir CO^2.

Alternate business models which shift the investment towards OPEX costs rather than CAPEX costs where there is limited appetite for high upfront investment (such as facilities with limited lifespan or independent contractors who are responsible for the operation of the emissions intensive equipment).

R.3.4 Supply chain constraints

The lack of access to a sufficient supply of firmed low emissions electricity is currently a key barrier to the electrification of the resources sector. The authority heard that it is difficult for industry to create a business case to electrify their operations without a reliable source of firmed low emissions electricity. This challenge arises due to the remote locations of many resource projects.

There are uncertainties in the supply and availability of key decarbonisation levers including electric mining haulage and equipment and alternative fuels.

> *'There are also likely to be supply chain pressures when electrified fleets become widely available for deployment, so it will not be feasible to replace all global mining equipment fleets simultaneously.'*
>
> Glencore submission, 2024

Government actions could accelerate access to firmed renewable electricity by developing common use infrastructure, renewable energy hubs and incentivising all Safeguard facilities to switch to renewable electricity.

R.3.5 Planning, approvals and coordination

A number of submissions to the authority's 2024 Issues paper highlighted that approval processes for decarbonisation activities can be long, inefficient and duplicative between state and federal jurisdictions.

> *'A crucial consideration for AIGN members revolves around the approvals processes for developing new projects which could contribute to Australia's decarbonisation pathway. In short, Australia's approvals policy framework is no longer fit for purpose'.*
>
> Australian Industry Greenhouse Network submission, 2024

> *'One key issue we believe is important in enabling deployment of emission abatement or reduction technologies, is the streamlining of regulatory approvals and removal of duplication in policy across federal and state jurisdictions. This is a major area of concern to Glencore.'*
>
> Glencore submission, 2024

> *'Improving legislation to ensure approvals are provided in a timely manner and with certainty is a key enabler of Australia's energy transition, by providing a framework to streamline the approvals process required for renewable energy projects, the transmission network, and the energy and critical minerals sectors.'*
>
> Woodside submission, 2024

R.3.6 Regulatory inconsistency and gaps

Improved regulation within oil and gas operations for non-emergency venting and flaring, and equipment standards, could accelerate adoption. This should be done in conjunction with measures to improve measurement, monitoring, reporting and verification of fugitive methane emissions under the NGER scheme, as highlighted in the authority's 2023 Review of the National Greenhouse and Energy Reporting Legislation (CCA, 2023).

R.3.7 Workforce and skills shortages

The transition will require complex and digital skills from the resources workforce. The government's Critical Minerals Strategy aims for greater onshore refining (DISR, 2023). Processing capabilities represent a new driver for skilled roles that do not exist within the mining workforce (DISR, 2023). The use of automated and digital technologies in mining is giving rise to higher paying jobs and opportunities for remote and flexible work (AUSMASA, 2023).

The growth of remote operations centres is seeing an increase in workers being able to support mining operations from metropolitan rather than remote locations, providing an opportunity to expand workforce diversity (Australia Resources and Energy Group, 2018). These jobs will require higher digital skills and many need specialised job qualifications (AUSMASA, 2023).

The electrification of the mining industry will also see a need for upskilling (AUSMASA, 2023). Electrification will involve an ongoing transition of mobile plant and light vehicles away from diesel and on to battery-electric systems which will require workers on mine sites to be upskilled to support both diesel and electric plant vehicles (AUSMASA, 2023).

> *'…shortages of necessary skillsets risks delaying the transition. In an increasingly automated and decarbonised world, Australia's mining and energy sectors will need new skillsets and capabilities to prosper. Decarbonisation will radically increase the demand for electrical and trade skills and implementing more technology in the continued shift towards automation will require higher order capabilities across analytics and data science.'*
>
> BHP submission, 2024

The resources sector has an ageing workforce which could exacerbate pre-existing shortages. The number of young people choosing to work in the mining sector is being outstripped by those approaching retirement (AUSMASA, 2023).

A barrier to attracting younger workers to the sector is a negative perception of the mining industry and a lack of understanding of its role in the net zero transition. Research conducted by Year 13 noted that almost three quarters of respondents felt the mining industry did more harm than good and only 27% knew that the industry mined lithium, a necessary critical mineral for transition technologies (AUSMASA, 2023; Year 13, 2023). The same research also noted that career advice in relation to the mining industry is lacking.

Critical minerals mining may offer opportunities for coal mining workforces to be retrained and re-engaged. Analysis by the International Energy Agency (2021) found that reaching the goals of the Paris Agreement (climate stabilising at 'well below 2°C global temperature rise') would require a quadrupling of mineral requirements for clean energy technologies by 2040. Australia has some of the world's largest recoverable resources of critical minerals (Geoscience Australia, 2022) and could build a new critical minerals industry. These jobs could see regional workers moving to a different jurisdiction or to metropolitan hubs from which fly-in, fly-out operations are staged (AUSMASA, 2023).

As bioenergy industries develop, workers in petroleum refining are likely to experience demand for their skills in biofuels (JSA, 2023). Increasing global and domestic use of batteries to store renewable energy may increase demand for mining workers for lithium, graphite, nickel, cobalt and aluminium (JSA, 2023).

To attract younger workers, government and industry could communicate career opportunities and advise how the sector is addressing social and environmental issues. This includes the role the resource sector plays in providing the raw materials required for renewable technologies that will help Australia reach net zero.

Strong investment in VET across Australia could ensure the resources workforce has the skills needed for the transition. Investment in regions undergoing major workforce transitions (such as coal mining regions) is critical. Access to adequate training, facilities and educators must be available to not only meet the labour demands of the transition but to allow regions to benefit by producing local professionals.

R.3.8 Benefit sharing

> Decarbonising and diversifying the mining industry could unlock a new generation of high-wage, high-skilled, high-tech jobs in metals and minerals extraction and processing. This will help support Australia's regions by providing new employment opportunities while sustaining secure jobs for local businesses.

The growth of the critical minerals sector could provide opportunities to create intergenerational social and economic benefits for First Nations people. There will also be significant challenges involved in finding new work opportunities for First Nations people currently employed in emissions-intensive areas of the resources sector, including in low-skilled roles at risk of becoming redundant through automation.

Box R.1: First Nations opportunities in critical minerals growth

Growth of the critical mineral industry, being supported by more than $7 billion in federal funding (DISR, 2024b), can improve outcomes for First Nations people if combined with investments to reform engagement, negotiation, and delivery of projects.

Over the past few decades, progress has been made in increasing First Nations employment within the mining industry (Parmenter & Barnes, 2021). Many mining companies have entered into land use agreements which guarantee ongoing employment and training to First Nations communities (Commonwealth of Australia, 2016). Despite this progress, significant variability exists in employment and economic outcomes between communities (Taylor, 2018). As mining activities ramp-up to meet demand for critical minerals required to support renewables, regional planning is necessary to ensure that First Nations communities can share in associated benefits (Owen et al., 2022).

First Nations will have a crucial role to play in the growing critical minerals industry given the significant overlap between mineral reserves and the First Nations Estate[5] (Burton et al., 2024b). First Nations communities located alongside existing critical minerals projects have not always shared equitably in socio-economic benefits (Burton et al., 2024a). In communities which already host, or are likely to host future critical minerals projects, First Nations households can earn as little as 12% as much as non-Indigenous households, on a per capita basis (Burton et al., 2024a). Increasing automation of mines and the use of ‘fly-in fly-out’ workers may also limit opportunities for local workers, especially for First Nations people who are typically employed in lower skill roles (Holcombe & Kemp, 2019; Paredes & Fleming-Muñoz, 2021; Storey, 2010). Given these existing barriers to benefit sharing with First Nations, it must not be assumed that government investment in the critical minerals industry will result in better outcomes.

If barriers to benefit sharing with First Nations are to be overcome, representative bodies require equal access to information and expertise so that they can secure ongoing workforce and equity partnerships (Clean Energy Council and KPMG, 2024).

5 Also known as Australia’s Indigenous land and forest estate

During consultation, the authority heard that whilst First Nations representatives have an intimate understanding of their Country, they often lack the technical expertise required to assess the impacts of developments on future generations (CCA First Nations Roundtable, 2024). Existing governance frameworks for the mining industry are generally reliant on 'negotiated agreements' which are determined on a project-by-project basis (Kung et al., 2022). First Nations require clear, accessible and accurate information and appropriate education to understand impacts to community, so that they can negotiate from a position of strength (Tomlinson, 2019). Both government and industry have a role to play in supporting this capacity uplift (Clean Energy Council and KPMG, 2024).

An independent inquiry into the destruction of ancient rockshelters in Western Australia's Juukan Gorge found that, without clear, enforceable standards for what constitutes 'informed' consent, past industry conduct has caused significant harm to First Nations Cultural Heritage (Joint Standing Committee on Northern Australia, 2021). The inadequacy of historical policy settings for protecting First Nations values from the impacts of mining has been detailed in academic analysis (Annandale et al., 2021; Burton et al., 2024a; Graetz, 2015; Kemp et al., 2023) and previous submissions from First Nations stakeholders, which detail lasting deleterious impacts to Community, Culture and Country (Janke et al., 2021).

Changes to legislative frameworks to ensure Free, Prior and Informed Consent (FPIC) in the expansion of critical mineral mining could reduce the risk of future harm to First Nations communities and values. The government's Critical Minerals Strategy commits to 'genuine engagement and collaboration with First Nations communities that promotes benefit sharing and respects the land and water rights and interests of First Nations people and communities' (DISR, 2023). The authority also welcomes the federal government's acceptance of a recommendation from the Juukan Gorge inquiry that '*the Australian Government legislate a new framework for cultural heritage protection at the national level… [which]… should set out the minimum standards for state and territory heritage protections consistent with relevant international law (including the United Nations Declaration on the Rights of Indigenous People UNDRIP)…*' (DCCEEW, 2022). Implementation of these cultural heritage reforms is an important pre-requisite to ensuring socially responsible expansion of critical minerals mining and refinement in Australia.

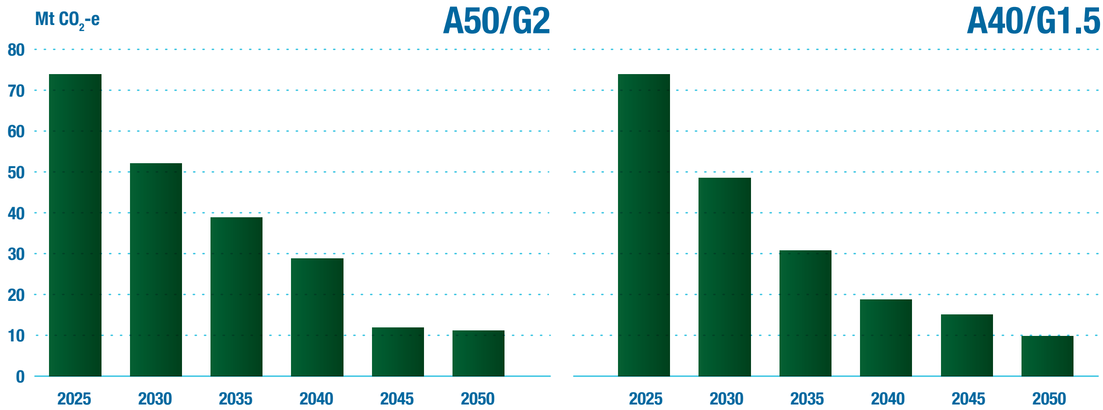
R.3.8 Information and data gaps

There is room to improve understanding of the application and safe deployment of gas drainage systems for surface coal mines and VAM abatement technologies.

R.4 Emissions pathways

In addition to the ground up analysis, the authority also commissioned modelling (conducted by CSIRO) of emissions from the resources subsector from 2025 to 2050 under various scenarios. The results for the A50/G2 and A40/G1.5 scenarios are shown in Figure R.6.

Figure R.6: Modelled emissions for the resources subsector, under A50/G2 and A40/G1.5 scenarios, 2025-2050



Source: CSIRO modelling in AusTIMES commissioned by the Climate Change Authority

Modelled emissions under both scenarios show significant reductions for the resources sector out to 2050. These reductions in emissions are driven by:

- Emissions from combustion reducing across the mining sector, partly due to fuel switching. Final energy use shows a sharp decline in diesel, which is predominantly replaced by electricity and, to a lesser extent, hydrogen.
- Emissions from fuel combustion declining within gas extraction, partly due to fuel switching from natural gas to electricity.
- Fugitive emissions decreasing across the coal mining, and oil and gas subsectors (due in part to the reduction in fossil fuel production as shown in Figure R.1).

A comparison between the authority's estimates of emissions from the Resources sector in 2050 from the ground up analysis and modelling are presented in Table R.11 (CCA, 2024b). It is important to note the emissions estimate from the ground up analysis does not take into account any change in production levels for any subsector. Estimates from the modelling scenarios incorporate projected changes in production (shown in Figure R.1) but do not explicitly account for efficiency gains through improved recycling.

Table R.11: Projections of emissions reductions to 2050 using estimates from AusTIMES modelling and ground-up analysis

Reference: emissions in 2022 were 99 Mt CO_2-e Subsector	Projected emissions reductions to 2050 (Mt CO_2-e)[6]		
	Modelling Scenario A50/G2	Modelling Scenario A40/G1.5	Ground-up
Coal mining	20	23	12
All other mining	11	11	14
Oil and gas extraction and processing (including LNG production)	30	28	28
Total	60	62	54

Projected emissions reductions were calculated as the difference between base year emissions and the projected 2050 emissions from each model. In AusTIMES the base year for the abatement calculation was 2025 and in ground-up estimates the base year for estimates was 2022.

R.4.1 Residual emissions

The modelling results indicate there could be 10-11 Mt CO_2-e of remaining emissions in the resources sector by 2050.

For some sources of emissions, there are limited opportunities for direct abatement in the near term due to lack of mature technologies. This includes decarbonising mining haulage and equipment, and abating fugitive emissions from underground and open cut coal mines.

In the longer term, the authority identified several sources of emissions which are currently expected to largely remain unabated out to 2050 due to the limited opportunities to decarbonise. These include emissions from offshore oil and gas facilities (due to space constraints and restricted access to renewable electricity) and fugitive emissions from open cut coal mines (due to unknown technical feasibility of open cut gas drainage systems).

6 Emissions estimates from the modelling scenarios take into account modelled changes in production (shown in Figure R.1), whereas the ground up analysis estimates assume constant production levels between 2022 to 2050 for all subsectors.

R.5 References

Advisian. (2022). *Stationary energy (excluding electricity) - mining and energy technology and efficiency opportunities.* https://www.dcceew.gov.au/sites/default/files/documents/stationary-energy-excluding-electricity-mining-energy-technology-efficiency-opportunities-advisian.pdf

AngloAmerican. (2023). *Sustainability Performance Update*. https://www.angloamerican.com/~/media/Files/A/Anglo-American-Group-v5/PLC/investors/investor-presentations/sustainability-performance-script-h1-2023.pdf

Annandale, M., Meadows, J., & Erskine, P. (2021). Indigenous forest livelihoods and bauxite mining: A case-study from northern Australia. *Journal of Environmental Management*, *294*, 113014. https://doi.org/https://doi.org/10.1016/j.jenvman.2021.113014

APPEA. (2020). *Industry Action on Emissions Reduction*. https://www.appea.com.au/wp-content/uploads/2020/06/Industry-Action-on-Emissions-Reduction.pdf

AUSMASA (Mining and Automotive Skills Alliance). (2023). *Workforce Plan The Future is Now*. https://ausmasa.org.au/media/b5mjmwen/ausmasa-initial-workforce-plan-2023.pdf

Australia Resources and Energy Group. (2018). *A New Horizon. Guiding Principles for the Future of Work*. https://www.areea.com.au/wp-content/uploads/2018/12/20191203_AMMA_A_New_Horizon_Guiding_Principles_for_the_Future_of_Work.pdf

BHP. (2022). South Flank autonomous haulage rolls out. https://www.bhp.com/news/articles/2022/01/south-flank-autonomous-haulage-rolls-out

BHP. (2023). Operational decarbonisation investor briefing: Presentation & speech. https://www.bhp.com/-/media/documents/media/reports-and-presentations/2023/230621_operationaldecarbonisationinvestorbriefing_slidesspeakernotes.pdf

Burton, J., Kemp, D., Barnes, R., & Parmenter, J. (2024a). A socio-spatial analysis of Australia's critical minerals endowment and policy implications. *Resources Policy*, *88*, 104448. https://doi.org/https://doi.org/10.1016/j.resourpol.2023.104448

Burton, J., Kemp, D., Barnes, R., & Parmenter, J. (2024b). Mapping critical minerals projects and their intersection with Indigenous peoples' land rights in Australia. *Energy Research & Social Science*, *113*, 103556. https://doi.org/https://doi.org/10.1016/j.erss.2024.103556

CCA. (2023). *2023 Review of the National Greenhouse and Energy Reporting Legislation*. https://www.climatechangeauthority.gov.au/sites/default/files/documents/2023-12/2023%20NGER%20Review%20-%20for%20publication.pdf

CCA. (2024a). *Analysis based on emissions reported under the National Greenhouse and Energy Reporting (NGER) Scheme*.

CCA. (2024b). *Internal analysis informed by Worley, literature, stakeholder engagement and emissions reported under the National Greenhouse and Energy Reporting (NGER) scheme*.

CCA. (2024c). *National Sectoral Pathways Emissions Mapping based on estimates published in Australia's National Greenhouse Accounts and emissions reported under the National Greenhouse and Energy Reporting (NGER) Scheme*.

Chevron. (2021). *Chevron Australia CO_2 injection milestone*. https://australia.chevron.com/news/2021/co2-injection-milestone

Chevron. (2023). *Gorgon Gas Development and Jansz Feed Gas Pipeline. Environmental Performance Report*. ABU220700410 ENV-GOR-EPR 2021-2022 (chevron.com)

Chevron. (2024a). *Reducing greenhouse gas emissions for a lower carbon future*. https://australia.chevron.com/what-we-do/gorgon-project/carbon-capture-and-storage

Chevron. (2024b). *Wheatstone LNG Plant Greenhouse Gas Management Plan*. https://australia.chevron.com/-/media/australia/our-businesses/documents/wheatstone-ghg-management-plan.pdf

Clean Energy Council and KPMG. (2024). *Leading Practice Principles: First Nations and Renewable Energy Projects*. https://assets.cleanenergycouncil.org.au/documents/resources/reports/Leading-Practice-Principles-First-Nations-and-Renewable-Energy-Projects.pdf

Clean Energy Finance Corporation, & Minerals Research Institute of Western Australia. (2022). *Technology solutions for decarbonisation: Mining in a low-emissions economy*. https://www.cefc.com.au/media/omzlxjpl/cefc_mriwa_technology-solutions-for-decarbonisation.pdf

Clean Energy Regulator. (2023). *Estimating emissions and energy from coal mining guideline*. https://cer.gov.au/document/estimating-emissions-and-energy-coal-mining-guideline

Commonwealth of Australia. (2016). *Working With Indigenous Communities - Leading Practice Sustainable Development Program for the Mining Industry.* https://www.industry.gov.au/sites/default/files/2019-04/lpsdp-working-with-indigenous-communities-handbook-english.pdf

Commonwealth of Australia. (2022). *Pre-Feasibility study into Curtis Island LNG Electrification*. https://federalfinancialrelations.gov.au/agreements/pre-feasibility-study-curtis-island-lng-electrification

CSIRO. (Commonwealth Scientific and Industrial Research Organisation). (2023). *Australia's Carbon Sequestration Full Report.* https://research.csiro.au/tnz/australias-carbon-sequestration-potential/

CSIRO, & Global Methane Initiative. (2018). *Expert Dialogue on Ventilation Air Methane (VAM)*. https://www.globalmethane.org/documents/res_coal_VAM_Dialogue_Report_20181025.pdf

DCCEEW. (Department of Climate Change Energy the Environment and Water). (2022). *Australian Government response to the Joint Standing Committee on Northern Australia's: A Way Forward: Final report into the destruction of Indigenous heritage sites at Juukan Gorge and Never Again: Inquiry into the destruction of 46,000 year old caves at the Juukan Gorge in the Pilbara region of Western Australia- Interim Report*. https://www.dcceew.gov.au/sites/default/files/documents/australian-response-to-destruction-of-juukan-gorge.pdf

DCCEEW. (2023). *Australian National Greenhouse Accounts Factors.* https://www.dcceew.gov.au/sites/default/files/documents/national-greenhouse-account-factors-2023.pdf

DCCEEW. (2024). *National Greenhouse and Energy Reporting Scheme*. https://www.dcceew.gov.au/climate-change/emissions-reporting/national-greenhouse-energy-reporting-scheme

DISR. (Department of Industry Science and Resources). (2024a). *Resource and Energy Quarterly March 2024*. https://www.industry.gov.au/sites/default/files/2024-03/resources-and-energy-quarterly-march-2024.pdf

DISR. (2023). *Critical Minerals Strategy 2023–2030*. https://www.industry.gov.au/sites/default/files/2023-06/critical-minerals-strategy-2023-2030.pdf

DISR. (2024b). *Investments to capitalise on Australia's critical minerals and the global clean energy transition*. https://www.industry.gov.au/news/investments-capitalise-australias-critical-minerals-and-global-clean-energy-transition

ExxonMobil. (2024). *Low Carbon Solutions: Low carbon technology*. https://lowcarbon.exxonmobil.com/lower-carbon-technology/our-technology#Deliveringrealworldprogress

EY Port Jackson Partners. (2024). *Internal assessment, unpublished.*

First Mode. (2023). *World's Largest Fuel Cell Electric Vehicle Completes Successful Year of Trials*. https://firstmode.com/updates/worlds-largest-fcev-vehicle-completes-trials/

Fortescue. (2020). *Fortescue automation deployment reaches significant milestone*. https://fortescue.com/news-and-media/news/2022/07/01/fortescue-automation-deployment-reaches-significant-milestone-2020-06-23

Fortescue. (2023). *Fortescue Climate Transition Plan: The Road to Real Zero*. https://fortescue.com/docs/default-source/announcements-and-reports/climate-transition-plan.pdf?sfvrsn=45690705_11

Fortescue. (2024). *Fortescue's first operational electric excavator reaches one million tonne milestone*. https://fortescue.com/news-and-media/news/2024/03/22/fortescue-s-first-operational-electric-excavator-reaches-one-million-tonne-milestone

Geoscience Australia. (2022). *Australia's Identified Mineral Resources 2022*. https://www.ga.gov.au/digital-publication/aimr2022

Graetz, G. (2015). Energy for whom? Uranium mining, Indigenous people, and navigating risk and rights in Australia. *Energy Research & Social Science*, *8*, 113–126. https://doi.org/https://doi.org/10.1016/j.erss.2015.05.006

Holcombe, S., & Kemp, D. (2019). *Indigenous employment futures in an automated mining industry*. https://smi.uq.edu.au/indigenous-employment-futures-automated-mining-industry

ICMM (International Council on Mining and Metals). (2022). *Collaboration for Innovation: Accelerating the Implementation of Zero Emission Vehicles for the Mining and Metals Industry*. https://www.icmm.com/en-gb/stories/2022/accelerating-implementation-of-zero-emission-vehicles

IEA. (International Energy Agency). (2021). *The Role of Critical Minerals in Clean Energy Transitions*. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

IEA. (2023a). *Global Energy and Climate Model*. https://www.iea.org/reports/global-energy-and-climate-model

IEA. (2023b). *Global Methane Tracker: Strategies to reduce emissions from oil and gas operations*. https://www.iea.org/reports/global-methane-tracker-2023/strategies-to-reduce-emissions-from-oil-and-gas-operations

IEA. (2023c). *Net Zero Roadmap A Global Pathway to Keep the 1.5 °C Goal in Reach*. https://iea.blob.core.windows.net/assets/9a698da4-4002-4e53-8ef3-631d8971bf84/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf

IEA. (2024). *Methane Tracker: Interactive database of country and regional estimates for methane emissions and abatement options*. https://www.iea.org/data-and-statistics/data-tools/methane-tracker

Inpex. (n.d.). *Bonaparte Carbon Capture and Storage*. Retrieved July 10, 2024, from https://www.inpex.com.au/media/kg5ekprl/bonaparte-carbon-capture-and-storage.pdf

Janke, T., Cumpston, Z., Hill, R., Woodward, E., Harkness, P., S, von G., & Morrison, J. (2021). Indigenous: People and industry. In *Australia State of the environment 2021*. Australian Government Department of Agriculture, Water and the Environment. https://doi.org/10.26194/3JDV-NH67

Joint Standing Committee on Northern Australia. (2021). *Final report into the destruction of Indigenous heritage sites at Juukan Gorge*. https://www.aph.gov.au/Parliamentary_Business/Committees/Joint/Former_Committees/Northern_Australia_46P/CavesatJuukanGorge/Report

JSA. (2023). *The Clean Energy Generation*. https://www.jobsandskills.gov.au/publications/the-clean-energy-generation

Kemp, D., Kochan, K., & Burton, J. (2023). Critical reflections on the Juukan Gorge parliamentary inquiry and prospects for industry change. *Journal of Energy & Natural Resources Law*, *41*(4), 379–402. https://doi.org/10.1080/02646811.2022.2156202

KPMG. (2021). *Bowen Basin Concept Study*. https://www.resources.qld.gov.au/__data/assets/pdf_file/0008/1592855/bowen-basin-study-final-report.pdf

KPMG. (2023). *Review of IPG1 Greenhouse Gas Management Plan*. https://www.epa.wa.gov.au/sites/default/files/Referral_Documentation/Appendix%207%20GHGMP%20Peer%20Review%20%28KPMG%202023%29.pdf

Kung, A., Holcombe, S., Hamago, J., & Kemp, D. (2022). Indigenous co-ownership of mining projects: a preliminary framework for the critical examination of equity participation. *Journal of Energy & Natural Resources Law*, *40*(4), 413–435. https://doi.org/10.1080/02646811.2022.2029184

NSW Government. (2014). *Work Health and Safety (Mines) Regulation 2014*. https://legislation.nsw.gov.au/view/html/inforce/current/sl-2014-0799

Owen, J. R., Kemp, D., Harris, J., Lechner, A. M., & Lèbre, É. (2022). Fast track to failure? Energy transition minerals and the future of consultation and consent. *Energy Research & Social Science*, *89*, 102665. https://doi.org/https://doi.org/10.1016/j.erss.2022.102665

Paredes, D., & Fleming-Muñoz, D. (2021). Automation and robotics in mining: Jobs, income and inequality implications. *The Extractive Industries and Society*, *8*(1), 189–193. https://doi.org/https://doi.org/10.1016/j.exis.2021.01.004

Parmenter, J., & Barnes, R. (2021). Factors supporting indigenous employee retention in the Australian mining industry: A case study of the Pilbara region. *The Extractive Industries and Society*, *8*(1), 423–433. https://doi.org/https://doi.org/10.1016/j.exis.2020.11.009

Queensland Government. (2022). *Coal Mining Safety and Health Regulation 2017*. https://www.legislation.qld.gov.au/view/pdf/inforce/current/sl-2017-0165

Rio Tinto. (2022). *Rio Tinto purchases first battery-electric trains for the Pilbara*. https://www.riotinto.com/news/releases/2022/Rio-Tinto-purchases-first-battery-electric-trains-for-the-Pilbara

Rio Tinto. (2023). *Climate Change Report 2023*. https://data-api.marketindex.com.au/api/v1/announcements/XASX:RIO:3A636910/pdf/inline/2023-climate-change-report

Rio Tinto. (2024). *Pioneering automation and robotics in mining*. https://www.riotinto.com/en/mn/about/innovation/automation

Rystad Energy. (2023). *Methane Tracking Technologies Study*. https://www.edf.org/sites/default/files/documents/Methane%20Tracking%20Technologies%20Study%20Oct%2018%202023.pdf

Santos. (n.d.). *Santos Energy Solutions*. Retrieved July 2, 2024, from https://www.santos.com/santos-energy-solutions/

Santos. (2023a). *Climate Change Report 2023*. https://www.santos.com/wp-content/uploads/2023/02/Climate-Change-Report-2023.pdf

Santos. (2023b). *Moomba CCS progressing at pace and on track for 2024*. https://www.santos.com/news/moomba-ccs-progressing-at-pace-and-on-track-for-2024/

Shell. (2020). *Prelude FLNG Environment Plan 2020*. https://docs.nopsema.gov.au/A763756

South32. (2024). *Electric mobile equipment trials underway at Cannington.* https://www.south32.net/news-media/latest-news/electric-mobile-equipment-trials-underway-at-cannington

Storey, K. (2010). Fly-in/fly-out: implications for community sustainability. *Sustainability*, 2(5), 1161–1181. https://www.mdpi.com/2071-1050/2/5/1161

Taylor, J. (2018). *Change in Aboriginal Social Indicators in the Pilbara: 2001-2016*. https://www.aph.gov.au/DocumentStore.ashx?id=1c958d56-21cd-4241-a018-5fc3ccbe3cfe&subId=670352

Tomlinson, K. (2019). Indigenous rights and extractive resource projects: negotiations over the policy and implementation of FPIC. *The International*

Journal of Human Rights, *23*(5), 880–897. https://doi.org/10.1080/13642987.2017.1314648

United Nations Economic Commission for Europe. (2021). *Best Practice Guidance for Effective Management of Coal Mine Methane at National Level: Monitoring, Reporting, Verification and Mitigation*. https://unece.org/sites/default/files/2022-07/2119167_E_ECE_ENERGY_139_WEB.pdf

U.S. Environmental Protection Agency. (2018). *Coal Mine Methane Developments in the United States*. https://www.epa.gov/sites/default/files/2016-03/documents/cmm_developments_in_the_us_2013.pdf

WA Government. (2009). *Gorgon Gas Development Revised and Expanded Proposal: Barrow Island Nature Reserve*. https://www.epa.wa.gov.au/sites/default/files/Ministerial_Statement/00800.pdf

Whitehaven Coal. (n.d.). *Whitehaven Solar Farm Project*. Retrieved June 28, 2024, from https://whitehavencoal.com.au/whitehaven-solar-farm-project/

Wood Mackenzie. (2021). *CCS could have material impact on carbon emissions of LNG projects*. https://www.woodmac.com/press-releases/ccs-could-have-material-impact-on-carbon-emissions-of-lng-projects

Woodside. (2018). *World First Offshore Battery*. https://www.woodside.com/media-centre/news-stories/story/world-first-offshore-battery

Woodside. (2021). *Pluto LNG Facility Greenhouse Gas Abatement Program*. https://www.woodside.com/docs/default-source/our-business---documents-and-files/pluto---documents-and-files/pluto-lng-facility-greenhouse-gas-abatement-program.pdf?sfvrsn=7ebd04e3_19

Woodside. (2024). *Lower Carbon Services: Pursuing lower carbon energy sources*. https://www.woodside.com/what-we-do/new-energy/lower-carbon-services

WorleyParsons, & Australia Pacific LNG. (2014). *Australia Pacific LNG Project Commissioning and Start-Up Environmental Management Plan*. https://aplng.com.au/wp-content/uploads/2021/08/Commissioning_and_Start-Up_Management_Plan.pdf

Year 13. (2023). *What Gen Zs Think of Mining*. https://year13.com.au/business/reports/what-gen-zs-think-of-mining

Built environment

BUILT ENVIRONMENT

Sector summary

The built environment sector has a clear and potentially rapid decarbonisation pathway, with the required technologies being almost all commercially available now. A net zero built environment would have high energy performance, be well-adapted to climate change impacts, and be highly liveable.

A decarbonised built environment requires a vision with a sequenced, national approach to drive abatement and unlock opportunities for businesses and consumers. This could deliver significant benefits for Australians, including improved living standards and wellbeing, lower costs of housing and energy, and resilience to climate change hazards.

Significant decarbonisation opportunities lie in electrification and energy efficiency, including by replacing gas appliances with high-efficiency and grid-integrated electric ones. Decarbonisation also requires abatement of refrigerant gas emissions by adoption of low-Global Warming Potential (GWP) gases and addressing gaps in end-of-life management of refrigerant gases in appliances.

The sector's decarbonisation is dependent on other sectors: it relies on decarbonisation of the electricity grid, and lower-carbon building materials manufactured by the industry sector. Other opportunities include consideration of climate change in urban planning. Planning has the potential to reduce emissions at the precinct level, including by improving building design and implementing circular economy principles to reduce embodied and lifecycle emissions of materials.

Challenges to reducing built environment emissions include high upfront costs for some technologies and retrofits, workforce shortages and supply chain pressures. There are also challenges arising from incomplete or non-existent data, including for comprehensive product comparisons, building energy efficiency ratings and embodied carbon ratings. Improving this information could aid consumers' choices for lower-emissions products and drive changes to building practices.

Greater coordination between levels of government on measures to drive decarbonisation provides opportunities to accelerate abatement in the built environment, including in relation to enhancements of the National Construction Code, expansion of energy rating schemes, data and disclosures, and phasing out gas connections in residential and commercial buildings.

BE.1 Sector state of play

The built environment is the residential and commercial buildings, and physical infrastructure (such as footpaths, roads and bridges), that provide the settings for human activities. This chapter discusses the direct emissions associated with the operation of the built environment (scope 1 emissions) and the emissions associated with electricity consumption in the built environment (scope 2 emissions). Emissions associated with the manufacture of the components of the built environment (e.g. cement and steel) are discussed in a reference Box BE.1 on scope 3 emissions and are covered in detail in the Industry and Waste chapter of this report.

Currently, there are about 11 million residential buildings and 1 million commercial buildings in Australia (ABS, 2022a; DCCEEW, 2022b). Most of these buildings have poor energy efficiency, with houses built before 2003 having an average Nationwide House Energy Rating Scheme (NatHERS) rating of 1.8 stars (CSIRO, 2021). The minimum requirement for new houses and apartments is 7 stars (ABCB, 2023a).

The sector contributes to Australia's economy through trades and the construction industry. Construction-related subsectors in the built environment sector account for about 7% of Australia's gross domestic product (Appendix B) (Master Builders Australia, 2024).

BE.1.1 Emissions profile

Scope 1 emissions in the built environment were 28 Mt CO_2-e in 2022, about 7% of Australia's emissions (see Table BE.1 and Appendix B) (CCA, 2024). The sector's scope 2 emissions, arising from the generation of grid electricity used by the sector, amounted to 77 Mt CO_2-e, or 49% of Australia's total emissions from electricity generation. These electricity-based emissions were the largest of any sector in 2022 (see Appendix B) (CCA, 2024).

Residential and commercial scope 2 emissions are 41 Mt CO_2-e and 35 Mt CO_2-e respectively, and together account for nearly all scope 2 built environment emissions. Scope 2 emissions from construction are relatively small at 1 Mt CO_2-e (DCCEEW, 2022a).

The authority has not quantified scope 3 emissions embodied in building materials or enabled by assets, as these emissions are counted in the scope 1 emissions of other sectors in this review. Embodied emissions are discussed in Box BE.1.

Table BE.1: Breakdown of the built environment's scope 1 and scope 2 emissions sources, and percentage share of total scope 1 and 2 emissions, 2022, see Appendix B. Source: (CCA, 2024; DCCEEW, 2024a)[1 2]

Subsector	Mt CO_2-e*	Subsector share of total scope 1 and 2 (%)*
Scope 1 emissions		
Construction	2	2
Commercial stationary combustion	6	5
Residential stationary combustion	11	10
Commercial refrigeration	6	5
Domestic refrigeration	0	0
Stationary air-conditioning	3	3
Fugitive emissions from fuels - natural gas	0	0
Aerosols and metered dose inhalers	0	0
Wastewater treatment and discharge - unsewered population	0	0
Total scope 1 emissions	28	27
Scope 2 emissions		
Construction	1	1
Commercial services (scope 2)	35	33
Residential	41	39
Total scope 2 emissions	77	73
Total emissions (scope 1 and scope 2)	106	100

* All values are greater than zero, but some subsectors are listed as zero in the table due to the authority's rounding. The subsectors listed as zero cumulatively account for a total of 1 Mt CO_2-e or 4% of scope 1 emissions.

BE.1.2 Current trends and future changes

There is significant work to do to decarbonise the built environment. Analysis indicates the sector could reduce emissions by 69% on 2005 levels by 2030 (DCCEEW, 2019). However, current and proposed Australian policies are projected to achieve only an 11% reduction on 2005 levels by 2030 (DCCEEW, 2019).

Onsite electricity generation through residential rooftop solar photovoltaic (PV) systems has been an important driver of decarbonisation. There are over 3.4 million rooftop solar PV systems installed, generating over 9% of Australia's electricity in 2022 (CEC, 2023). In addition, an estimated 50,000 household battery systems were installed in 2022, up from 34,731 in 2021 (CEC, 2023).

Electrification and energy efficiency create reduced energy costs for consumers and emissions, but policy incentives to drive further improvements are needed. The 2022 National Construction Code (NCC) mandated new residential buildings meet 7-star equivalent energy ratings and ensure space is reserved for solar PV panels (ABCB, 2023a). However, jurisdictions have not uniformly implemented the NCC, and retrofitting buildings remains a significant challenge (ABCB, 2023b; Sustainability Victoria, 2015; C. White et al., 2023). Building Ministers have also agreed that climate resilience should be a specific objective for the Australian Building Codes Board from 2025 and this is expected to be reflected in future NCC requirements (DISR, 2024c).

1 The figures in Table BE.1 differ from those being used by the Built Environment Sector Plan as part of the Australian Government's Net Zero Plan. These differences are explained in Appendix B.

2 The consideration of scope 2 emissions by the built environment sector is in contrast to other sectors. These emissions occur in the electricity and energy sector.

All levels of government are currently implementing policies for the sector, including:

- Energy performance reporting programs such as NatHERS and the National Australian Built Environment Rating System (NABERS) (NABERS, 2024; NatHERS, 2024)
- Policies to improve energy efficiency, such as the Trajectory for Low Energy Buildings and the National Energy Performance Strategy (DCCEEW, 2018; DCCEEW, 2024e)
- The Greenhouse and Energy Minimum Standards (GEMS) program, which establishes minimum energy efficiency requirements for certain appliances (Australian Government, 2024a)
- 'White certificate' energy efficiency schemes in New South Wales, Victoria, South Australia and the Australian Capital Territory (S. White, 2024)
- The phase out of gas connections in buildings in the ACT and Victoria (ACT Government, 2021; DTP, 2023).

These policies remain patchy and inconsistent across jurisdictions and levels of government.

BE.2 Existing and prospective technologies

During expert consultation and research, the authority found that most technologies needed to decarbonise the built environment sector are already technically ready and commercially available (Table BE.2).

Table BE.2: Summary of the largest emissions sources in the built environment and identified abatement levers, see Appendix B. Source: (CCA, 2024; DCCEEW, 2022a)

Emissions source	Percent of sector emissions	Priority abatement lever to address emissions source	Readiness	Barriers to adoption
Residential and commercial stationary combustion (scope 1)	· ~58% of scope 1 BE emissions (2022) · 15% of total BE emissions (2022)	Electrification	Commercially available	· High upfront cost. · Challenges of retrofitting some buildings. · Absence of a gas phase-out plan.
Residential and commercial electricity use (scope 2)	· ~98% of BE scope 2 emissions (2022)	On-site electricity generation and storage	Commercially available	· High cost of storage options such as batteries can be prohibitively expensive. · Lower technical readiness of vehicle-to-grid storage systems.
		Energy performance and digitalisation	Most approaches are technically ready	· Lower technical readiness. · Potential workforce shortages.
		Grid integration	Technically ready	· Compatibility of local grid infrastructure and interoperability between systems. · Social license and approvals.
		Thermal efficiency	Commercially available	· High upfront cost. · Lack of financial or regulatory incentives for landlords to upgrade properties. · Standards and regulation vary across jurisdictions.
Residential and commercial refrigeration and stationary air-conditioning (scope 1)	32% of BE scope 1 emissions (2022)	Switching to lower GWP refrigerants	Technically ready/ Commercially available for most uses	Not all emissions can be abated through retrofits or appliance upgrades. High upfront cost for new systems, retrofitting, differences in gas costs. Poor maintenance and end-of-life practices.

BE.2.1 Building electrification

BE.2.1.1 Electrification

Electrification, or fuel substitution, refers to the replacement of fossil fuel appliances, processes, or products with electric equivalents, including water heating, air-conditioning and cooking (IEA, 2023a). The authority's research and consultation has indicated that although electrification has high upfront costs, in the long-term it is the cheapest way to decarbonise the sector's scope 1 emissions, including emissions from construction (Renew, People's Climate Assembly, Labor Environment Action Network, GBCA, ACOSS, submissions, 2024). As identified across this Review, decarbonisation of the Built Environment through electrification relies on the decarbonisation of the electricity system.

Some stakeholders suggested that both gas and electrical systems could be maintained with renewable gases (e.g. hydrogen or biomethane), that broad electrification is cost-prohibitive and faces significant workforce challenges (Australian Gas Infrastructure Group, Renewable Gas Alliance, submissions, 2024). The authority is of the view, however, that in the long-term complete electrification of buildings is the optimal decarbonisation approach and governments should develop strategies to efficiently and equitably realise this.

> *"Unlike in harder-to-abate sectors, zero-carbon new homes and large-scale retrofits of existing homes including electrification can be delivered immediately. Australia will not meet its existing targets nor the more ambitious targets required to align with 1.5 Degree climate scenarios if action is delayed on this immediate opportunity."*
>
> Renew submission, 2024

> *"… relying on electrification only is likely to be more expensive than maintaining a dual-fuel system and is also likely to result in higher emissions in some jurisdictions… network blending is a readily available and large-scale source of demand that can kickstart the deployment of renewable gas at scale and provides the stepping stone for other sectors to start their decarbonisation journey… From a household cost perspective, the upfront capital costs of electrification can be prohibitive."*
>
> Australian Gas Infrastructure Group submission, 2024

The authority is of the view, however, that in the long-term complete electrification of buildings is the optimal decarbonisation approach and governments should develop strategies to efficiently and equitably realise this.

Achieving the required rate of electrification is a significant challenge and may require prohibiting new gas connections and appliance replacement in homes. CSIRO modelling commissioned by the authority projects a decline in emissions from gas consumption in buildings as buildings are electrified. Further information on the CSIRO modelling of emissions in the Built Environment is available later in this chapter. Approximately 5 million existing houses would need appliance replacement for full electrification to occur (ENA, 2021). While phasing out gas connections is not necessary to electrify buildings, phasing out the gas network minimises unnecessary ongoing operating and maintenance costs as well as reducing fugitive emissions from gas leaks across the network (Grattan Institute, 2023). Disconnecting buildings from the gas network in an orderly process is therefore the most efficient way to manage the electrification of buildings.

Assuming no further homes are connected, disconnecting all homes from gas networks by 2050 implies an annual disconnection rate of approximately 166,000 homes per year, an 11-fold increase on the current gross rate of disconnection (approximately 15,000 per year, which includes only abolishments and disconnections where the meter is removed) (AER, 2024). This is more ambitious than estimates from the Department of Industry, Science and Resources (DISR) which state that the east coast would need to disconnect gas from approximately 143,000 households annually over 20 years to meet household gas demand reductions laid out in AEMO's high-ambition modelling scenario (DISR, 2024b). However, the number of residential gas customers continues to grow, with approximately 68,000 households joining the gas network across NSW, Victoria, South Australia and the ACT in 2021 alone (DISR, 2024a). Further information on CSIRO modelling of gas consumption in the Built Environment is available later in this chapter.

Commercial building data is less readily available, but the subsector would require similarly significant declines in gas connections and use. An estimated 3.5% of Australia's current non-residential stock would also need to be retrofitted each year, a significant jump from the present rate of 1% (GBCA, 2023b). Australia's current rate of investment in retrofits ($500m per year) would need to increase to between $1.5b and $2b per year (GBCA, 2023b).

Most governments have been hesitant to mandate building electrification, except for the ACT and Victoria where new buildings cannot connect to the commercial gas network (see BE.3 barriers, opportunities and enablers). Even with limited policy action, gas demand on the east coast is still forecast to decline by between 49% and 72% on 2023 levels by 2043 in commercial and residential buildings (DISR, 2024a).

Electric technologies for water heating, air-conditioning and cooking are commercially available, demonstrated, and ready for deployment (ASBEC, 2016). Furthermore, electric appliances are becoming cheaper and more efficient (Butler et al., 2020), and can be 'cost positive' (i.e. the saved costs are larger than the cost of the appliance) over their lifetime (Denis-Ryan & Gordon, 2024; Krarti & Karrech, 2024). According to the Authority's ground-up analysis, this shift is already happening in residential buildings, with approximately 125,000 (3-year rolling average) residential gas hot water systems annually replaced with electric systems. Assuming a 12-year average appliance life (Sustainability Victoria, 2024b), this replacement rate could theoretically be accelerated to almost 408,000 units per year. Commercial buildings, strata and apartments face additional challenges to electrification, including technical limitations on retrofits, added costs and complex ownership or management structures (ACT Government, 2024; Grattan Institute, 2023).

The task of electrification requires considerable coordination and investment. Electrifying a house can cost between $8,000 and $15,000 (Tildemann et al., 2022). Through expert consultation, the authority heard that electrification of a commercial building can cost between $100,000 and $5 million. However, new gas connections lock consumers into paying gas network and usage costs for up to 20 years and this is likely to be more expensive than the running costs of electric appliances (ATO, 2023; Gordon, 2024).

Electrification and replacement of liquid fossil fuels with low emissions alternatives such as biodiesel and hydrogen have the potential to decarbonise equipment and vehicles used in construction (Forsgren et al., 2019; GBCA, 2022). The use of electric construction equipment has been growing overseas, with several Scandinavian countries taking the lead to drive changes to conventional equipment and practices (Keegan, 2021). This equipment can have higher upfront costs than diesel equipment, but these costs can be offset over time by lower operational costs (Keegan, 2021). These opportunities are discussed in the Transport sector chapter.

The amount of abatement achieved by electrifying the built environment will depend upon the emissions intensity of Australia's electricity grids (see the Electricity and Energy sector chapter). The electricity system has been decarbonising and the authority's modelling indicates that renewable energy generation is likely to comprise approximately 99% of total generation in 2050. However, stakeholders have emphasised the importance of buildings being net zero-ready (i.e. electrified) before 2050, and it is important that this happens regardless of the emissions intensity of the system (UDIA, GBCA, ACOSS, Climateworks Centre, submissions, 2024).

BE.2.1.2 On-site renewable electricity generation and storage[3]

On-site renewable electricity generation and storage refers to the production and storage of energy at point of use, reducing the need for external electricity sources and increasing energy self-sufficiency. The authority agrees with expert consultation feedback that full self-sufficiency (i.e. complete disconnection from energy grids) for most buildings is not likely to be practical or necessarily the most efficient approach to operating electricity networks. However, increasing the uptake of on-site renewable energy generation technology is important for decarbonising the built environment and displacing the use of high-emissions energy sources.

Renewable electricity generation and storage technologies (especially solar PV and batteries) are mature and commercially available (Graham et al., 2024). Vehicle-to-grid technology also has the potential to complement stationary storage and provide benefits for households and the energy system. There has been significant growth in the capacity of rooftop solar systems and the Australian Energy Market Operator projects further growth in the National Electricity Market (NEM) (AEMO, 2024).

On-site generation has large abatement potential in the residential subsector due to the roof area available on suburban homes. For many commercial buildings and strata, generation and storage systems can displace only some of their grid-supplied electricity consumption. The authority heard during expert consultation that some commercial buildings often have technical and space limitations, and their energy needs are different to the needs of residential buildings. Some buildings however, like warehouses, have the potential to substitute all their grid electricity consumption with onsite renewable generation. Consultation for the 2025 NCC includes proposed changes requiring solar PV to be installed on buildings (ABCB, 2024).

3 On-site renewable electricity generation and storage is covered by the Electricity and Energy Sector Plan as part of the Australian Government's Net Zero Plan.

The costs of onsite generation and storage continue to fall, but there are still significant cost barriers to the deployment of on-site generation and storage systems, especially for low-income households and communities (Graham et al., 2024). The CSIRO have modelled rooftop solar PV costs falling from $1,505/kW in 2024 to between $513/kW and $702/kW in 2055 (Graham et al., 2024). Residential solar PV and battery system installation can cost between $15,000 and $30,000 (BVR Energy, 2023). The costs of commercial systems depend on the sizes of buildings and systems. Battery storage has high upfront costs, and returns on investment for generation systems can be slow or negligible depending on electricity prices and feed-in tariffs (Kaka & Pendlebury, 2022). Despite these cost barriers, adoption of these technologies can provide asset owners with greater energy independence and reduced power bills over the assets' lifetimes (CSIRO, 2024; Ma & Yuan, 2023).

Decentralised energy systems (at smaller scale than national or regional grids, but larger than individual buildings) can also improve the resilience of systems to natural hazards, especially when neighbourhood- or precinct-scale microgrids can be formed (Xu et al., 2024). Rooftop solar generation especially lends itself to working in decentralised systems. Battery storage technologies, known as orchestrated batteries, can also be used to trade power with the grid at optimal times to maximise savings for consumers sand provide benefits for the wider energy system (CEC, 2024). Managing consumer-owned resources is a significant economic opportunity for Australia. Effective deployment of distributed energy resources could avoid network, generation and other costs (IEEFA, 2024). These technologies should be a part of a diverse energy strategy, as outlined in the Electricity and Energy sector chapter.

The deployment of on-site renewable electricity generation and storage technologies could be supported through education initiatives (e.g. training programs for communities and organisations), more incentives for consumers, targets for both government-owned assets and for technology adoption, and greater participation options for consumers to match their choices of and uses for consumer energy resources (CEC, 2024).

BE.2.2 Energy performance

BE.2.2.1 Energy efficiency and digitalisation

Improving energy efficiency is the process of using less energy to perform the same tasks or amount of work (DCCEEW, 2024e). It is critical to decarbonisation and underpins sustainable and affordable buildings (C. White et al., 2023). The authority considers energy efficiency (and demand flexibility) to be an element of energy performance, and while some sources include fuel switching in energy performance, the authority considers this to be standalone (DCCEEW, 2024e).

Australia's energy policies have historically focused on supply, but the authority's consultation and research found that there is significant abatement potential in demand-side measures at the national level (ASBEC, 2022; C. White et al., 2023). A cost-effective means of reducing emissions is through adopting energy efficiency as a first principle (C. White et al., 2023).

The Australian Government recognised the importance of energy efficiency at the 28th Conference of the Parties in 2023, where it joined the Global Renewables and Energy Efficiency Pledge. Pledging countries committed to (28th Conference of the Parties, 2023):

- triple the world's installed renewable energy generation capacity to at least 11,000 GW by 2030
- work together to double the global average rate of energy efficiency improvements from around 2% per year to over 4% per year until 2030
- put the principle of energy efficiency as the "first fuel" at the core of policymaking, planning, and major investment decisions.

Improving energy efficiency can reduce the amount of energy consumed by buildings, delivering abatement by reducing emissions from fossil fuel electricity generation. Significantly improving energy efficiency across the built environment could reduce the amount of new electricity generation and transmission capacity that would otherwise be needed to service increased electricity consumption, balancing growing energy demand (IEA, 2020b). Efficiency can also reduce peak loads on electricity grids, which would further limit the need to use short-term (often non-renewable) peaking generation.

Improving energy efficiency can reduce the amount of energy consumed by buildings, delivering abatement by reducing emissions from fossil fuel electricity generation. Significantly improving energy efficiency across the built environment could reduce the amount of new electricity generation and transmission capacity that would otherwise be needed to service increased electricity consumption, balancing growing energy demand (IEA, 2020b). Efficiency can also reduce peak loads on electricity grids, which would further limit the need to use short-term (often non-renewable) peaking generation.

Upgrading appliances can improve a building's energy efficiency. For example, LEDs require 75% less energy than halogen light bulbs and last 5 to 10 times longer (DCCEEW, 2024f). Heat pump hot water systems use 60% to 75% less electricity than conventional electric (i.e. resistive coil) hot water systems and are 300% to 400% more efficient than gas hot-water systems (ACT Government, n.d.; Sustainability Victoria, 2024a). Alongside replacement and upgrades, experts told the authority that timely maintenance of existing appliances is also a key means of improving and ensuring their operation at optimal energy efficiency over their lifetimes.

The adjusted cost of upgrading residential appliances and lighting in standalone and semi-detached houses is approximately $6,000 per household (Sustainability Victoria, 2015). For commercial buildings, costs for energy efficiency upgrades are expected to vary more widely depending on the building type and size. However, energy efficiency upgrades can provide cost savings over appliance lifecycles. The RACE for 2030 Cooperative Research Centre estimates that 'bespoke' residential retrofits can result in bill savings of $1,600 per year for average homes (RACE for 2030, 2021).

The authority's research and consultation found support for increasing minimum energy performance standards for space heating, hot water and cooking appliances (Climateworks Centre, Climate Council, GBCA, submissions, 2024). This action could ensure new dwellings are highly efficient and consumers receive long-term cost savings (Gordon, 2024). The Energy Efficiency Council has estimated that minimum appliance standards have saved consumers between $9.4 billion and $18.8 billion between 2000 and 2020 (EEC, 2023). The NSW Energy Savings Scheme saved over three million tonnes of CO_2 from efficiency measures in the years leading up to 2022 (IPART, 2024).

BE.2.2.2 Energy optimisation and behaviour change

Optimising the use of existing appliances is a low-cost demand-side measure to reduce emissions by reducing electricity use. This optimisation is enabled by technologies including the digitalisation of buildings using technologies like 'smart' thermostats and sensors for controlling lighting and air-conditioning systems to better align use with need (Otte et al., 2022; S. White et al., 2023). CSIRO reports that building digitalisation can potentially underpin new energy efficiency opportunities and save 6.6 Mt per year of CO_2 emissions at negative abatement cost (S. White et al., 2023). Distributed energy resources can also reduce electricity needs, providing flexible demand (IEEFA, 2024). There may be an emerging role for artificial intelligence to build on 'smart' technologies to automatically optimise energy use in buildings (IEA, 2019). Digitalisation in buildings has the potential to provide energy savings over the medium-to-long term by cutting energy use by up to 10% and there is evidence that it has already resulted in cost savings where it has been deployed in several locations–a residential complex in South Australia, a Wollongong shopping centre, a Sydney residential building, and a University of Wollongong building (ASBEC, 2016; IEA, 2017). Most emissions reductions activities related to digitalisation are technically ready and their use has been demonstrated, but deployment needs to be accelerated.

Behaviour change also plays a role in optimising energy consumption. In expert consultation, the authority heard that at a consumer level, this can include simple behaviours such as using appliances during the day when there is ample renewable energy available, switching off appliances when not in use, using heating and cooling efficiently and making upgrades to homes.

BE.2.2.3 Grid integration[4]

Grid integration refers to shifting from passive use of energy in buildings to active management of that use in conjunction with the operation of the wider energy systems (GBCA, 2023a). It can present opportunities to improve energy performance. Grid-integrated – or grid-interactive – buildings are electrified, efficient, flexible, and incorporate some automation, allowing for 'load shifting' (shifting optional energy use to different times of the day) to ensure energy is used when it is cheap, abundant and low emission (GBCA, 2023a). Load shifting has the potential to reduce Australia's annual greenhouse gas emissions by 1.9% and lower the cost of supplying power to buildings by $1.7 billion per year (Denniss & Roussac, 2024). Grid integration can be achieved through a mix of energy efficiency, controls, digitalisation and distributed generation and storage technologies. In consultation, experts noted this type of integration can range from text messages to asset operators to lower their electricity consumption during peak periods, through to high-tech automation of entire buildings and remote appliance management (e.g. pool pumps).

Grid integration provides an opportunity to reduce scope 2 emissions while supporting grid stability by reducing demand at peak periods and soaking up excess generation at times of high solar and/or wind generation. For example, shifting a third of the energy load of buildings by three hours per day for five days each week could reduce Australia's annual emissions by 0.6% and save building operators $1.7 billion in energy bills (GBCA, 2023a). 'Consumer energy resources' are discussed further in the Electricity and Energy sector chapter. A leading example in Australia is the University of Technology Sydney's first grid-interactive building, the Dr Chau Chak Wing Building. This building is prepared for peak summer electricity demand and has achieved cost savings from its automated demand response system (Schultz, 2023).

Grid integration technologies vary in readiness. In expert consultation, the authority heard that most are technically ready for deployment, but more sophisticated options have low commercial readiness (GBCA, 2023a). In consultation with experts, the authority heard that challenges to deploying these technologies include: retrofitting buildings can be difficult; electricity tariffs do not incentivise consumers to change behaviours and use appliances and energy in the middle of the day, and load shifting can potentially reduce energy efficiency ratings. Delivering grid stability and abatement from this action requires collaboration between the built environment and electricity sectors (S. White et al., 2023). Costs for grid integration technologies are still relatively unknown due to limited grid-scale deployment around the world.

BE.2.2.4 Thermal efficiency

Australia's buildings have some of the poorest thermal efficiency in the world. Houses built before 2003 have an average NatHERS rating of 1.8 stars (CSIRO, 2021). The impact of poor thermal efficiency is that buildings consume excess energy (Rajagopalan et al., 2023). Inadequate thermal efficiency, as well as poorly designed efficiency interventions, can also adversely affect human health (Ren et al., 2014). Around 81% of Australian homes have average winter indoor temperatures below the World Health Organisation's safe minimum. Prioritising thermal efficiency and taking a 'fabric first' approach is a key means of reducing building energy demand and scope 1 and 2 emissions (Climateworks Centre, 2023a). According to modelling by RACE, retrofitting 1,000,000 homes over 5 years could reduce home energy use by up to 9,000 kWh per year per home, equating to an emissions reduction of 5.8 tonnes of CO_2-e per year per home, and saving an average home $1,600 per year on energy bills (RACE for 2030, 2021). The scale of upgrades can vary however and research from the Climateworks Centre found that 'quick fix' and 'modest' upgrades can be most cost-effective for most households and have real efficiency benefits (Climateworks Centre, 2023a).

Technologies to improve building thermal efficiency are commercially available and ready for deployment. Approaches range from simple draught sealing or window covering to significant home insulation and window glazing upgrades (Rajagopalan et al., 2023). The Climate Safe Rooms project by Geelong Sustainability offers free home energy upgrades for low-income households where at least one resident received home care support services due to risk from heatwaves and extreme cold (Geelong Sustainability, 2023). The project has led to substantial energy savings, lowered gas consumption and reduced exposure to unhealthy temperatures (Geelong Sustainability, 2023).

Although upgrading existing residential buildings from existing low average NatHERS ratings is technically possible, comprehensive upgrades are expensive and not all thermal efficiency upgrades are eligible for subsidies under state-run schemes (Sustainability Victoria, 2015). The cost to upgrade a home to a 6-star energy efficiency rating could be between $9,000 and $18,000 for a semi-detached house, and between $42,000 and $63,000 for a detached house (based on a study examining housing stock in Melbourne) (Harrison, 2018). Although costs of thermal 'shell' upgrades can be significant, when implemented in the design phase they can be substantially cheaper than retrofits (Rajagopalan et al., 2023). Minor residential upgrades for improved thermal efficiency can

4 Grid integration of buildings is covered by the Electricity and Energy Sector Plan as part of the Australian Government's Net Zero Plan.

provide net cost savings in three years (Rajagopalan et al., 2023). Thermal efficiency also improves health: for every $1 saved on energy costs $10 is saved by the healthcare system (Sustainability Victoria, 2022).

BE.2.3 Refrigerants[5]

Refrigerant gases are critical for the operation of refrigerators, air-conditioners and heat pumps. Refrigerant gases can leak during equipment installation, operation and maintenance and at the end of an appliance's life. These emissions contribute about 9 Mt CO_2-e or 32% of the sector's 2022 scope 1 emissions. While Australia is not a signatory to the COP28 Global Cooling Pledge, Australia is implementing a HFC phase-down in line with the Montreal Protocol as discussed in the Industry and Waste sector chapter (Cool Coalition, n.d.; DCCEEW, 2023c).

Many refrigerant gases have a high GWP (IPCC, 2021), meaning emissions of small quantities can have a significant global warming impact. For example, R-404a is commonly used in low- and medium-temperature refrigeration systems and has a GWP of 3,922 (based on IPCC AR4) (DCCEEW, 2024h). This means every 1 kg of R-404a emitted has the equivalent warming effect of 3,922 kg of CO_2 over a 100-year period.

The impact of refrigerant gases can be mitigated through the utilisation of low-GWP alternatives (IEA & UNEP, 2020). Low-GWP refrigerants are commercially available, but according to the authority's consultation, there are still some technical limitations that are a barrier to their wider implementation. Typically, different refrigerant gases or blends have different operating requirements. This almost always makes retrofitting existing systems impossible, meaning owners usually need to obtain entirely new systems to take advantage of these products. This has been put into practice in some commercial settings. For example, in Woolworths' Rouse Hill store, the installation of a cascade CO_2 refrigeration system has reduced the GWP of the refrigerant gas by 3,700 (CO_2 by definition has a GWP of 1) (Blundell, 2010).

Commercial refrigeration systems commonly use R-404a and some of these can be retrofitted with refrigerants that have a GWP of approximately 1,300 or about one-third the GWP of R-404a (Makhnatch et al., 2017). Some refrigerants are not replaceable due to context-specific safety or technical constraints. Therefore, high-GWP refrigerants are expected to be used in small amounts beyond the end of the HFC phase down in 2036 (DCCEEW, 2021). Environmental impacts unrelated to global warming are concerns for alternative refrigerants that contain highly persistent 'forever chemicals', per- and polyfluoroalkyl substances (PFAS) (Glüge et al., 2020). Governments around the world, including in Australia, are currently considering the regulatory approach to PFAS chemicals (DCCEEW, 2023f).

Refrigerant gases need to be addressed in both new appliances, and in the 'bank' or stock of gas in existing appliances and systems. The HFC phase-down discussed in the Industry and Waste sector chapter addresses new gases, but in expert consultation the authority heard that the existing bank poses a significant challenge that is only partially managed through a licencing system and end-of-life destruction. There are currently more than 62 million appliances with lifespans of 15 to 60 years using refrigerant gases in Australia (DCCEEW (unpublished), 2024c). The authority expects that this equipment stock will continue to grow, especially as the use of heat pumps increases due to electrification (CCA, 2023).

The refrigerant bank has the potential to be a significant source of emissions if inadequately managed. Australian appliances contain over 4 million kg of R-404a as of 2022, with the potential to release the equivalent of about 17 Mt of CO_2 into the atmosphere (DCCEEW (unpublished), 2024c). Despite the projected growth of the mass of the refrigerant bank until 2030, the HFC phase-down is expected to reduce the bank's potential climate impact (DCCEEW, 2023c). The authority's analysis found that under optimal circumstances, the bank could reach near zero in the early 2050s. The existing bank is managed through a licencing program and by end-of-life destruction (DCCEEW, 2023e; Ozone Protection and Synthetic Greenhouse Gas Management Act 1989). During expert consultation stakeholders estimated that the 530 tonnes destroyed in 2022 represents between 20% and 25% of gas reaching end of life (UNEP Ozone Secretariat, 2023). Increasing the rate of destruction is a significant opportunity to reduce emissions.

DCCEEW analysis suggests that routine maintenance of air conditioning equipment has a significant impact on equipment energy consumption (DCCEEW (unpublished), 2024c). A focus on proper installation and routine equipment maintenance is an opportunity to reduce refrigerant emissions, and it is expected that this will have limited imposition on the community. There is also a link between refrigerant selection and equipment efficiency, with over 80% of emissions from refrigeration and air-conditioning equipment deriving from energy use (Refrigerants Australia and AREMA submission, 2024). (DCCEEW, 2023b)

5 Refrigerant emissions are jointly covered by the Built Environment Sector Plan and the Industry Sector Plan as part of the Australian Government's Net Zero Plan.

Box BE.1: Scope 3 embodied emissions

Definition

Embodied emissions are the emissions generated during the material manufacture, construction, maintenance and demolition of buildings and infrastructure (GBCA & Thinkstep-anz, 2021). They are calculated as the 'sum of greenhouse gas emissions and greenhouse gas removals in a product system, expressed as CO_2-e and based on a life cycle assessment …' (ISO, 2018).

The problem

While the built environment may have lower operational (scope 1 and scope 2) emissions relative to other sectors, the sector is a major driver of emissions through high embodied-emissions materials, construction practices and upstream activities (scope 3 embodied emissions) (ASBEC, Property Council of Australia (PCA), GBCA, Better Futures Australia, PIA, submissions, 2024).

Scope 3 emissions in the built environment contributed an estimated 11% to national carbon emissions in 2022-23 (Infrastructure Australia – Hybrid Analysis, 2024). In another analysis, average annual upfront embodied carbon was estimated to be 51 Mt CO_2-e per year over the 5 years analysed, ranging from 40 Mt CO_2-e to 56 Mt CO_2-e (Infrastructure Australia – Hybrid Analysis, 2024). Of these emissions, 75% were generated during the manufacture of building materials (Infrastructure Australia – Hybrid Analysis, 2024). Most of these emissions are from concrete (~11 Mt CO_2-e per year) and steel (~12 Mt CO_2-e per year). The sectors with the highest scope 3 emissions in 2022-23 were calculated to be buildings (24 Mt CO_2-e), followed by transport infrastructure (10 Mt CO_2-e) and utilities (5 Mt CO_2-e) (Infrastructure Australia – Hybrid Analysis, 2024).

On average, there are 118 to 158 tonnes of emissions embodied in a typical detached home (Schmidt et al., 2020). Through the National Housing Accord, the Australian Government is aiming to build 1.2 million new homes by mid-2029, which equates to between 142 to 190 Mt CO_2-e of embodied emissions (The Treasury, 2023).

The opportunity

Across the sector there is growing awareness of and interest in addressing scope 3 emissions. This includes opportunities to reform the approach to design, planning and construction of buildings and infrastructure (NABERS, 2023b).

Demand for low-carbon construction materials could be driven by heightened building construction code requirements or by property seeking to reduce their scope 3 emissions. A 10% reduction in embodied emissions in new buildings is estimated to correspond to avoided emissions of at least 19.9 Mt CO_2-e between 2022 and 2030, and at least 63.5 Mt CO_2-e avoided between 2022 and 2050 (GBCA & Thinkstep-anz, 2021).

Embodied emissions are also crucial when considering the entire lifecycle of buildings and infrastructure. By repurposing or renovating existing buildings, as opposed to decommissioning or demolishing them, additional embodied carbon emissions can be avoided and existing materials can be re-used or recycled to provide a second (or extended) lives to material and structures (Dunn, 2023; NABERS, 2023b).

The solutions

Reducing embodied carbon in the built environment requires systemic changes at all stages of the construction process through both supply-side and demand-side interventions (GBCA & Thinkstep-anz, 2021). This will involve a shift in how we consume materials, as well as changes to how industry produces and delivers goods and services (DCCEEW, 2024e). Measurement of embodied emissions is fundamental to this and the authority notes the development from Building Ministers who have agreed that the NCC 2025 will include voluntary guidance to report and measure embodied emissions using the NABERS tool (DISR, 2024c). The Australian Sustainable Built Environment Council is currently leading development of a policy framework to manage embodied emissions (ASBEC, 2024).

Reducing embodied carbon in the built environment requires systemic changes at all stages of the construction process through both supply-side and demand-side interventions (GBCA & Thinkstep-anz, 2021). This will involve a shift in how we consume materials, as well as changes to how industry produces and delivers goods and services (DCCEEW, 2024e).

Material substitutions mean swapping out high-carbon materials for those with lower emissions intensity (e.g. substituting fly ash for cement used in concrete mixtures) and are potentially a multibillion-dollar industry (CEFC, 2021; GBCA & Thinkstep-anz, 2021). However, this is only a partial abatement solution. As a demand driver, the greatest opportunities for reducing the sector's embodied carbon are in the initial stages of the design and planning process, where material requirements can be optimised for lower embodied emissions. This would require revising established approaches to building and development, alongside avoiding construction and reducing material use in the first place. Public sector investment in both buildings and infrastructure can drive this change.

1. Design and Planning

During expert consultation the authority heard that improvements in building design can reduce embodied emissions by up to an estimated 60%. The strategies for achieving net zero embodied carbon can be organised under four principles, which should be considered in the following order (Prasad et al., 2021):

- avoid building and/or build at the 'right' (smaller) size
- build less and/or dematerialise (use less material for the same functions)
- build low carbon or 'smarter' (adopting the lowest carbon elements, for example prefabricated elements)
- leverage supply chain and procurement methods (material substitution).

Design needs to consider sufficiency as well as resource efficiency to reduce embodied carbon, where sufficiency is about long-term non-technological actions that consume less in absolute terms (IPCC, 2022). Examples of sufficiency measures include avoiding construction by repurposing empty buildings, ensuring building size meets changing household needs, and encouraging multifamily homes (IPCC, 2022).

Australia has some of the largest houses in the world, averaging 84m^2 per person, many of which are in sprawling urban fringes (Wingrove & Heffernan, 2024). This means that Australian houses have higher embodied emissions compared to other countries, and that energy use is higher for a given level of energy efficiency performance (Wingrove et al., 2024). This highlights the need to reconsider design and building principles, including the size of houses being built and the scale of current and future development.

An example of effective design reducing embodied emissions is the Atlassian tower in Sydney, a 40-storey building made of hybrid concrete and timber, resulting in up to a 50% reduction in embodied carbon (Built Australia, n.d.). At a precinct level, the City of Vincent in Western Australia has had major successes in embodied carbon reduction. The City made changes to their planning approval processes via a voluntary mechanism which incentivises lower-embodied carbon projects by providing an opportunity to fast-track development application approvals (MECLA, 2023).

Further discussion on the role of design and planning in decarbonisation of the built environment is in Box BE.2 below.

2. Circular economy principles

Circular economy principles involve sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products for as long as possible when producing and consuming (European Parliament, 2023).

> *"Embedding circular economy principles and practices represents a substantial means of reducing carbon emissions through the application of embedded carbon in the buildingindustry."*
>
> Urban Development Institute of Australia submission, 2024

The built environment stands to gain significant abatement from implementing circular economy measures, including reducing embodied emissions (Henderson, 2023; Wang et al., 2022). The opportunity lies in avoiding the creation of new buildings and materials, and instead preserving and reusing products, materials and structures which have already been manufactured (Clean Energy Finance Corporation, 2021). This approach reduces lifecycle emissions, creates less demand for resources, and reduces waste.

Examples of how the built environment can reduce embodied carbon and increase circularity include:

- Rewarding investment in circular solutions and business models (e.g. by implementing standards and regulations to prioritise renovation, retrofitting and adaptive reuse) (CEF, 2024)
- Mandating consideration of embodied carbon through the NCC, as recommended in the Circular Economy Ministerial Advisory Group interim report (DCCEEW, 2024b)
- Reusing and repurposing buildings, as opposed to creating new buildings, saving up to 50% in embodied emissions (Tirelli & Besana, 2023)
- Using recycled asphalt in road construction, which can avoid 96,148 tonnes of CO_2 per year in New South Wales alone (Marsden Jacob Associates, 2022)
- Incentivising investment in circular building projects (e.g. cutting property taxes or providing tax credits for circular construction) (CEF, 2024)
- Targeting education and policy to support labour and skills needed for circular design and construction practices (Nicholson & Miatto, 2024; ICLEI, 2023).

This can also be tied to the manufacturing industry, of which the built environment is an end-user. Targeting manufacturing and increasing awareness of the built environment's end-user role can encourage products to be designed for circularity (easier to reuse, repair and recycle), and utilise pricing to promote sufficiency, and foster a cultural shift of production and construction through education and legislation (CEF, 2024).

Opting to renovate and retrofit existing buildings in place of demolition can save significant amounts of the embodied carbon of a rebuild approach (Pelly, 2023; Storck et al., 2023; Seo & Foliente, 2021). For example, the renovation of 50 Bridge St, Sydney into the Quay Quarter Tower maintained 60% of the existing core structure, saving 12,079 metric tons of embodied carbon, and reducing both construction time and environmental impact (CEFC, 2022; Quay Quarter, n.d.).

3. Material substitutions

Embodied emissions can be lowered by replacing high-emissions materials with low-emissions materials, particularly steel, cement and aluminium. The supply side levers are discussed in the Industry and Waste sector chapter.

There has been significant effort in developing building products with lower embodied emissions. Cement is a key example of a material that has been engineered to lower its emissions intensity. The emissions intensity of cement produced domestically from Australian clinker fell 17% in the eight years to 2018-19, from 0.94 kg CO_2-e/kg cement to 0.77 kg CO_2-e /kg cement (GBCA & Thinkstep-anz, 2021; CIF, 2020). In addition, manufacturers such as Holcim Australia are planning further reductions by replacing general-purpose cement with supplementary cementitious materials (SCM) such as fly ash, slag, and silica fume (Climate Active, 2019).

As noted, material substitution has its limitations. While it can reduce embodied carbon, it cannot eliminate it, primarily due to the emissions associated with construction and transport of materials. In many situations, alternatives have different technical properties that mean they are not appropriate for the proposed application. There are also regulatory barriers to the use of alternative materials including lengthy timeframes to update Australian Standards. Economies of scale are expected to drive cost reductions and improve access to novel materials (CEFC, 2021).

Box BE.2: The role of building design and urban planning

Urban planning and building design play a crucial role in abating emissions in the built environment by shaping how individuals and communities consume energy (DITRDCA, 2024). In a submission to this review, the Australian Local Government Association (2024) explained that design changes can deliver a range of co-benefits including improved health and wellbeing outcomes for individuals and communities. Planning is also a key integrator to bring together actions across sectors.

Design can be considered from a 'macro' urban planning perspective to a 'micro' individual building design perspective.

Macro urban planning and precinct design

Urban planning and precinct design presents significant opportunities for driving decarbonisation in the built environment and other sectors (e.g., transport), while also delivering a range of co-benefits for individuals and communities.

- Effective planning can drive the adoption of lower carbon materials in the development of new precincts, communities, and infrastructure (Bunning et al., 2013).
- Designing compact cities and precincts can reduce transport emissions and encourage active or public transport rather than a reliance on driving (Fan & Chapman, 2022; Infrastructure Victoria, 2023b) and digitalisation can encourage 'mode shifts' such as sharing private transport (Reich, 2023). Active transport also has benefits for human wellbeing (Central Coast Health Promotion Service, 2024).
- Proactive planning of urban areas can encourage increased density and reduce urban sprawl, reducing embodied emissions (Infrastructure Victoria, 2023a). Higher density urban areas also enable other opportunities to reduce emissions, such as grid integration of buildings.
- Planning can create better adapted and climate resilient cities by employing a range of techniques such as shading, appropriate material use, and drought and flood resistance. Urban green infrastructure (e.g. tree cover) can reduce cooling demand (IEA, 2021; Feyisa et al., 2014; The Nature Conservancy submission, 2024). In this case, green infrastructure is a key link between climate mitigation, adaptation, and resilience.

Estimates indicate that improved urban design can reduce the average citizen's carbon footprint by up to 60% (IEA, 2021). Retrofitting costs for adding green spaces, walking and cycling infrastructure, and public transport (e.g. railways and tramways) to existing cities are enormous. Therefore, considering these factors at the planning phase can have significant cost benefits over long timescales.

Building design, planning and zoning should also consider future climate conditions and risk to ensure buildings have energy security and minimise exposure to climate and natural disaster risk.

Individual building design

Decisions made at the design phase can lock in emissions for the lifetime of the building. Poor building design frequently leads to draughts and poor solar efficiency which ultimately results in heat loss and excessive energy use (Brinsmead et al., 2023).

The design phase therefore presents the greatest opportunity for reducing operational and embodied emissions in buildings, whilst delivering co-benefits for building users. Building designers, contractors and developers should engage with consumers to ensure they understand the climate and energy implications of building design decisions.

While widespread construction of ‘passive’ houses may be unachievable, retrofitting poorly designed buildings is also difficult and expensive. The most effective time to implement technologies for improving thermal efficiency is early in a building or project’s design phase.

It is also important to recognise current attitudes and cultural practices when designing homes. This is particularly relevant in Australia, where relatively large homes are commonplace, with some states and territories recording significant growth in the past two decades (Australian Bureau of Statistics, 2023). A 2024 study of Australian houses found that while houses are being designed to be more energy efficient, their increasing size has led to an overall increase in energy consumption (Wingrove et al., 2024). Improving building thermal efficiency can have unintended consequences by increasing material use and therefore embodied emissions, however lifecycle emissions still report large improvements (Kneifel et al., 2018).

For these reasons, emissions avoidance should be entrenched in all phases of the design, planning, building and certification process. By decarbonising across sectors and the supply chain, and by rethinking building practices, it is possible to reduce emissions from buildings even if they have greater energy requirements.

BE.3 Barriers, opportunities and enablers

BE.3.1 Green premiums

The lifecycle cost of electrified technologies is usually less than the lifecycle costs of existing fossil fuel-powered approaches (Grattan Institute, 2023). However, the upfront installation costs of high-efficiency electric appliances remain a fundamental barrier to adoption (IPCC, 2022). Upfront costs can also act as strong disincentives to implement entirely new systems, due to long payback periods relative to the useful lifetimes of appliances and equipment (BCG, 2021; Sustainability Victoria, 2019).

Financial incentives are a key enabler to overcoming high upfront costs, driving earlier adoption of commercially available emissions reduction technologies associated with retrofitting and energy efficiency upgrades. Appropriate financial instruments must recognise the differing incentives of various actors when determining how to spend public money (or concluding private finance is sufficient). The authority heard that owner-occupiers are likely to accept upfront capital expenditure, whereas lower income households, such as those in public housing or renting, will be less able to absorb those costs despite comparative reductions in lifetime operational costs.

To ensure equal opportunity across income groups and housing types, financing approaches for this sector will require a suite of tailored financial instruments for individuals' incentives. This may look like concessional loans, tax rebates or grants depending on the financing need. Local governments or community groups can work to receive and deliver this funding in their local area to improve administrative efficiencies and roll out for all parties.

> To ensure equal opportunity across income groups and housing types, financing approaches for this sector will require a suite of tailored financial instruments for individuals' incentives.

The role of low-income housing in reducing energy use is often overlooked, and barriers include limited financial resources of occupants as well as technical challenges such as retrofitting ageing and multiple-household buildings. Government support is a must. By building on the existing social housing retrofit funds, governments could also demonstrate best-practice upgrades and smooth approval processes by coordinating with development regulators. In consultation, stakeholders noted the recently established Housing Australia Future Fund Facility as an example of an existing government entity that could be modified to require minimum climate-resilient developments as part of eligibility criteria.

BE.3.2 Planning, approvals and coordination

All building types, including free-standing homes, commercial buildings and buildings under strata management will need to decarbonise. Strata arrangements face unique challenges that require planning and coordination across different levels of government. The authority has heard, for example, that "supporting the implementation of suitable technologies in strata buildings that serve to target emissions reductions can assist the Federal Government in reaching their goals of an electrified future and greener future" (Strata Community Association submission, 2024).

BE.3.3 Regulatory inconsistencies and gaps

The lack of nationally consistent and contemporary regulations impedes progress. For example, construction and planning experts raised concerns with the authority that material substitutions for building products and changes to urban planning are often prohibited due to outdated regulations and standards.

Improvements to the existing regulatory environment could drive a substantial uplift in building quality while also working to overcome the split incentive barrier (i.e. where a building owner pays for an upgrade, but the tenant receives the benefit, disincentivising the building owner from acting), cut administrative costs for development, boost housing supply and improve emissions outcomes. Examples include:

- Introducing and raising minimum standards for homes and rental properties, mandatory energy rating disclosures and net zero building standards (Climateworks Centre, PCA, ACOSS, Renew, GBCA, Climate Council, submissions, 2024).
- Building the existing refrigerant gas policy by placing further limits on the GWP of refrigerant gases in specific types of appliances (e.g. commercial refrigeration and stationary air-conditioning), with a similar approach to comparable countries such as the European Union, the United States and Japan (European Commission, 2024; EPA, 2016; Ministry of the Environment, n.d.).
- Strengthening minimum energy performance standards for appliances (Climateworks Centre, 2023a; GBCA, City of Sydney, IEEFA, PCA, submissions, 2024). This also reduces energy costs of the lifetime of appliances, as energy efficient appliances can reduce energy bills by reducing energy consumption (DCCEEW, n.d.). Standards can also help overcome data barriers for consumers and support supply chains (Climateworks Centre, 2023a). This could be achieved in part by expanding the GEMS to cover appliances such as space heaters and cooktops. Maximum benefit can be achieved by combining standards for electric and gas systems to recognise efficiency benefits and emissions savings. The costs of delaying minimum standards updates are $3.4 billion in lifetime costs that are locked in (Gordon, 2024). These accumulate for every year that the lifting of minimum standards is delayed. This figure does not consider the additional benefits of increased thermal efficiency or optimisation upgrades.
- Developing product and engineering standards to target embodied emissions by enabling alternative products and low carbon designs (GBCA & PCA, 2023). There is an opportunity to introduce further mandated maximum embodied carbon standards for buildings, following international examples such as Denmark, the Netherlands and Finland (Toth & Volt, 2021).
- Mandatory disclosures of building energy performance and efficiency - a low cost and foundational policy for sectoral decarbonisation (GBCA & PCA, 2023). Disclosures drive action in a competitive market striving for low carbon buildings, as seen by the national Commercial Building Disclosure (CBD) program driving a 40% reduction in average energy intensity from mandatorily rated buildings since 2011 (NABERS, 2023a). Expert stakeholders recommended the implementation of mandatory disclosures for home energy efficiency ratings and building performance (Climateworks Centre, ACOSS, PCA, Better Futures Australia, submissions, 2024). Stakeholders also told the authority during consultation that there is potential to expand the national CBD program to subsectors and introduce similar policies for residential buildings and the Australian Government is currently consulting on similar changes (PCA submission, 2024; DCCEEW, 2024d).

The authority's 2023 Annual Progress Report recommended the Australian Government "work with state and territory governments to agree on a coordinated, nationally consistent approach to phasing out new gas connections for residential and small commercial buildings and phase-out for existing gas connections" (CCA, 2023). The government disagreed with this recommendation (DCCEEW, 2023a). Since this recommendation was made, the government has acknowledged that the current rate of conversion from gas to electric appliances is insufficient to meet Australia's net zero targets (DISR, 2024b).

The electrification of buildings is central to the sector's decarbonisation and the absence of a national plan to phase out gas connections to buildings remains a critical barrier (Australian Sustainable Built Environment Council, 2022; Climateworks Centre, GBCA, Renew, City of Sydney, Sydney Environment Institute, submissions, 2024). In this absence, jurisdictions are taking different approaches to decarbonising gas emissions. Some jurisdictions such as the ACT and Victoria are acting independently to phase out gas connections through policies banning new gas connections and enforcing adoption of electric appliances in new buildings (ACT Government, 2021; DISR, 2024b; DTP, 2023) and the Australian Building Codes Board (ABCB) is currently consulting on the 2025 NCC to include measures to support commercial building electrification (ABCB, 2024). In contrast, Tasmania's Future Gas Strategy committed to not regulate new gas connections and prioritises the deployment of renewable gases to decarbonise emissions (Tasmanian Government, 2023).

Box BE.3: High upfront costs on retrofitting poor quality housing

The French Government has legislated increasingly stringent regulation to support financial instruments to decarbonise the built environment. The Loi Climat et Résilience mandates increasingly stringent minimum rental standards over time to address split-incentives between investors and renters. To encourage retrofitting, from 2025, landlords will not be permitted to lease buildings with the lowest standard (Jousseaume, 2022). This baseline will successively be tightened, with the next lowest standard not permitted for leasing from 2028. In parallel, government grants of up to €35,000 ($58,200) are available to owner-occupiers or investors to complete energy retrofits (Government of France, 2023). The program aims to finance 370,000 fully renovated homes per year by 2030, eventually reaching 700-800,000 (IEA, 2023b).

BE.3.4 Supply chain constraints

Opportunities to decarbonise the built environment are inextricably linked to progress with reducing emissions in other sectors. For example, abatement via electrification relies on the decarbonisation of electricity supply, and reducing embodied emissions relies on the decarbonisation of industry (e.g. steel and cement).

The supplies needed to decarbonise the built environment will be in high demand across Australia and the decarbonising world. Regional and rural areas face additional supply challenges due to the additional freight. Proper prior planning and monitoring relevant supply chains will be key to overcoming these barriers.

BE.3.5 Workforce and skills shortages

The workforce necessary to enable energy efficiency upgrades, demand-side and energy management will be significant – and overlaps with the workforce for the renewable energy buildout detailed in the AEMO's Integrated System Plan (discussed in the Electricity and Energy sector pathway) (AEMO, 2024). The Institute of Sustainable Futures estimated that this energy efficiency workforce could be between 200,000 and 400,000 by 2030 (Rutovitz et al., 2021).

The installation of the critical technologies for the sector is carried out by tradespeople, including electricians and air-conditioning and plumbing professionals. The technologies are commercially available with many of these skills already in the market, but the challenge is scaling up a workforce that is already experiencing shortages. For example, hot water heat pump systems require a licenced plumber for installation (DCCEEW, 2023d), but plumbers are currently in shortage in all states and territories (JSA, 2023a). The Australian Sustainable Built Environment Council (ASBEC) calls for significant and well-planned government action to increase the availability of appropriate training and qualification frameworks to meet the retrofitting and electrification challenges (ASBEC, 2023).

Jobs and Skills Australia (2023b) identified that as governments move forward with energy efficiency and electrification standards like NatHERs and the NCC, the demand for energy auditors will rise (JSA, 2023b). Skilled roles in performance and energy management systems do not have dedicated national training courses, and training for these roles is being managed by the Energy Efficiency Council (EEC) (JSA, 2023b).

BE.3.6 Information and data gaps

A lack of accurate emissions data is a barrier for managing and reducing embodied emissions in the built environment. Trusted 'one-stop-shops' for information about building energy efficiency could help consumers navigate the complexity and drive the commercial readiness and scale of retrofits and new builds for all housing, including in low-income housing (ACOSS, 2024).

Inability to compare costs between products and services can prevent the uptake of commercially available abatement opportunities. For example, the Equipment Energy Efficiency (E3) program doesn't rate all appliances and does not allow for simple comparisons between gas and electric appliances (Australian Government, 2024b).

Information gaps about appliance and building energy efficiency could be addressed by expanding existing disclosure schemes and mandating disclosure of building energy performance at the point of sale or lease, or for some commercial buildings at periodic intervals.

BE.4 Emissions pathways

As gas is phased out and more buildings electrify, electricity is projected to dominate building energy supply by 2050 in the modelled scenarios. Scope 1 and scope 2 emissions are projected to reduce significantly. The scenarios modelled by the authority using AusTIMES broadly reflect the findings of the authority's ground-up analysis (Table BE.3).

Table BE.3: Comparison of change in annual emissions for the built environment and its subsectors based on the AusTIMES modelling and ground-up estimates. Ground-up estimates are determined from technology uptake in ideal conditions

Reference: emissions in 2022 were 28 Mt CO_2-e	Projected emissions reductions to 2050 (Mt CO_2-e)[1]		
	AusTIMES modelling (A50/G2 scenario)	AusTIMES modelling (A40/G1.5 scenario)	Ground-up
Residential buildings	9	9	11
Commercial buildings	3	3	6
Construction	2	2	2
Refrigeration and air-conditioning	7	7	8
Sector total	22	22	27

Note: [1] Abatement was calculated as the difference between base year emissions and the projected 2050 emissions from each model. In AusTIMES, the base year for the abatement calculation was 2025 and in bottom-up estimates the base year for estimates was 2022.

The modelled decarbonisation scenarios align with varying levels of global ambition (see Appendix C). The A50/G2 scenario aligns with global warming remaining below 2°C and Australia reaching net zero emissions in 2050. The A40/G1.5 scenario aligns with a 1.5°C world and Australia reaching net zero emissions in 2040.

Modelled final energy demand for commercial and residential buildings under different scenarios are shown in Figures BE.1 and BE.2. Building stock is projected to grow from 2021 to 2050, with the total number of residential buildings assumed to grow by 65% and commercial floor space by 56% (Climateworks Centre, 2023b). However, final energy demand decreases in both A50/G2 and A40/G1.5 scenarios for residential and commercial buildings. Energy performance is projected to improve across all scenarios.

Commercial buildings are not projected to see the same increase in electricity consumption over time as residential buildings. This is due to residential buildings moving to rely more heavily on electricity for energy as natural gas and liquid petroleum gas (LPG) are phased out, while some natural gas and oil consumption remain in commercial buildings. This discrepancy reflects the greater challenges in electrifying commercial buildings compared to residential buildings, as discussed in this chapter.

Oil consumption in commercial buildings is projected to decrease significantly from 20 PJ to under 2 PJ in both scenarios. Biomethane is an almost pure source of methane produced by purifying biogas or through the gasification and then methanation of solid biomass (IEA, 2020a). Biomethane is not projected to form part of the energy mix for residential or commercial buildings, as electrification is a cheaper way to decarbonise. Commercial buildings are projected to have a small amount (less than 1 PJ) of hydrogen consumption in 2050 which will be used in pipeline blending. Residential buildings, however, are not projected to consume hydrogen. LPG is typically a bottled fuel and is commonly used for water heating, space conditioning and cooking in regional and mobile applications, but LPG emissions in residential buildings are projected to be phased out in both scenarios due to electrification (GEA, 2023). Biomass as a residential fuel source (i.e. wood combustion) grows in both scenarios. This biomass growth is an artefact of the model, as there is no option for fuel switching from biomass. The model considers biomass to be a net zero energy source, although in reality there are other positive and negative effects associated with the use of wood as a fuel.

Total scope 1 emissions for buildings decrease in both scenarios at almost the same rate (Figure BE.3). This is consistent with the strong ambition needed and potential for the sector that many expert stakeholders emphasised to the authority during consultation.

This chapter has identified electrification coupled with decarbonisation of the electricity system as critical to decarbonising the built environment. The modelling shows that in both scenarios the decarbonisation of electricity generation is critical to reducing the built environment's scope 2 emissions. As expected, the A40/G1.5 scenario sees electricity sector emissions reduce further and faster than the A50/G2 scenario (Figure BE.3).

The 2021 Census found that 70% of private dwellings were separate houses, 16% were apartments and 13% were townhouses (ABS, 2022b). Consistent with this data, approximately 82% of residential building emissions come from detached dwellings, 8% from apartments and 10% from semi-detached dwellings (Figure BE.4). While the A40/G1.5 scenario sees slightly faster decarbonisation of residential buildings, both scenarios project that the three residential building types almost completely decarbonise due to electrification.

Figure BE.1: Final energy demand by commercial buildings

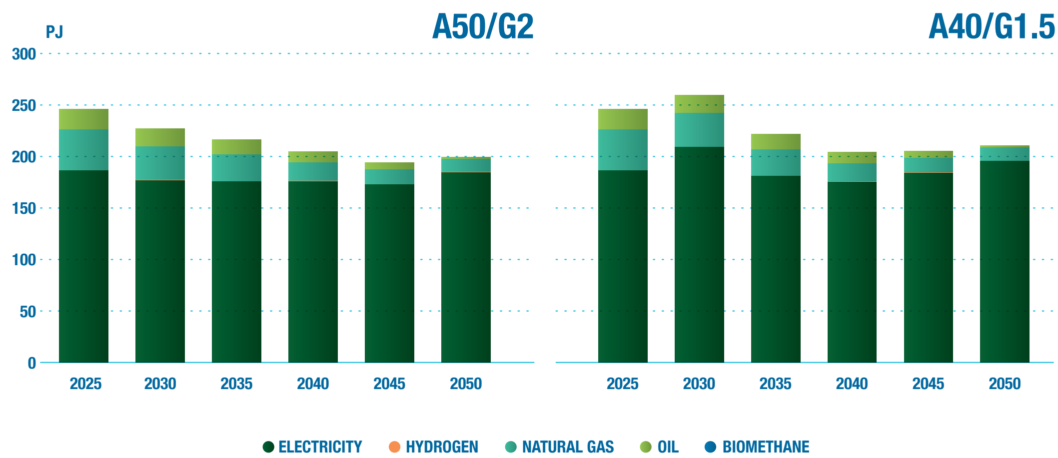


Figure BE.2: Final energy demand by residential buildings

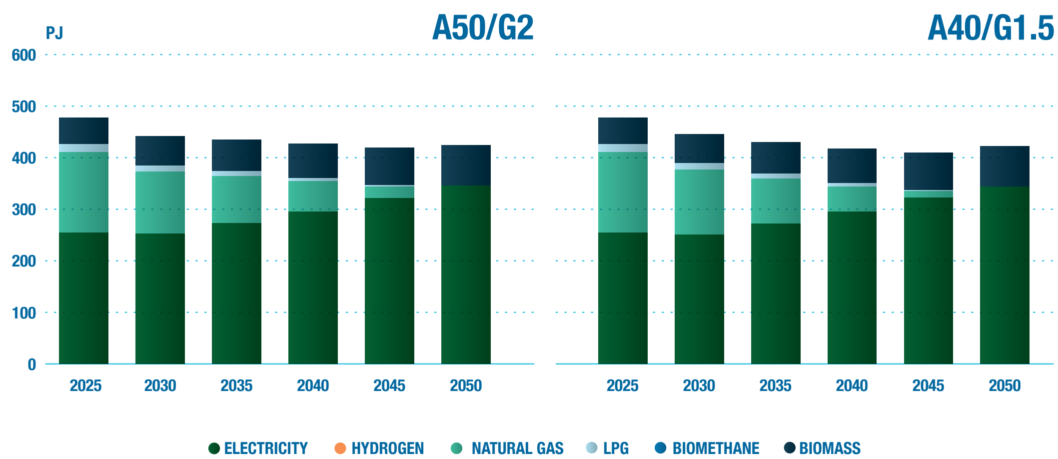


Figure BE.3: Total building emissions, scope 1 and scope 2 emissions (Mt CO_2-e)

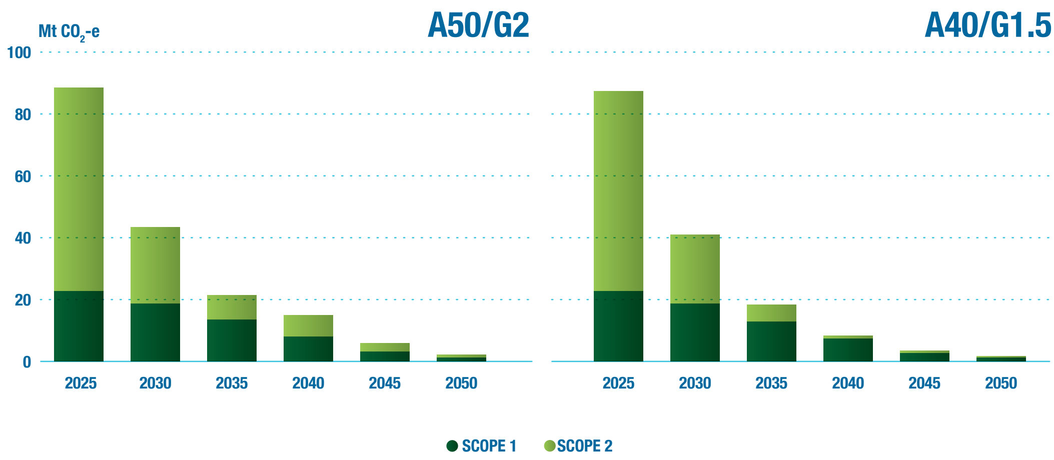
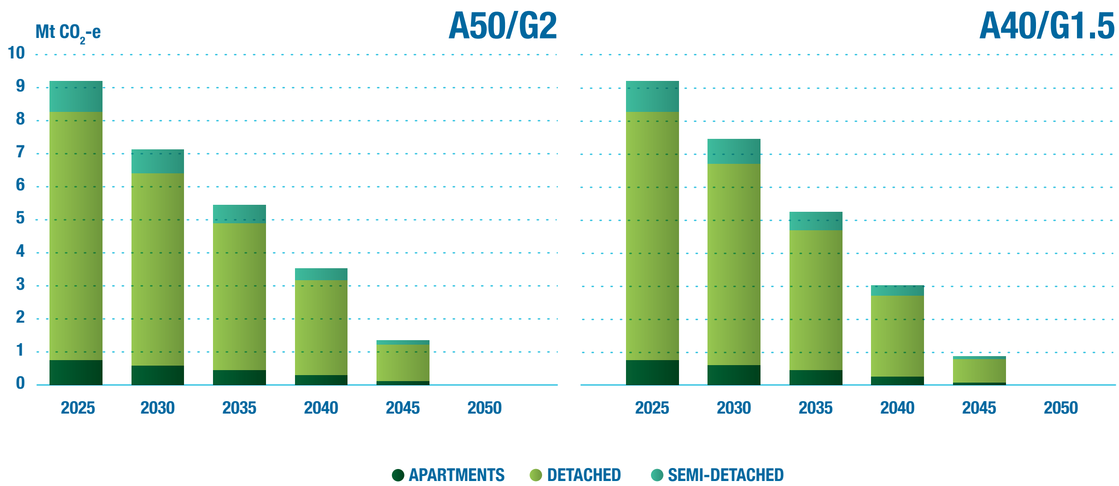


Figure BE.4: Residential building scope 1 emissions, split by building type (Mt CO_2-e)



Source: CSIRO modelling in AusTIMES commissioned by the Climate Change Authority

The built environment sector has many data gaps and areas of incomplete information. While the authority has made every effort to ensure the robustness of this analysis, there are many relevant data sets that are simply not collected.

BE.4.1 Residual emissions

The authority's analysis and most other relevant analyses indicate there could be approximately 1 Mt CO_2-e of residual emissions in the built environment sector by 2050 (Table BE.4), potentially comprising refrigerant gases, consumption of biomass and biomethane in residential buildings, and diesel and biomethane in commercial buildings. These could be further addressed by accelerating building electrification, improving management of refrigerant gases, a faster asset replacement cycle for assets with refrigerants, and a coordinated national gas phase out.

Table BE.4: Estimates of built environment residual emissions

Source	Residual emissions by 2050 (Mt CO2-e)
CCA scenario A50/G2	1
CCA scenario reference A40/G1.5	1
CSIRO Rapid Decarbonisation (CRD) scenario (Brinsmead et al., 2023).	2.2 (0.7 from residential and 1.5 from commercial buildings)
Climateworks Decarbonisation Futures (1.5°C warming scenario) (Climateworks Centre, 2023b).	0.3
Climateworks Decarbonisation Futures (<2°C warming scenario) (Climateworks Centre, 2023b).	0.9

BE.5 References

28th Conference of the Parties. (2023). *Global renewables and energy efficiency pledge.* CoP28 UAE Website. https://www.cop28.com/en/global-renewables-and-energy-efficiency-pledge

ABCB. (Australian Building Codes Board) (2023a). *National Construction Code 2022 Volume 2*. https://ncc.abcb.gov.au/system/files/ncc/ncc2022-volume-two-20230501b.pdf

ABCB. (2023b). *NCC 2022 state and territory adoption dates.* Australian Building Codes Board Website. https://www.abcb.gov.au/ncc-2022-state-and-territory-adoption-dates

ABCB. (2024). *PCD 2025 - Commercial building energy efficiency*. https://www.abcb.gov.au/pcd/pcd-2025-commercial-building-energy-efficiency

ABS (Australian Bureau of Statistics). (2022a). *Estimated dwelling stock.* ABS Website. https://www.abs.gov.au/statistics/industry/building-and-construction/estimated-dwelling-stock/latest-release

ABS. (2022b). *Housing: Census. Census 2021.* https://www.abs.gov.au/statistics/people/housing/housing-census/latest-release

ABS. (2023). *Average Floor Area of New Residential Dwellings.* https://www.abs.gov.au/articles/average-floor-area-new-residential-dwellings

ACOSS (Australian Council of Social Services). (2024). Funding and financing energy performance and climate-resilient retrofits for low-income housing. https://www.acoss.org.au/wp-content/uploads/2024/02/ACOSS-Report-Funding-and-Financing-Low-income-retrofits-January-2024-.pdf

ACT Government. (n.d.). *Singing in the shower – a guide to hot water heat pumps*. Retrieved July 2, 2024, from https://www.climatechoices.act.gov.au/policy-programs/sustainable-household-scheme/buyers-guides/singing-in-the-shower-a-guide-to-hot-water-heat-pumps

ACT Government. (2021). *Preventing new gas network connections.* Everyday Climate Choices Website. https://www.climatechoices.act.gov.au/policy-programs/preventing-new-gas-network-connections

ACT Government. (2024). *The Integrated Energy Plan 2024-2030: Our pathway to electrification.* https://www.climatechoices.act.gov.au/__data/assets/pdf_file/0006/2509458/integrated-energy-plan-2024-2030.pdf

AEMO. (2024). *2024 Integrated System Plan (ISP).* https://aemo.com.au/en/energy-systems/major-publications/integrated-system-plan-isp/2024-integrated-system-plan-isp

AER (Australian Energy Regulator). (2024, June 21). *Gas quarterly disconnection reporting.* https://www.aer.gov.au/documents/aer-gas-quarterly-disconnection-reporting-21-june-2024

ASBEC (Australian Sustainable Built Environment Council). (2016). *Low carbon, high performance: How buildings can make a major contribution to Australia's emissions and productivity goals.* https://www.asbec.asn.au/wordpress/wp-content/uploads/2016/05/160509-ASBEC-Low-Carbon-High-Performance-Summary-Report.pdf

ASBEC. (2022). *Unlocking the pathway: Why electrification is the key to net zero buildings.* https://www.asbec.asn.au/research-items/unlocking-the-pathway-why-electrification-is-the-key-to-net-zero-buildings/

ASBEC. (2023). *Future gas strategy consultation response.* https://www.asbec.asn.au/wordpress/wp-content/uploads/2023/12/231123-FINAL-ASBEC-response_Future-Gas-Strategy.pdf

ASBEC. (2024). *Embodied Carbon Emissions in Australia's Built Environment.* https://www.asbec.asn.au/wordpress/wp-content/uploads/2024/06/ASBEC-ZP103756_Embodied_carbon_emission_Issues_paper_v1.2.pdf

ATO (Australian Taxation Office). (2023, August 10). *Residential rental property items.* Australian Taxation Office Website. https://www.ato.gov.au/forms-and-instructions/rental-properties-2023/residential-rental-property-assets/residential-rental-property-items

Australian Government. (2024a). *GEMS Act*. https://www.energyrating.gov.au/

Australian Government. (2024b). *Save energy, save money, reduce emissions.* https://www.energyrating.gov.au/

Australian Treasury. (2023). *Delivering the National Housing Accord*. The Treasury Website. https://treasury.gov.au/housing-policy/accord

BCG (Boston Consulting Group). (2021). *Climate paths 2.0: A program for climate and Germany's future development*. https://www.bcg.com/germany/climate-paths

Blundell, L. (2010, January 3). *Case study – Woolies gets a green light.* The Fifth Estate.

Brinsmead, T., Verikios, G., Cook, S., Green, D., Khandoker, T., Kember, O., Reedman, L., Rodriguez, S., & Whitten, S. (2023a). *Pathways to Net Zero Emissions - An Australian Perspective on Rapid Decarbonisation*. https://doi.org/10.25919/gdxj-vv11

Built Australia. (n.d.). *Advancing the industry forward for Atlassian*. Built. Retrieved July 4, 2024, from https://www.built.com.au/projects/atlassian-central/

Bunning, J., Beattie, C., Rauland, V., & Newman, P. (2013). *Low-Carbon Sustainable Precincts: An Australian Perspective. Sustainability,* 5(6), 2305–2326. https://doi.org/10.3390/su5062305

Butler, C., Denis-Ryan, A., & Kelly, R. (2020). *Decarbonisation Futures: Solutions, actions and benchmarks for a net zero emissions Australia*. https://www.climateworkscentre.org/resource/decarbonisation-futures-solutions-actions-and-benchmarks-for-a-net-zero-emissions-australia/

BVR Energy. (2023, October 13). *Reduce Cost Of Solar Panels Through Effective Battery Storage Solutions*. BVR Energy Website. https://www.bvrenergy.com.au/blog/maximising-your-solar-investment-with-battery-storage-options

CCA (Climate Change Authority). (2023). *2023 Annual Progress Report.* https://www.climatechangeauthority.gov.au/annual-progress-advice-0

CCA. (2024). *National Sectoral Pathways Emissions Mapping based on estimates published in Australia's National Greenhouse Accounts.*

CEC (Clean Energy Council). (2023). *Clean Energy Australia: Report 2023.* https://www.cleanenergycouncil.org.au/resources/resources-hub/clean-energy-australia-report

CEC. (2024). *Powering homes, empowering people: A national Consumer Energy Resources roadmap*. https://assets.cleanenergycouncil.org.au/documents/resources/reports/Powering-Homes-Empowering-People-CER-Roadmap.pdf

CEF (Circle Economy Foundation). (2024). T*he Circularity Gap Report 2024*. https://www.circularity-gap.world/2024

CEFC (Clean Energy Finance Corporation). (2021). *Australian buildings and infrastructure: Opportunities for cutting embodied carbon*. https://www.cefc.com.au/insights/market-reports/australian-buildings-and-infrastructure-opportunities-for-cutting-embodied-carbon/

CEFC. (2022). *Landmark buildings and the path to net zero emissions*. https://www.cefc.com.au/media/qpjiif3t/awof-mwof.pdf

Cement Industry Federation. (2020). *2020 Industry Report.* http://cement.org.au/australias-cement-industry/industry-report/

Central Coast Health Promotion Service. (2024). Active transport. NSW Government Website. https://www.healthpromotion.com.au/programs-and-projects/active-transport/

Climate Active. (2019). *Holcim*. https://www.climateactive.org.au/buy-climate-active/certified-members/holcim

Climateworks Centre. (2023a). *Climate-ready homes: Building the case for a renovation wave in Australia*. https://www.climateworkscentre.org/resource/climate-ready-homes-building-the-case-for-a-renovation-wave-in-australia/

Climateworks Centre. (2023b). *Climateworks Centre decarbonisation scenarios 2023*. https://www.climateworkscentre.org/scenarios2023

Cool Coalition. (n.d.). *Global Cooling Pledge.* Retrieved July 2, 2024, from https://coolcoalition.org/global-cooling-pledge/

CSIRO (Commonwealth Scientific and Industrial Research Organisation). (2021). *It's in the stars! How scientists figure out your home's energy rating.* Commonwealth Scientific and Industrial Research Organisation. https://www.csiro.au/en/news/all/articles/2021/september/its-in-the-stars-how-scientists-figure-out-your-homes-energy-rating

CSIRO. (2024). *Rapid decarbonisation pathways for Australia.* https://www.csiro.au/en/research/environmental-impacts/decarbonisation/pathways-for-australia-report

DCCEEW (Department of Climate Change Energy the Environment and Water). (n.d.). *Appliances*. Energy.Gov.Au. Retrieved July 4, 2024, from https://www.energy.gov.au/households/appliances

DCCEEW. (2021). *Hydrofluorocarbon* (HFC) phase-down. DCCEEW Website. https://www.dcceew.gov.au/environment/protection/ozone/hfc-phase-down

DCCEEW. (2022a). *Australia's national greenhouse accounts: Data on Australia's greenhouse gas emissions*. Australia's National Greenhouse Accounts Website. https://greenhouseaccounts.climatechange.gov.au/

DCCEEW. (2022b). *Commercial Building Baseline Study 2022.* https://www.dcceew.gov.au/energy/publications/commercial-building-baseline-study-2022

DCCEEW. (2018). *Trajectory for low energy buildings.* https://www.energy.gov.au/energy-and-climate-change-ministerial-council/energy-ministers-publications/trajectory-low-energy-buildings

DCCEEW. (2019). *Achieving Low Energy Existing Commercial Buildings in Australia.* https://www.dcceew.gov.au/energy/publications/achieving-low-energy-existing-commercial-buildings-australia

DCCEEW. (2023a). *Annual Climate Change Statement 2023*. https://www.dcceew.gov.au/sites/default/files/documents/annual-climate-change-statement-2023.pdf

DCCEEW. (2023b). *Australia's emissions projections 2023.* https://www.dcceew.gov.au/sites/default/files/documents/australias-emissions-projections-2023.pdf

DCCEEW. (2023c). *Cold Hard Facts 2022 – Key developments and emerging trends in the refrigeration and air conditioning industry in Australia*. https://www.dcceew.gov.au/environment/protection/ozone/publications/cold-hard-facts-2022

DCCEEW. (2023d). *Heat pumps – Emerging trends in the Australian market*. https://www.dcceew.gov.au/sites/default/files/documents/heat-pumps-emerging-trends-in-australian-market.pdf

DCCEEW. (2023e). *Ozone Depleting Substances and Synthetic Greenhouse Gases.* Department of Climate Change, Energy, the Environment and Water. https://www.dcceew.gov.au/environment/protection/ozone

DCCEEW. (2023f). *Per- and poly-fluoroalkyl substances (PFASs). Department of Climate Change, Energy, the Environment and Water.* https://www.dcceew.gov.au/environment/protection/chemicals-management/pfas

DCCEEW. (2024a). *Australia's national greenhouse accounts: Data on Australia's greenhouse gas emissions.* Australia's National Greenhouse Accounts Website. https://greenhouseaccounts.climatechange.gov.au/

DCCEEW. (2024b). *Circular Economy Ministerial Advisory Group Interim Report.* https://www.dcceew.gov.au/sites/default/files/documents/circular-economy-ministerial-advisory-group-interim-report.pdf

DCCEEW. (2024c). *Cold Hard Facts 4* (unpublished).

DCCEEW. (2024d). *Commercial Building Disclosure (CBD) Program Expansion Public Consultation Paper.* https://storage.googleapis.com/files-au-climate/climate-au/p/prj2de77ad47d17c41065a89/page/CBD_Expansion_Consultation_Discussion_Paper_WCAG.pdf

DCCEEW. (2024e). *Environmentally Sustainable Procurement Policy.*

DCCEEW. (2024f). *Housing: Lighting. Energy Gov Website*. https://www.energy.gov.au/households/lighting

DCCEEW. (2024g). *National Energy Performance Strategy.* https://www.dcceew.gov.au/energy/strategies-and-frameworks/national-energy-performance-strategy

DCCEEW. (2024h). *Global warming potential values of hydrofluorocarbon refrigerants.* Department of Climate Change, Energy, the Environment and Water. https://www.dcceew.gov.au/environment/protection/ozone/rac/global-warming-potential-values-hfc-refrigerants

Denis-Ryan, A., & Gordon, J. (2024). *Fast, efficient, flexible electrification can cut energy bills and support the shift to renewables.* Institute for Energy Economics and Financial Analysis. https://ieefa.org/resources/fast-efficient-flexible-electrification-can-cut-energy-bills-and-support-shift-renewables

Denniss, R., & Roussac, C. (2024). *Buildings as batteries: How buildings can support the clean energy transition*. https://australiainstitute.org.au/wp-content/uploads/2024/04/P1278-Buildings-as-batteries-2024-update-Web.pdf

DISR (Department of Industry Science and Resources). (2024a). *Future Gas Strategy.* https://www.industry.gov.au/publications/future-gas-strategy

DISR. (2024b). *Future Gas Strategy Analytical Report.* https://www.industry.gov.au/publications/future-gas-strategy-analytical-report

DISR. (2024c, June 21). *Building Ministers' Meeting: Communiqué June 2024.* https://www.industry.gov.au/news/building-ministers-meeting-communique-june-2024

DITRDCA (Department of Infrastructure, Transport, Regional Development, Communications and the Arts). (2024). *National Urban Policy Consultation Draft.* https://www.infrastructure.gov.au/sites/default/files/documents/draft-national-urban-policy.pdf

DTP (Department of Transport and Planning). (2023). *Victoria's gas substitution roadmap*. https://www.planning.vic.gov.au/guides-and-resources/strategies-and-initiatives/victorias-gas-substitution-roadmap

Dunn, S. (2023, September 1). Embodied carbon in buildings: a new frontier in greenhouse gas reduction. UNSW Newsroom. https://www.unsw.edu.au/newsroom/news/2023/09/embodied-carbon-in-buildings--a-new-frontier-in-greenhouse-gas-r

EEC (Energy Efficiency Council). (2023). *Clean Energy, Clean Demand*. https://www.eec.org.au/uploads/Projects/EEC%20Clean%20Energy%20Clean%20Demand%20-%202023.pdf

ENA (Energy Networks Australia). (2021). *Reliable and clean gas for Australian homes.* https://www.energynetworks.com.au/resources/fact-sheets/reliable-and-clean-gas-for-australian-homes-2/

EPA (Environmental Protection Agency). (2016). Protection of Stratospheric Ozone: New Listings of Substitutes; Changes of Listing Status; and Reinterpretation of Unacceptability for Closed Cell Foam Products Under the Significant New Alternatives Policy Program;

and Revision of Clean Air Act Section 608 Venting Prohibition for Propane, Pub. L. No. 81 FR 86778. https://www.federalregister.gov/documents/2016/12/01/2016-25167/protection-of-stratospheric-ozone-new-listings-of-substitutes-changes-of-listing-status-and

European Commission. (2024). *EU-Rules Guidance on the EU's F-gas Regulation and its legal framework.* Climate Action. https://climate.ec.europa.eu/eu-action/fluorinated-greenhouse-gases/eu-rules_en

European Parliament. (2023, May 24). *Circular economy: definition, importance and benefits.* European Parliament Website. https://www.europarl.europa.eu/topics/en/article/20151201STO05603/circular-economy-definition-importance-and-benefits

Fan, T., & Chapman, A. (2022). *Policy Driven Compact Cities: Toward Clarifying the Effect of Compact Cities on Carbon Emissions.* Sustainability, 14(19). https://doi.org/10.3390/su141912634

Feyisa, G. L., Dons, K., & Meilby, H. (2014). Efficiency of parks in mitigating urban heat island effect: An example from Addis Ababa. *Landscape and Urban Planning, 123*, 87–95. https://doi.org/https://doi.org/10.1016/j.landurbplan.2013.12.008

Forsgren, M., Östgren, E., & Tschiesner, A. (2019, April 9). *Harnessing momentum for electrification in heavy machinery and equipment.* McKinsey & Company: Automotive & Assembly. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/harnessing-momentum-for-electrification-in-heavy-machinery-and-equipment

GBCA (Green Building Council of Australia). (2022). Fossil Fuel Free Construction Site. https://www.gbca.org.au/get resources/2084/495BB-0287852FA00287B632CB34C16BD

GBCA. (2023a). F*rom net zero to zero: A discussion paper on grid-interactive efficient buildings.* https://gbca-web.s3.amazonaws.com/media/documents/grid-interactive-efficient-buildings-discussion-paper_Q0FoGV8.pdf

GBCA. (2023b). *Unlocking the value: A practical guide for sustainable finance in the Australian real estate sector*. https://gbca-web.s3.amazonaws.com/media/documents/gbca-sustainable-finance-final.pdf

GBCA, & PCA (Property Council Australia). (2023). *Every Building Counts.* https://everybuildingcounts.com.au/wp-content/uploads/sites/37/2023/04/Every-Building-Counts-2023-Edition.pdf

GBCA & Thinkstep-anz. (2021). Embodied carbon and embodied energy in Australia's buildings. https://new.gbca.org.au/news/gbca-news/gbca-and-thinkstep-release-embodied-carbon-report/

GEA (Gas Energy Australia). (2023, November 13). Submission to Future Gas Strategy consultation. https://www.gasenergyaus.au/read/2054/future-gas-strategy.html

Geelong Sustainability. (2023, September). Climate Safe Rooms. https://www.geelongsustainability.org.au/project/climate-safe-rooms/

Glüge, J., Scheringer, M., Cousins, I. T., DeWitt, J. C., Goldenman, G., Herzke, D., Lohmann, R., Ng, C. A., Trier, X., & Wang, Z. (2020). An overview of the uses of per- and polyfluoroalkyl substances (PFAS). Environmental Science: Processes & Impacts, 22(12), 2345–2373. https://doi.org/10.1039/D0EM00291G

Gordon, J. (2024). Briefing note: Appliance standards are key to driving the transition to efficient electric homes. https://ieefa.org/resources/appliance-standards-are-key-driving-transition-efficient-electric-homes

Government of France. (2023). MaPrimeRénov' evolves: new products in 2023. MaPrimeRénov' evolves: new products in 2023

Graham, P., Hayward, J., & Foster, J. (2024). GenCost 2023-24. https://www.csiro.au/en/research/technology-space/energy/GenCost

Grattan Institute. (2023). Getting off gas: why, how, and who should pay? https://grattan.edu.au/report/getting-off-gas/

Harrison, G. (2018, March 8). Does it pay to improve your home's efficiency? Pursuit. https://pursuit.unimelb.edu.au/articles/does-it-pay-to-improve-your-home-s-efficiency

Henderson, P. (2023, September 18). The circular economy: a missing piece in city climate action plans? Ellen MacArthur Foundation Website. https://www.ellenmacarthurfoundation.org/articles/the-circular-economy-a-missing-piece-in-city-climate-action-plans

ICLEI (Local Governments for Sustainability Europe). (2023). Stimulating demand for circular construction skills - a guide for public authorities. https://busgocircular.eu/wp-content/uploads/BGC_Guide_for_public_authorities.pdf

IEA (International Energy Agency). (2017). Digitalisation and Energy. https://www.iea.org/reports/digitalisation-and-energy

IEA. (2019). Case Study: Artificial Intelligence for Building Energy Management Systems. https://www.iea.org/articles/case-study-artificial-intelligence-for-building-energy-management-systems

IEA. (2020a). An introduction to biogas and biomethane. Outlook for Biogas and Biomethane: Prospects for Organic Growth. https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/an-introduction-to-biogas-and-biomethane

IEA. (2020b). Energy Efficiency 2020. https://www.iea.org/reports/energy-efficiency-2020

IEA. (2021). Net Zero by 2050: A Roadmap for the Global Energy Sector. https://www.iea.org/reports/net-zero-by-2050

IEA. (2023a). Electrification. International Energy Agency. https://www.iea.org/energy-system/electricity/electrification

IEA. (2023b). France's "MaPrimeRénov" Programme. International Energy Agency.

IEA & UNEP (United Nations Environment Program). (2020). Cooling emissions and policy synthesis report: Benefits of cooling efficiency and the Kigali amendment. https://www.iea.org/reports/cooling-emissions-and-policy-synthesis-report

IEEFA (Institute for Energy Economics and Financial Analysis). (2024). DER could provide $19 billion economic boost by 2040. https://ieefa.org/resources/der-could-provide-19-billion-economic-boost-2040

Infrastructure Australia. (2024). Embodied Carbon Projections for Australian Infrastructure and Buildings. https://www.infrastructureaustralia.gov.au/reports/embodied-carbon-projections-australian-infrastructure-and-buildings

Infrastructure Victoria. (2023a). Choosing Victoria's future: Five urban development scenarios. https://www.infrastructurevictoria.com.au/resources/choosing-victorias-future

Infrastructure Victoria. (2023b). Victoria's cities must be more *compact and connected to shape a better future.* Infrastructure Victoria. https://www.infrastructurevictoria.com.au/news-events/victorias-cities-must-be-more-compact-and-connected-to-shape-a-better-future

IPART (Independent Pricing and Regulatory Tribunal NSW). (2024). Energy Security Safeguard Schemes 2022-23. https://www.energysustainabilityschemes.nsw.gov.au/sites/default/files/cm9_documents/Energy-Security-Safeguard-Schemes-Schemes-update-202223.PDF

IPCC (Intergovernmental Panel on Climate Change. (2021). *The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity (Supplementary Material)*. In Climate Change 2021: The Physical Science Basis. https://doi.org/10.1017/9781009157896.009

IPCC (Intergovernmental Panel on Climate Change). (2022). *Buildings. In Climate Change 2022: Mitigation of Climate Change.* Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_Chapter09.pdf

ISO (International Organization for Standardization). (2018). *ISO 14067: Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification.* International Organization for Standardization. https://www.iso.org/standard/71206.html

Jousseaume, M. (2022). *The French Climate and Resilience Law. Centre de Politique Europeenne.* https://www.cep.eu/fileadmin/user_upload/cep.eu/Studien/cepInput_Franzoesisches_Klima-_und_Resilienzgesetz/cepInput_The_French_Climate_and_Resilience_Law.pdf

JSA (Jobs and Skills Australia). (2023a). *Skills Priority List.* https://www.jobsandskills.gov.au/data/skills-shortages-analysis/skills-priority-list

JSA (Jobs and Skills Australia). (2023b). *The Clean Energy Generation.* https://www.jobsandskills.gov.au/publications/the-clean-energy-generation

Kaka, M., & Pendlebury, R. (2022). *Turning point for incentives to invest in residential batteries.* https://www.aemc.gov.au/turning-point-incentives-invest-residential-batteries

Keegan, M. (2021, June 23). *The Scandinavian way to zero-carbon construction.* British Broadcasting Corporation. https://www.bbc.com/future/article/20210622-the-scandinavian-way-to-zero-carbon-construction

Kneifel, J., O'Rear, E., Webb, D., & O'Fallon, C. (2018). *An exploration of the relationship between improvements in energy efficiency and life-cycle energy and carbon emissions using the BIRDS low-energy residential database.* Energy and Buildings, 160, 19–33. https://doi.org/https://doi.org/10.1016/j.enbuild.2017.11.030

Krarti, M., & Karrech, A. (2024). *Cost Benefits of Net Zero Energy Homes in Australia.* Buildings, 14(4), 1107. https://doi.org/10.3390/buildings14041107

Ma, J., & Yuan, X. (2023). *Techno-economic optimization of hybrid solar system with energy storage for increasing the energy independence in green buildings.* Journal of Energy Storage, 61, 106642. https://doi.org/10.1016/j.est.2023.106642

Makhnatch, P., Mota-Babiloni, A., Rogstam, J., & Khodabandeh, R. (2017). *Retrofit of lower GWP alternative R449A into an existing R404A indirect supermarket refrigeration system.* International Journal of Refrigeration, 76, 184–192. https://doi.org/https://doi.org/10.1016/j.ijrefrig.2017.02.009

Marsden Jacob Associates. (2022). *Carbon abatement opportunities for circular economy, report for NSW EPA: Final Report.* https://www.epa.nsw.gov.au/publications/recyclereuse/carbon-abatement-opportunities-for-circular-economy

Master Builders Australia. (2024). *2024-25 Pre-budget Submission.* https://masterbuilders.com.au/2024-25-pre-budget-submission/

MECLA (Materials & Embodied Carbon Leaders' Alliance). (2023, December). *MECLA Spotlight on Decarbonisation for Local Councils.* Materials and Embodied Carbon Leaders Alliance. https://mecla.org.au/spotlight-on-local-councils/

Ministry of the Environment. (n.d.). *Revised F-Gas Law in Japan. Government of Japan*. Retrieved July 4, 2024, from https://www.env.go.jp/earth/ozone/hiyasu-waza/eng/revised_f-gas_law_in_japan.html

NABERS (National Australian Built Environment Rating System). (2023a). *Annual Report 2022/23.* https://nabers.info/annual-report/2022-2023/

NABERS. (2023b, November 6). *NABERS embodied carbon public consultation.* NABERS Website. https://www.nabers.gov.au/publications/nabers-embodied-carbon-public-consultation

NABERS. (2024). *What is NABERS?* NABERS Website. https://www.nabers.gov.au/about/what-nabers

NatHERS. (2024). *About NatHERS.* NatHERS Website. https://www.nathers.gov.au/

Nicholson, V., & Miatto, A. (2024). *Architects as catalysts of reuse in construction.* Nature Cities, 1(3), 179–181. https://doi.org/10.1038/s44284-024-00042-8

Otte, K., Stelmach, T., Chandan, V., & Delgado, A. (2022). *Digitalisation for the Energy Efficiency of Buildings Operations: Lessons Learned from the EE Hub Digitalisation Working Group.* https://energyefficiencyhub.org/wp-content/uploads/2022/10/DWGReport.pdf

Ozone Protection and Synthetic Greenhouse Gas Management Act 1989, Federal Register of Legislation (2023). https://www.legislation.gov.au/C2004A03755/latest/text

Pelly, R. (2023). Renovation not demolition: a case study of saving carbon on a private residence. *The Structural Engineer,* 101(2), 32–37. https://doi.org/10.56330/FIYN2454

Prasad, D., Dave, M., Kuru, A., Oldfield, P., Ding, L., Noller, C., & He, B. (2021). *Race to Net Zero Carbon: A Climate Emergency Guide for New and Existing Buildings in Australia.* https://www.unsw.edu.au/arts-design-architecture/our-schools/built-environment/our-research/clusters-groups/high-performance-architecture/latest-news/race-to-net-zero-carbon--a-climate-emergency-guide-for-new-and-e

Quay Quarter. (n.d.). *World First Innovation.* Retrieved July 2, 2024, from https://www.quayquartersydney.com.au/articles/sustainability/

RACE for 2030. (2021). *Pathways to scale: Retrofitting One Million+ homes.* https://www.racefor2030.com.au/wp-content/uploads/2021/12/One-Million-Homes_Final-Report-9.12.21.pdf

Rajagopalan, P., Nararajan-Rajeswari, K., Andamon, M. M., Moore, T., Woo, J., Cheng, D., Ambrose, M., Reynolds-Fox, K., Willand, N., Pears, A., Simko, T., & Horne, R. (2023). *Opportunity assessment: Enhancing home thermal efficiency.* https://racefor2030.com.au/wp-content/uploads/2023/05/H2-OA-0199-Final-Report_.pdf

Reich, T. (2023, December). *What digitalization means for transport.* Sustainable Transport Magazine. https://itdp.org/publication/sustainable-transport-magazine-issue-no-35/

Ren, Z., Wang, X., & Chen, D. (2014). *Heat stress within energy efficient dwellings in Australia.* Architectural Science Review, 57(3), 227–236. https://doi.org/10.1080/00038628.2014.903568

Rutovitz, J., Visser, D., Sharpe, S., Taylor, H., Jennings, K., Atherton, A., Briggs, C., Mey, F., Niklas, S., Bos, A., Ferraro, S., Mahmoudi, F., Dwyer, S., Sharp, D., & Mortimer, G. (2021). *Developing the future energy workforce. Opportunity assessment for RACE for 2030*. https://www.racefor2030.com.au/wp-content/uploads/2021/10/RACE-E3-Opportunity-Assessment-FINAL-REPORT-October-2021.pdf

Schmidt, M., Crawford, R. H., & Warren-Myers, G. (2020). *Quantifying Australia's life cycle greenhouse gas emissions for new homes.* Energy and Buildings, 224, 110287. https://doi.org/https://doi.org/10.1016/j.enbuild.2020.110287

Schultz, B. (2023). *University of Technology Sydney's first grid-interactive building!* Buildings Alive. https://buildingsalive.com/university-of-technology-first-grid-interactive-building/

Seo, S., & Foliente, G. (2021). *Carbon Footprint Reduction through Residential Building Stock Retrofit: A Metro Melbourne Suburb Case Study.* Energies, 14(20). https://doi.org/10.3390/en14206550

Storck, M., Slabik, S., Hafner, A., & Herz, R. (2023). Towards Assessing Embodied Emissions in Existing Buildings LCA—Comparison of Continuing Use, Energetic Refurbishment versus Demolition and New Construction. *Sustainability*, 15(18). https://doi.org/10.3390/su151813981

Sustainability Victoria. (2015). *Energy efficiency upgrade potential of existing Victorian homes.* https://assets.sustainability.vic.gov.au/susvic/Report-Energy-Energy-Efficiency-Upgrade-Potential-of-Existing-Victorian-Houses-Sep-2016.pdf

Sustainability Victoria. (2019). *Comprehensive energy efficiency retrofits to existing Victorian houses.* https://assets.sustainability.vic.gov.

au/susvic/Report-Energy-Comprehensive-Energy-Efficiency-Retrofits-to-Existing-Victorian-Houses-PDF.pdf

Sustainability Victoria. (2022). *The Victorian healthy homes program: Research findings.* https://www.sustainability.vic.gov.au/research-data-and-insights/research/research-reports/the-victorian-healthy-homes-program-research-findings

Sustainability Victoria. (2024a, January 30). *Heat-pump hot water systems.* Sustainability Victoria Website. https://www.sustainability.vic.gov.au/energy-efficiency-and-reducing-emissions/save-energy-in-the-home/water-heating/choose-the-right-hot-water-system/heat-pump-water-heaters

Sustainability Victoria. (2024b, April 11). *Reduce water heating costs at home*. Sustainability Victoria Website. https://www.sustainability.vic.gov.au/energy-efficiency-and-reducing-emissions/save-energy-in-the-home/water-heating

Tasmanian Government. (2023). *Tasmanian Future Gas Strategy.* https://recfit.tas.gov.au/__data/assets/pdf_file/0010/486973/Tasmanian_Future_Gas_Strategy.pdf

Tildemann, C., Rayner, J., & Cheung, H. (2022). *Switch and save: How gas is costing households.* https://www.climatecouncil.org.au/wp-content/uploads/2022/10/CC_MVSA0323-CC-Report-Gas-vs-Electricity_V4-Single.pdf

Tirelli, D., & Besana, D. (2023). Moving toward Net Zero Carbon Buildings to Face Global Warming: A Narrative Review. *Buildings*, 13(3), 684. https://doi.org/10.3390/buildings13030684

Toth, Z., & Volt, J. (2021). *Whole-Life Carbon: Challenges and Solutions For Highly Efficient and Climate-Neutral Buildings.* https://www.bpie.eu/wp-content/uploads/2021/05/BPIE_WLC_Summary-report_final.pdf

UNEP (United Nations Environment Program) *Ozone Secretariat. (2023).* Australia. United Nations Environment Programme. https://ozone.unep.org/countries/profile/aus

Wang, K., Costanza-van den Belt, M., Heath, G., Walzberg, J., Curtis, T., Barrie, J., Schröder, P., Lazer, L., & Altamirano, J. C. (2022). *Circular economy as a climate strategy: current knowledge and calls-to-action.* https://www.nrel.gov/docs/fy23osti/84141.pdf

White, C., Odell, P., & Oke, C. (2023). *Many hands make light work: Connecting governments to accelerate climate action.* https://citiespowerpartnership.org.au/many-hands-make-light-work-connecting-governments-to-accelerate-climate-action/

White, S. (2024). *WP1 Energy Management Information System (EMIS) Activity Analysis: Final Report.* https://racefor2030.com.au/wp-content/uploads/2024/03/Progress-report-2-WC.pdf

White, S., Foo, G., Rottcher, P., & Bannister, P. (2023). *Scoping the Digital Innovation Opportunity for Energy Productivity in Non-Residential Buildings.* https://www.dcceew.gov.au/energy/energy-efficiency/buildings/commercial-buildings/digital-innovation-opportunity

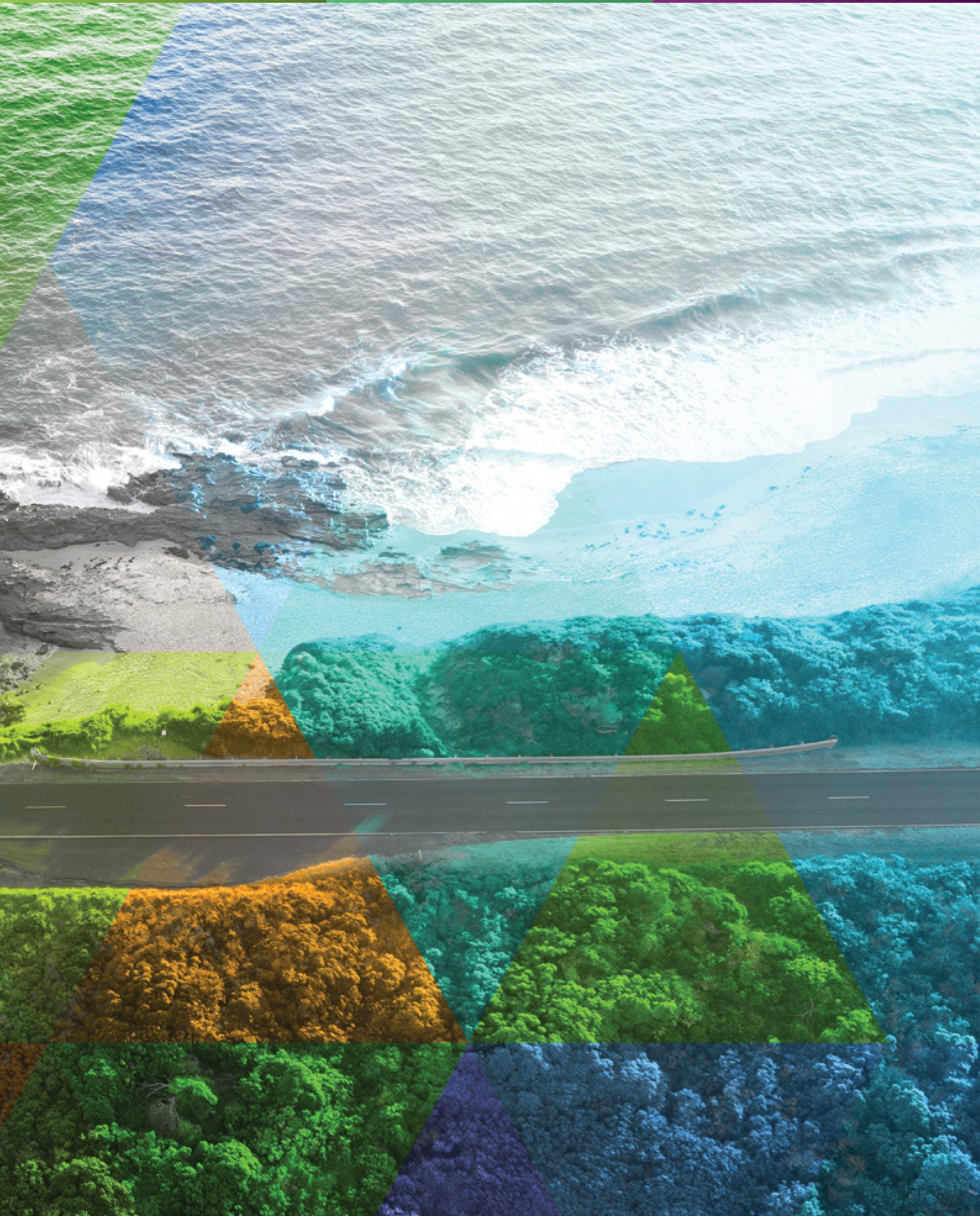
Wingrove, K., & Heffernan, E. (2024). *Australian homes are getting bigger and bigger, and it's wiping out gains in energy efficiency.* The Conversation. https://theconversation.com/australian-homes-are-getting-bigger-and-bigger-and-its-wiping-out-gains-in-energy-efficiency-224741

Wingrove, K., Heffernan, E., & Daly, D. (2024). *Increased home energy use: unintended outcomes of energy efficiency focused policy.* Building Research & Information, 1–19. https://doi.org/10.1080/09613218.2023.2301574

Xu, L., Feng, K., Lin, N., Perera, A. T. D., Poor, H. V., Xie, L., Ji, C., Sun, X. A., Guo, Q., & O'Malley, M. (2024). *Resilience of renewable power systems under climate risks.* Nature Reviews Electrical Engineering, 1(1), 53–66. https://doi.org/10.1038/s44287-023-00003-8

PART 2

National Pathway



National pathway

The technologies described in this report cannot be deployed in isolation, but instead need to be integrated and coordinated as part of rapidly transforming systems, some of which cut across multiple sectors, regions and jurisdictions. Forging a viable national pathway involves addressing sector-specific barriers, some of which will be common to multiple sectors, as well as resolving economy-wide questions that stem from the need for integration, from feedback and from the need to prioritise. All levels of government, industry and communities will need to engage if these national challenges are to be met.

This part of the report reviews pathways to net zero from the national perspective and, together with the sector pathways above, identifies six strategies and sets of actions for Australia to double down on to achieve net zero emissions by 2050, as set out at the start on pages 11-15 of this report:

1. Overcome the ‘green premium’

2. Accelerate the deployment of net zero infrastructure

3. Strengthen the foundations for social licence and a just transition

4. Think global, act local

5. Rapidly address workforce shortages

6. Address information and data gaps

NP.1 How do the sector pathways add up to net zero?

For Australia to reach net zero emissions, every sector must contribute, but emissions in each sector will decline at different rates. Figure NP.1 shows the emissions reduction pathways for each sector under the two scenarios the CSIRO modelled for the authority for this review. In its ground-up analysis of each sector, the authority considered the range of real-world factors not well captured by economic modelling that enhance understanding of the unique emissions trajectories available to each sector and their respective roles in the economy as a whole achieving net zero. The authority’s analysis and the CSIRO’s modelling of potential sector pathways are summarised in Figure S.1 in the Summary section, with green bands illustrative of the range of potential pathways. See Appendices B and C for more information about the authority’s analysis and modelling approaches.

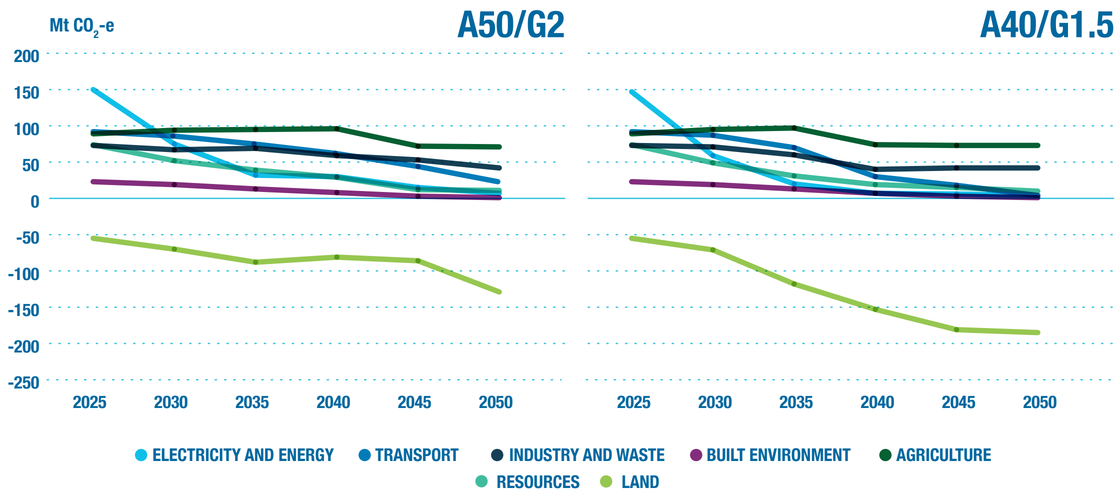
For some sectors, the authority’s ground-up analysis and the two modelled scenarios closely align. In the electricity and energy sector, the technologies exist, the transition is well underway, and there is more certainty about what can be achieved with the right policies. This is also the case for the transport and built environment sectors, although their transitions are less well progressed.

For other sectors there is more uncertainty, reflected by the range of outcomes across the modelling scenarios and ground-up analysis. In the resources, and agriculture and land sectors, the authority’s ground-up analysis found that there are considerable real-world barriers that make the modelled outcomes difficult to achieve. Conversely, the authority's view is that there are opportunities in the industry and waste sector to achieve greater emissions reductions than the modelling suggests.

Ultimately, there are many sets of sector pathways that can combine to achieve net zero by 2050. A clear conclusion from the authority's analysis is that none of the potential sets of pathways will be easy and every sector will need to play a unique but important role. Across all sectors, a significant and urgent ramp up in effort, investment and coordination is required and there are barriers that will need to be overcome if Australia is to achieve its target.

> An economy-wide net zero target does not mean that all emissions from a sector are necessarily eliminated by 2050. There are likely to be residual emissions in most sectors that need to be counterbalanced with carbon dioxide removals to achieve net zero emissions economy-wide.

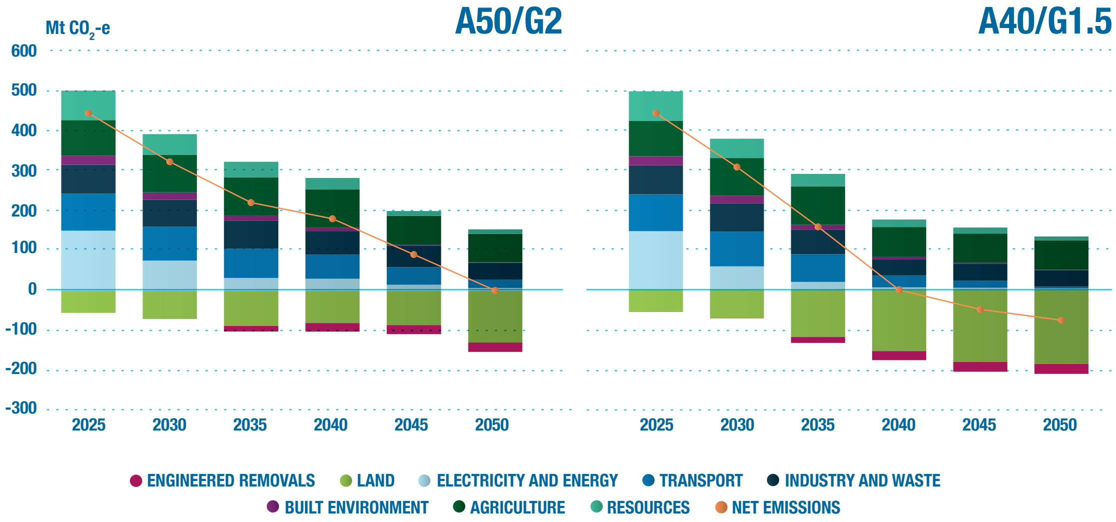
Figure NP.1: Different sectors will reduce emissions at different rates



Source: CSIRO modelling in AusTIMES commissioned by the Climate Change Authority
Note: This figure separates the agriculture and land sector into agriculture and land subsectors. See Figures S.1 and S.2 in the Summary section and the sector chapters for the results of the authority's ground-up analysis.

Australia's most feasible pathways to net zero emissions by 2050 involve reducing emissions as quickly as possible while at the same time scaling up the removal of carbon dioxide from the atmosphere. Figure NP.2 illustrates how the emissions of each sector and carbon removals together achieve net zero emissions by 2050.

Figure NP.2: Gross emissions, removals and a net emissions trajectory, 2025 to 2050



Source: CSIRO modelling in AusTIMES commissioned by the Climate Change Authority
Note: This figure separates the agriculture and land sector into agriculture and land subsectors. See Figures S.1 and S.2 in the Summary section and the sector chapters for the results of the authority's ground-up analysis.

The land sector is the only sector to remove more carbon than it emits. There is broad agreement among business, academia and environmental groups that removals must not delay urgent emissions reductions and that any offsetting of avoidable emissions be limited (Investor Group on Climate Change, Australian Council of Superannuation Investors, Climateworks Centre, Green Building Council of Australia, Qantas Group, Climate Recovery Institute, Australian Council of Social Service, Environmental Defenders Office, Bushfire Survivors for Climate Action, Biocare Projects, Climate Integrity, Sydney Environment Institute, WWF Australia, Australian Conservation Foundation, submissions, 2024).

> *"In the short term, CDR [carbon dioxide removal] is essential in counterbalancing residual emissions from sectors that are difficult to decarbonise quickly. Crucially, CDR is not a substitute for deep and rapid emissions reductions of these sectors – rather it is now necessary to buy back time we have lost from not acting sooner. In the long term, CDR is essential in becoming 'net negative' and removing historical emissions to return Earth's climate to a safe balance. It is an industry that will outlast the energy transition and will likely grow well into the 22nd century."*
>
> Climate Recovery Institute submission, 2024

Policy guardrails could be deployed to ensure Australia's carbon removal potential is used in ways that optimise economic and environmental outcomes. This includes considering how to manage access to different removals for compensating different emissions activities. Access should be prioritised for emissions with no near-term decarbonisation options. Further information about carbon removals can be found in the authority's 2023 insights paper, Reduce, remove and store: The role of carbon sequestration in accelerating Australia's decarbonisation (CCA, 2023b).

Market-based approaches to allocating removals across the economy entail risks. The authority heard concern from stakeholders that landholders were selling the carbon stored on their land as offsets, without realising that they could not also count the abatement themselves. Furthermore, land-based removals are a one-shot option because once the carbon is removed from the atmosphere it must be stored for a very long term (known in carbon markets as 'permanence'). For that reason, land-based removals should be treated as a finite resource. The authority observed that market participants have a low level of understanding of the finite nature of Australia's land-based removals resources. The authority further notes this could indicate a market failure if, due to low levels of 'climate literacy', permanence is not appropriately valued in offsets markets.

In developing its Net Zero Plan, the government could consider other ways to allocate removals across the economy. Policy options include setting sector targets and policy interventions based on the removal potential of the sector in the absence of trading, capping the use of offsets (particularly land-based removals), and allocating different types and/or quantities of removals to different sectors. For example, biological removals could be prioritised for use within the agriculture and land sector.

NP.2 What is the government's role?

The government has an important role in articulating the vision for a net zero Australia, how the different parts of the economy can contribute to that vision, and leading Australia to overcome the barriers that stand in the way. The transition to a net zero economy requires collaboration and coordination across many decision-makers in governments, businesses and communities. By providing a compelling and credible vision for decision-makers to work towards, governments can lay the groundwork for more effective collaboration. The Australian Government's Net Zero Plan is an opportunity for it to provide this vision.

> A zero-carbon mindset must become the new normal so that it permeates operational, policy and investment decisions across governments, businesses and communities.

Governments also set the institutional landscape in which the transition will take place. Having the right institutions working together in the right ways can enable planning and coordination that spans political cycles. In Australia, the primary institutions at the national level that focus on the long-term pursuit of the net zero vision include the Net Zero Economy Authority, the Clean Energy Finance Corporation, the Australian Renewable Energy Agency, the Clean Energy Regulator, and the Climate Change Authority. The energy market bodies, including the Australian Energy Market Operator, also form an important part of the institutional landscape.

All levels of government must work together in planning for and coordinating the transition to net zero emissions, to ensure policy architecture, investment horizons and regulatory environments are aligned (BCA, 2023). Although the Australian Government is the relevant party to the Paris Agreement and therefore accountable for fulfilling its legal obligations, the states and territories have a significant role to play given their authority over many energy, infrastructure and transport projects (DCCEEW, 2022a). Close cooperation between the Australian Government and states and territories will therefore be necessary to ensure policy and legislative alignment. Similarly, responsibility for skills, education and training is shared between the federal and state and territory governments. Local governments play a significant role in land use planning and development within their jurisdiction, and are often best-placed to engage with the community to provide education and gather input and feedback on planning and development matters (ICLEI Local Governments for Sustainability & Ironbark Sustainability, 2021).

The scale of financing needed to achieve net zero requires all levels of government to accelerate and coordinate financial contributions. Cost-sharing arrangements between the Australian Government, state and territory governments at a whole of economy level are guided by the Federation Funding Agreements Framework (CFFR, 2020). In addition, the National Energy Transformation Partnership, agreed in 2022 by Commonwealth, state and territory energy ministers, provides a framework for cooperation across governments to support the transformation of Australia's energy sector (Energy Ministers, 2022). It provides for the Australian Government to negotiate new bilateral Renewable Energy Transformation Agreements with state and territory governments to meet shared objectives in the renewable energy transition (DCCEEW, 2024). Implementing similar frameworks for cooperation across all sectors of the economy, with first ministers overseeing coordination across portfolios, could help progress towards net zero.

> *'This rate of growth cannot be achieved unless Australian federal and state governments work together with industry to expedite projects, mobilise capital, and prepare Australian workers to make the most of this opportunity.'*
>
> Tesla submission, 2024

The Australian Government's Net Zero Economy Authority can play a central role in coordinating place-based implementation of net zero measures across governments, industry, and communities. It could also coordinate co-design of initiatives with local governments to support the development of place-based responses, which account for the different needs and aspirations of individual communities (see also sections NP.4 and NP.8).

Box NP.1: System transformation: Renewable electricity

The transformation of the electricity system requires the concurrent and rapid deployment of renewable generation, firming and transmission. The build out of supply must be timed to match rising demand due to electrification in the transport, built environment, resources and industry sectors as ageing coal generators exit the system.

At the same time, the grid will need to be geographically extended to provide renewable energy to electrifying industry and mines and to connect Renewable Energy Zones. Consumer energy resources will also need to be orchestrated to contribute to grid stability and reduce costs.

Governments will also need to carefully coordinate the contributions of different energy sources to the economy across time and locations, including optimising the mix of electricity, gas, hydrogen, and renewable fuels.

> *'Cost-effective, reliable, secure, renewable, and low GHG emissions energy is fundamental to delivering the large-scale emissions reductions required to achieve the world's collective climate goals and producing the commodities to drive the transition.'*
>
> BHP submission, 2024

Box NP.2: System transformation: Industrial decarbonisation

Low emissions industrial precincts can facilitate the decarbonisation of the industry sector by co-locating industrial facilities and supporting infrastructure such as renewable electricity generation and storage, transport hubs, carbon capture and storage infrastructure, hydrogen infrastructure, water infrastructure, waste processing facilities, training centres, higher education and research institutions, and housing and amenities for workers.

> *'[Government should use] …a suite of policies to enable the design and implementation of Net Zero Industrial Precincts (NZIPs)… NZIPs are the international gold standard for enabling heavy industry to engage with and support a 1.5°C temperature goal. They offer an economic and policy approach that can rapidly transition existing industries and build new green exports. Australia has room to catch up in regard to the formal declaration of NZIPs, associated targets, and in the public-private investment needed to build infrastructure and deploy clean technologies.'*
>
> Climateworks submission, 2024

NP.3 How do we prioritise competing land uses?

While Australia is a large country, the transition to net zero requires balancing competing priorities for land use. Agriculture and forestry make up around 57% of the country, protected areas and other natural environments around 39%, and water around 3%. Only around 1% is for all other uses (DAFF, 2024a). Overlapping with these land use categories, the First Nations estate makes up 57% of the country (DAFF, 2022). As Australia transitions to net zero emissions, competing land uses are likely to include:

- cultural, social, biodiversity and environmental uses
- resource extraction, location of heavy industry, renewable generation and transmission projects
- production of food, fibre, timber products, carbon credits, and biomass for energy.

Much of Australia's environment is arid and at risk of becoming more so due to climate change (CSIRO & BOM, 2022) and this is likely to exacerbate competition for suitable land.

> Australia can successfully transition to net zero while protecting important cultural and environmental priorities and maintaining its food security and agricultural industries.

Australia can successfully transition to net zero while protecting important cultural and environmental priorities and maintaining its food security and agricultural industries. Reforming Australia's planning system in a way that manages competing priorities while also accelerating planning and approval decisions, will need to be a key priority for governments. This will involve establishing benefit sharing practices with governments, landholders, developers, First Nations people and communities (see also section NP.8). Community participation and acceptance should be central to decisions about how Australia uses its land.

A sustainably focused agriculture and land sector can manage and enhance carbon stored in vegetation and soils (land-based removals), generate employment, provide timber and wood products, and reduce climate risks to biodiversity. Stakeholders consulted by the authority highlighted the opportunity to achieve both biodiversity and carbon benefits through the integration of environmental outcomes with carbon markets, such as the ACCU Scheme (Climateworks Centre, Department for Environment and Water – South Australia, Infrastructure Sustainability Council, Eco-Markets Australia, Climate Friendly, Australian Climate and Biodiversity Foundation, submissions, 2024).

Others called for greater coordination of land use policies and strategies across sectors and levels of government (AFI, 2023). This can help ensure decisions made about the transition to net zero balance community values with other environmental and economic outcomes.

Regional-scale planning that supports inclusive community participation can help ensure emissions reduction and removals activities are successful, balance competing priorities and achieve multiple positive outcomes (Dumbrell et al., 2024).

NP.4 How can planning and approval processes accelerate and enable the transition?

Government coordination is essential for effective community consultation and approval processes for major transition projects. Planning and coordination can also help to ensure that a skilled workforce is available at the location where the new infrastructure and industries are being built (see also section NP.7). The authority observes that the Net Zero Economy Authority would be well-placed to lead such efforts, with the appropriate mandate and resources.

Australia's energy transition requires an unprecedented infrastructure build, often with multiple projects and proponents in the same region. For example, the development of renewable energy zones with generation, storage and transmission infrastructure, and low emissions industrial precincts with multiple facilities and pieces of infrastructure involve concentrating multiple projects in a relatively small area. Separate consultation processes for multiple projects in the same community can cause consultation fatigue and diminish community support for energy transition projects (DCCEEW, 2024b). Governments can assist by proactively leading and coordinating engagement with communities to provide information, facilitating benefit sharing, receiving feedback and negotiating outcomes.

> In formulating its Net Zero Plan, the Australian Government will need to consider how regulatory frameworks can enable the rapid development of infrastructure required for decarbonising the economy.

In formulating its Net Zero Plan, the Australian Government will need to consider how regulatory frameworks can enable the rapid development of infrastructure required for decarbonising the economy. Australian planning processes are often complex, requiring the involvement of multiple government agencies and multiple levels of government to progressively approve elements of a project. The authority welcomes the Australian Government's decision in the 2024 Budget to provide $134.2 million to strengthen and streamline environmental approval decisions on priority projects, including renewables and critical minerals projects. The commitment includes $24.5 million for improving planning and working with state and territory governments in seven priority regions to clarify where developments can and can't occur.

Another essential role for governments is anticipating and coordinating solutions to 'chicken-and-egg' problems. Common user infrastructure such as electricity transmission, pipelines, hydrogen infrastructure and ports need sufficient certainty there will be customer demand before they can attract investment. But customers need to know the infrastructure will be there, costs will not be prohibitive, and the risk of extended downtime of their new equipment can be managed before making their own investment decisions. Government coordination and financial support can help plan for and de-risk investment and enable progress of these developments.

> *'Significant coordination of public and private planning and investment will be required to transform and replace industries that have been at the centre of our historic economic growth and create a new green industrial base.'*
> National Australia Bank submission, 2024

Coordination is also required to ensure the size of the infrastructure build matches industry demand over time. The authority welcomes the Australian Government's Critical Minerals National Productivity

Initiative, which provides $10 million to work in partnership with states and territories to develop pre-feasibility studies of common user infrastructure for the critical minerals sector (Australian Treasury, 2024a).

> *'Regionally targeted approaches to developing common-use infrastructure for electricity transmission, under programmes like Rewiring the Nation, will be critical, particularly in mining centres like the Pilbara.'*
>
> Fortescue submission, 2024

NP.5 How will these technologies be financed?

Globally, it is estimated more than USD 10 trillion will be needed annually from 2031 to 2050 to support a 1.5°C compatible pathway (CPI, 2023). In Australia, recent modelling by the Australian Energy Market Operator found the lowest-cost path to reduce emissions in the National Electricity Market in line with the government's net zero by 2050 target would require $122 billion in upfront capital investment (the present value of investment required over the period in utility-scale generation, storage, firming and transmission infrastructure) (AEMO, 2024). The cost of Australia's transition will depend on the policy mix, which if developed well, can capture new opportunities for economic growth (see also section NP.9).

> Governments around the world, including the United States with its *Inflation Reduction Act 2022* and the European Union with its Green Deal Industrial Plan, have taken the lead on co-financing the net zero transition.

Governments around the world, including the United States with its *Inflation Reduction Act 2022* and the European Union with its Green Deal Industrial Plan, have taken the lead on co-financing the net zero transition. The Australian Government has set out its plan—Future Made in Australia—for maximising the economic and industrial benefits of the move to net zero (see Figure NP.3). A key objective of the plan is attracting and enabling investment. It builds on Australia's other co-funding initiatives, implemented through institutions and programs such as the CEFC, ARENA, the National Reconstruction Fund, the Capacity Investment Scheme and Rewiring the Nation. The government also has in place measures that put a value on reducing greenhouse gas emissions, thereby encouraging finance to flow to low and zero emissions activities, including the Safeguard Mechanism and ACCU Scheme.

Figure NP.3: Summary of the Future Made in Australia package announced by the Australian Government in the 2024-2025 budget

The 2024-25 Budget provided $22.7 billion for the Future Made in Australia Package

GREEN METALS AND CRITICAL MINERALS PROCESSING	RENEWABLE HYDROGEN	LOW CARBON LIQUID FUELS	SOLAR AND BATTER SUPPLY CHAINS	ENABLING ENVIRONMENT
$7 billion from 2027-2040 for production tax incentive associated with refining and processing of critical minerals plus $10 million for pre-feasibility studies for critical minerals common-user processing facilities $1.2 billion in strategic critical minerals projects including through the Critical Minerals Facility $18.1 million over six years from 2024-25 for supporting the emergence of Australia's green metals industry	$6.7 billion over ten years from 2027 through the Hydrogen Production Tax Incentive for renewable hydrogen Additional $1.3 billion to the existing Hydrogen Headstart program	$20.9 Million over four years for the consultation work to explore expansion of the Guarantee of Origin scheme to low carbon liquid fuels	$835.6 million over ten years to establish the Solar Sunshot program $523.2 million Battery Breakthrough Initiative	$1.7 billion allocated for a Future Made in Australia Fund (administered by ARENA) $17.3 million over four years from 2024-25(and $3.1 million per year ongoing) to improve sustainable finance markets $68.0 million over four years from 2024-25 to support investment $182.7 million over eight years from 2023-24 (and $4.5 million ongoing from 2031-32) to improve approval processes $68.4 million over seven years from 2024-25 for initiatives delivered through the new Skills and Training Academy

Source: Budget Paper No. 2 (Australian Treasury, 2024a).
Note: listed initiatives do not cover all Future Made in Australia funding.

There is no one-size-fits-all financial instrument that is appropriate for public finance for Australia's transition. However, the best approaches will ensure efficient public investment leverages private investment to align risk and return profiles with the appetites of both parties. The authority's analysis in each sector chapter shows that understanding the context is fundamental to making sure the investment instrument is suitable (summarised in Table NP.1).

Table NP.1: Summary of financial instruments responding to sectoral barriers and enablers

Financial Barrier	Possible Financial Instrument	Example Enabler
Commercial viability of investment	Grants or concessional finance to support technology development	Investment in research and development for agriculture and carbon removal technologies
Low return on investment	Direct investment or debt/equity finance	Common user infrastructure
Limited evidence of commercial returns	Targeted subsidies directed at improving risk-return ratio	Tax credits to incentivise faster asset turnover
Unfavourable risk profile	Guarantees or insurance measures to underwrite investments	Contracts for difference for energy projects
High upfront costs	Concessional finance through grants, low-cost loans or incentive schemes	Discounted household upgrades
		Electric vehicle incentives

Australia will need to attract foreign investment to support its transition to net zero. However it recently became a net exporter of capital for the first time since the mid-1970s (RBA, 2023). The authority heard from stakeholders including private investors, industry and business that policy stability and predictability are fundamental for investment and particularly important when investing in new technologies or industries.

> *'Compared to international competitors, Australia has low rates of investment relative to the size of its economy. Capital follows the strongest investment signals and Australia's policy signals are currently too weak to attract globally relevant industrial abatement and investment capital.'*
>
> Australian Aluminium Council submission, 2024

A 'National Interest Framework' to guide public investment under the government's Future Made in Australia plan is currently before the parliament (Future Made in Australia Bill 2024). It has two streams for identifying investment aligned with in the national interest:

- The Net Zero Transformation Stream will include industries that will make a significant contribution to the net zero transition and are expected to have an enduring comparative advantage, and in which public investment is needed for the sector to make a significant contribution to emissions reductions at an efficient cost.
- The Economic Resilience and Security Stream will include industries where some level of domestic capability is necessary or efficient to deliver adequate economic resilience and security, and the private sector would not invest in this capability in the absence of public investment.

In addition to articulating the rationale for public investment under the Future Made in Australia plan, the framework commits the government to applying community benefit principles to investments. The authority considers that further articulation of community benefit principles should include non-financial considerations such as climate resilience and intellectual property rights.

Government should also establish a clear and transparent process for ending investment at a point of project success or failure. Finite public capital means investments should be outcome-focused and time-bound to avoid inefficiency and over-subsidisation. Clear exit strategies that are publicly communicated and consistent can support this investment approach. In its submission, Chevron Australia noted "incentive oriented programs should be designed with the goal of ultimately enabling technologies and products to compete without government support" and encouraged the incorporation of established sunset dates (Chevron Australia submission, 2024, 2024). The authority supports clear end dates or principles for ceasing public investment, supported by regular monitoring and reviewing of investments against pre-established and transparent performance metrics such as cost declines, efficiency increases, or emissions reductions (Meckling et al., 2022; Productivity Commission, 2008).

Transparency mechanisms, such as climate-related financial risk disclosures and the Guarantee of Origin assurance scheme (being designed to track and verify emissions associated with hydrogen and renewable electricity made in Australia), also play an important role in informing investment and consumer decisions (CER, 2024). Standards and labelling are another way to mandate or assist consumer decisions and channel finance towards the transition, while also helping householders choosing products that reduce cost-of-living over time. Examples include Australia's Greenhouse and Energy Minimum Standards (GEMS) scheme that promotes the development and adoption of appliances and equipment that use less energy and produce less emissions.

> Standards and labelling are another way to mandate or assist consumer decisions and channel finance towards the transition, while also helping householders choosing products that reduce cost-of-living over time.

The government is well progressed in overcoming information barriers to private investment, with policies and measures addressing climate-related financial disclosures and the development of a sustainable finance taxonomy. However, barriers remain. The development of sustainable finance policy in Australia must be met by an uplift in a domestic workforce capable of understanding sustainable finance needs. Research by the Australian Sustainable Finance Institute found "a significant skills and capability gap in sustainable finance professionals remains" and improved skills are necessary given forthcoming mandatory climate disclosures (ASFI, 2023). Improving market competence must happen quickly and there is opportunity for government, industry and academia to come together to develop the training and implementation of comprehensive and targeted courses for market participants.

Data gaps remain a key barrier to mobilising finance for decarbonisation. Digital reporting is only voluntary under Australia's financial reporting requirements (ASIC, 2014). The authority suggests anticipated mandatory climate-related financial disclosures could be used as a pilot for widespread digital reporting. Digital reporting should create opportunities to enhance the availability and accessibility of accurate, consistent and comprehensive information on emissions and decarbonisation, which will help decision-makers reduce risk and realise opportunities.

A review of the Australian tax and transfer system could potentially reveal opportunities to reallocate public funding to better align with the government's Net Zero Plan. For example, the Fuel Tax Credit could be phased out and revenue redeployed towards the deployment of low and zero emissions vehicles and machinery instead. The Fuel Tax Credit currently costs taxpayers 1.4% or $10 billion of government expenditure annually (Parliamentary Budget Office, 2023) and provides a refund for a proportion of fuel costs associated with the tax for eligible types of vehicles and machinery (ATO, 2021). The mining industry has obtained the largest total value of credits claimed – more than triple that of the agriculture sector (Grattan Institute, 2023).

> A review of the Australian tax and transfer system could potentially reveal opportunities to reallocate public funding to better align with the government's Net Zero Plan.

A competitive economy is fundamental in supporting the innovation and efficiency necessary to reach net zero. However, the authority heard from several stakeholders that a lack of clarity around competition law was creating reluctance to collaborate and innovate. With the government taking a more active role in industry participation (Productivity Commission, 2023a), the time is right to ensure laws foster innovation and collaboration, while promoting competitive markets. For example, the government could permit the pooling of resources or time-limited regulatory sandboxes to encourage innovation and collaboration while retaining oversight (Hellenic Competition Commission, 2024).

Box NP.3: Common user infrastructure

The role of public finance in establishing new industries and overcoming high-upfront costs through developing common user infrastructure has a strong precedent in Australia. The West Australian and Australian Governments were integral in establishing the North-West Shelf gas venture off Western Australia in the 1970s. Government provided a demand signal by committing to allow exports for 20 or more years of 6.5 million tonnes per annum of liquefied natural gas, with the state government committing to long-term (20-year) contracts for fixed volumes of gas (Western Australian Government, 1979). Alongside demand signals, the state government also committed to:

- financing and development of the gas pipeline from Dampier and Bunbury
- contributing to the construction costs of new public roads in Dampier
- establishing and operating a local port authority
- constructing public facilities (such as schools or hospitals) to support operations
- making land available for land sale to house workers.

This common user infrastructure model is being adopted in other jurisdictions to accelerate net zero industrial policy. Through the United States' Infrastructure Investment (US) *and Jobs Act 2021*, the Department of Energy is investing USD 7 billion to create regional hydrogen hubs. These hubs will form the foundation of a national clean hydrogen network that will contribute to decarbonising sectors of the economy like heavy industries and heavy-duty transportation (United States Department of Energy, 2023). This funding will mainly be provided through grants, contracts or cooperative agreements, and complement Inflation Reduction Act (2022) tax credits related to hydrogen (United States Department of Energy, 2022).

Beyond hydrogen, the Inflation Reduction Act 2022 (US) is already having an impact with USD 265 billion in new investment in the United States in 12 months across the manufacture and deployment of clean energy, clean vehicles, building electrification and carbon management technology, up 39% from the previous year (CIM, 2024).

NP.6 How can we better signal the cost of carbon across the economy?

Achieving net zero requires that emissions reduction opportunities are pursued across all the sectors of the economy. As the Climate Change Authority (2020) and Productivity Commission (2023b) have observed, a broad, market-based policy approach that establishes a consistent price for emissions is generally accepted to be the most efficient way to achieve emissions reductions across the economy. Policy to establish a price signal is necessary because otherwise the cost of greenhouse gas emissions in causing global warming is not reflected in the activity that led to the emissions. Price signals alone are not sufficient to deliver the net zero transition – additional policies are required to solve coordination problems, build social licence and address other barriers.

Climate policy has evolved in Australia in a manner that has led to federal, state and territory governments implementing a variety of policy measures across different sectors of the economy, resulting in a fragmented approach to establishing a signal for the cost of carbon. At the federal level, market mechanisms currently in place include:

- the ACCU Scheme, which enables voluntary carbon abatement to be credited with saleable carbon units (ACCUs) and in practice has operated mainly in the land sector
- the Safeguard Mechanism, which imposes declining emissions-intensity baselines on Australia's highest-emitting industrial facilities and allows companies to trade Safeguard Mechanism Credits (SMCs) and ACCUs to meet their baselines
- the Capacity Investment Scheme, which uses auctions to award underwriting agreements to competitive renewables and storage projects
- the Renewable Energy Target, which allocates tradeable certificates for the output of renewable generation
- the New Vehicle Efficiency Standard, which allow trading of credits between manufacturers to stay below a baseline efficiency level.

There are a range of other policy interventions across levels of government that drive lower emissions outcomes, including emissions and energy efficiency standards and regulations, and government subsidies. None of these approaches directly impose a price on carbon, but they do all have the effect of imposing indirect, implicit or 'shadow' carbon prices (Productivity Commission, 2023b).

In addition, many companies and, more recently, areas of government at both the federal and state level, are using various estimates or projections of the cost of carbon, or value of emissions reductions, to inform decision-making (Infrastructure Australia, 2024; NSW Government, 2023). Should the government decide to implement a carbon border adjustment mechanism (DCCEEW, 2023b) that will necessitate determining the penalty to apply to the emissions-content of certain imported goods.

The authority notes there can be significant political and social challenges in implementing a broad-based market mechanism for pricing greenhouse gas emissions. Attempting to do so in Australia currently is likely to be disruptive and create, rather than alleviate, policy uncertainty at a time when several new and important measures (e.g. the expanded Safeguard Mechanism, the New Vehicle Efficiency Standard and the expanded Capacity Investment Scheme) are commencing. It is also the case that much of the policy and institutional architecture currently in place, or being put in place by the government (e.g. Net Zero Economy Authority), is required for a successful transition to net zero irrespective of whether implementation of a broad-based mechanism is revisited.

However, there are two ways in which the government can work towards achieving a more consistent carbon pricing signal across the economy over time and hence more efficient, least-cost pathways to net zero.

First, as a means of harmonising and simplifying the approach to pricing carbon across the economy, the government can look to expand the coverage of the ACCU Scheme and Safeguard Mechanism, and possibly link them with other schemes. Relatedly, the authority has previously recommended (CCA, 2022; 2023a) the government develop a National Carbon Market Strategy, and the government has indicated that its Net Zero Plan will articulate Australia's vision for ensuring robust and high-integrity carbon markets, and how the government intends to engage in carbon markets to meet its emissions reduction targets (DCCEEW, 2023a).

Second, the government can seek to establish an authoritative voice on estimates of the cost of carbon now and into the future, to promote consistent and robust analysis and decision-making in a range of settings. Such a function could be performed by the Treasury or an independent advisory body such as the Climate Change Authority.

NP.7 Who will build what Australia needs?

Workforce shortages are already seen as a barrier to decarbonising almost every sector of the economy, as set out in Part 1. Workforce demand in several transition trades will exceed supply in the coming decade according to modelling undertaken for Jobs and Skills Australia (JSA, 2023b). Failing to address these shortages present significant risk to costs and project delivery schedules necessary in the transition (Infrastructure Australia, 2021).

> *'If we don't fine tune our workforce pipelines, skills shortages could prevent us from reaching net zero by 2050, and opportunities to broaden our industrial base will be missed.'*
>
> JSA, 2023b

Jobs and Skills Australia's The Clean Energy Generation report suggested decarbonisation plans embed workforce planning to address shortages and enable the workforce of the future. The authority recommends governments work together and with businesses to prioritise workforce diversification and a fit-for-purpose education system.

Workforce mobility

The build out and transformation of facilities and infrastructure required across the country will require a workforce that is flexible and mobile. Much of this work will be in regional and remote areas and will require different numbers and kinds of workers for various stages, from initial construction to ongoing maintenance. Ensuring that workers can easily move to where they are needed will enable an efficient transition.

> The build out and transformation of facilities and infrastructure required across the country will require a workforce that is flexible and mobile.

Providing incentives for temporary housing solutions, such as modular housing, can help accommodate workers in these areas. Programs that offer financial support or subsidies for relocation costs will also encourage workers to move to where they are needed most. Governments and project proponents will need to be sensitive to impacts on local communities from a temporary influx of workers and heavy equipment, such as damage to local roads, and price increases caused by sudden increases in demand for food and housing.

Workforce diversification

Diversifying workforces can increase participation of under-represented groups and represents one of few ways to address the acute workforce shortages being experienced by transition industries now. As Jobs and Skills Australia (2023a) observed, workforce skill shortages are exacerbated when a large portion of the population faces barriers to entering and remaining in a sector. Analysis by Jobs and Skills Australia also found that the majority of occupations with skills shortages are dominated by one gender (JSA, 2023a).

In trade roles, gender discrimination, limited apprenticeship opportunities, lack of facilities (such as bathrooms), harassment and unsuitable workwear limit women's participation (Jobs Queensland, 2021). Many trade positions lack flexible working hours or training opportunities, particularly affecting women with family caring responsibilities (Jobs Queensland, 2021). Government, industry and other groups could encourage and enable employers to diversify by increasing awareness of the benefits and providing information about how the barriers listed above can be overcome. In addition, addressing lack of social services in regions could reduce barriers for those with family caring responsibilities from entering the transition workforce (ABS, 2022).

> *'Equal representation of women in engineering… will go a long way towards meeting Australia's need for vastly greater numbers of qualified engineers if we are to fulfil our ambitious development targets over the next decade'*
>
> Engineers Australia, 2022

A fit for purpose education system

Increasing the pipeline of adequately skilled workers is critical to meeting the short and long-term workforce needs of the transition (JSA, 2023b).

> *'A slow and unwieldy VET system has been a brake on the development of relevant and meaningful qualifications for electrical and mechanical tradespeople in renewable energy.'*
>
> Clean Energy Council, 2022

Australia has a trainer shortage to deliver the training necessary for the near-term priorities of deploying renewable energy and housing upgrades (JSA, 2023b). Educators in the VET system are often attracted to private industry and this pattern will likely intensify as industry demand increases (Tyler & Dymock, 2021).

Regional Australians face additional barriers to accessing training due to the limited offerings nearby. Lack of training opportunities within a reasonable distance from home can be a disincentive and barrier to entering transition workforces (JSA, 2023b). These disincentives can be partly addressed through on-the-job training and by increasing the supply of courses in regional areas experiencing – or projected to experience – increased labour demand (JSA, 2023b). Temporary job surges in regions (e.g. during construction phases of industry transition) also require anticipatory planning to ensure that local communities are not negatively impacted. For example, arranging temporary accommodation (such as dongas and portables) for an influx of transient workers can mitigate potential pressure on local housing supply (Jobs Queensland, 2018).

Australia's education system must be prepared for the new industries and skills required for the transition (JSA, 2023b). A well-planned education system with better integration of university and VET training systems can deliver the workforce of the future (Department of Education, 2023). TAFE Clean Energy Centres of Excellence could also provide an avenue for industries, universities, communities and governments to collaboratively build courses to meet the needs of regional industries and support local workforces to adapt to technologies (JSA, 2023b). Inspiring and encouraging school-aged students to pursue careers that will be in high demand will be important to foster enrolments in these university, VET and TAFE courses.

> A well-planned education system with better integration of university and VET training systems can deliver the workforce of the future.

As remote-based industries, including critical minerals and hydrogen production, grow, more innovative training models will be necessary (Beasy et al., 2023; DISR, 2023). Hub-and-spoke models combined with group training organisations permit trainees to complete competency requirements in regional centres while still working in remote sites (JSA, 2023b).

Regions are likely to experience a boom during the construction phase of a project before it settles into the operational stage (DITRCA, 2024). Modelling undertaken for Jobs and Skills Australia revealed that growth in job opportunities would be stronger in regional Australia than metropolitan areas (JSA, 2023b). Improving planning, access to training and education alongside robust workforce data is necessary to maximise these benefits and manage longer-term regional impacts (Rutovitz et al., 2021).

A lack of data is impeding planning for the impact of the transition on local labour markets. Jobs and Skills Australia advises that workforce data on what is necessary for Australia's future energy needs is limited and inconsistent (JSA, 2023b). Reinstating the Australian Bureau of Statistics Employment in Renewable Energy Activities series, with greater granularity of occupations and regional disaggregation, could provide greater assistance to regional planners. The National Energy Workforce Strategy may be an avenue to consider this option and ensure data can inform regular reports like an Australian Energy Employment Report.

Climate change will influence workforce productivity

At the same time as the workforce is delivering the transition to net zero, increased heat exposure will likely impact labour productivity, and require changes to work practices in exposed industries. Workers in industries where outdoor daytime work is common may need to change the way they work to reduce their exposure to heat. This is likely to reduce the outputs of the agriculture, construction, manufacturing and services sectors, with impacts worsening under higher global temperature scenarios (Australian Treasury, 2023). The impact of climate change on labour productivity is already being seen. In 2022, the global potential loss of earnings was $863 billion, equivalent to 0.87% of gross world product (Romanello et al., 2023).

NP.8 What does a fair and equitable transition for Australia look like?

For Australia to build the infrastructure necessary for the transition, government and industry must obtain the social licence to operate from affected communities. Gaining and maintaining social licence through trust, legitimacy and credibility is a critical success factor for projects necessary in Australia's transition to net zero. Without it, these projects are at risk of delays and additional costs, and even failure.

> *'For the net zero transition to be successful, all Australians must feel that they are sharing in the benefits.'*
> Centre for Policy Development submission, 2024

> Gaining and maintaining social licence through trust, legitimacy and credibility is a critical success factor for projects necessary in Australia's transition to net zero.

Repeated or consistent failures to obtain social licence and share benefits risk eroding the social and political support that will be required for the transition. The authority defines 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 continues to prosper as the world transitions to net zero emissions' (CCA, 2023a).

Australian governments, businesses and communities need to prepare for the unavoidable and varied impacts of the transition, particularly in regions. Regions where emissions-intensive industries are the 'lifeblood' of community generally have less diverse economies than other areas and therefore face greater economic and social challenges from the transition (Hammerle & Phillips, 2023). Emissions-intensive industrial regions must be provided the support and planning to transition and attract emerging industries. Effective transition planning should focus on the community as a whole and seek to support the broader economy to diversify and become more resilient (Hammerle & Phillips, 2023).

Subject to passage through parliament, Australia's *'Net Zero Economy Authority will promote orderly and positive net zero economic transformation for Australia, its regions, industries, workers and communities. It will do this by coordinating effort, brokering investments that create jobs in regions, and supporting workers through change'* (PM&C, 2024). As set out above, the Net Zero Economy Authority could play a central role in coordinating place-based implementation of net zero measures across government, industry, and communities. It could also coordinate co-design of initiatives with local governments to support the development of place-based responses, which account for the different needs and aspirations of individual communities.

First Nations voices must be central to the transition so that their ongoing contributions to Culture, caring for Country and Australia's economic prosperity can continue. First Nations peoples have occupied and cared for Australia's land and sea for over 65,000 years (McConnell et al., 2021). Modelling by Net Zero Australia suggests that to reach net zero, about 43% of renewable energy infrastructure will need to be co-located on the First Nations Estate (NZA, 2023). Therefore, First Nations peoples must have a leadership role in the transition if benefits are to be shared equitably (FNCEN, 2024).

Best practice engagement with First Nations communities can help Australia achieve a rapid transition while respecting First Nations' community decision-making and Culture. Here in Australia and overseas, failure to consider First Nations' rights has increased project costs, delayed approval timelines, prevented communities from sharing in transition benefits and threatened project viability (Kårtveit, 2021; Lee et al., 2023; Lyons et al., 2023). The Australian Council of Superannuation Investors noted that increased costs from unconstructive relationships with First Nations peoples represent a material risk, and that investors need assurance this risk is being mitigated through respect for rights and Culture (ACSI, 2021). Genuine engagement with First Nations can build social licence for low emissions industries.

For best practice engagement to occur, partnerships with First Nations peoples must be based on the principles of free, prior and informed consent (FPIC) and the right to self-determination (NIAA, 2022; UN General Assembly, 2007). FPIC means collective decisions made by communities that are free from coercion and produced with adequate time to consider all available information (UNHRC, 2018). The rapid rollout of transitional infrastructure is a potential risk to investing the necessary time for relationship and trust building with First Nations communities (CCA First Nations Roundtable, 2024). Nevertheless, emerging industry and First Nations partnerships on renewable energy projects demonstrate that when Community has ongoing participation in decision making, projects can be implemented quickly and traditional knowledge can assist in reducing impacts to Country and Culture (Yindjibarndi Energy, 2023).

The majority of First Nations representative bodies are not adequately resourced to build internal capacity and engage expertise when considering impacts of infrastructure on Country (Woods et al., 2021). To provide informed consent for developments and for industry to undertake best practice engagement, First Nations peoples require equal access to information and capacity to understand and utilise complex engineering, financial and policy subject matter (ASFI, 2024; Clean Energy Council and KPMG, 2024). Government has an important role to play in supporting this capability uplift, but existing mechanisms such as the Australian Government's PBC Capacity Building grant scheme have been identified as unfit for purpose and are under evaluation (NIAA, 2023). To enable Australia's transition to proceed at the pace required, the government should prioritise support for First Nations communities to realise meaningful opportunities in the transition (CCA First Nations Roundtable, 2024).

Historically, First Nations people have been excluded from accessing the capital necessary to develop decarbonisation projects themselves (ASIC, 2023). Lack of trust from financial institutions and mis-categorisation of First Nations assets are significant barriers to inclusion (Evans & Polidano, 2022). Recent initiatives, including start-up financing and procurement loans provided through Indigenous

Business Australia as well as grants through the Indigenous Advancement Strategy have assisted First Nations owned and led enterprises to acquire equity. However, limitations in longitudinal data can make the success of these policy interventions difficult to evaluate (Evans & Polidano, 2022). The Indigenous Economic Power Project has made progress towards achieving more comprehensive measurement, reporting and demonstration of the economic, employment and social contributions provided by First Nations businesses (Evans et al., 2024). Continued support and resources from government and industry are necessary to ensure First Nations people have access to capital and equity.

> Continued support and resources from government and industry are necessary to ensure First Nations people have access to capital and equity.

Supporting First Nations-led businesses in the transition has important benefits for Community, Culture and the Environment that should be formally acknowledged. Growth of the First Nations carbon industry, which now numbers over 38 projects (ICIN, 2024), has assisted in bringing First Nations peoples back to Country and supported the handing down of Traditional Knowledge from Elders to future generations (ILSC, 2022). Broader environmental benefits of the First Nations carbon industry include reduced wildfire risk, and increased habitat diversity and biodiversity (Gebbie et al., 2021). Initiatives that include a non-carbon benefit component, such as the Queensland Land Restoration Fund (2024) have the potential to improve the financial viability of First Nations carbon industry projects by rewarding caring for Country practices (ILSC, 2022). Further investment by government and industry to formalise recognition of these benefits could assist First Nations led projects to attract equity and diversify revenue streams (CCA First Nations Roundtable, 2024).

NP.9 What will it take for Australia to continue to prosper?

Australia is an emissions-intensive export economy. Its four largest exports are iron ore ($124 billion in 2022-23), LNG ($92 billion), thermal coal ($66 billion) and metallurgical coal ($62 billion) (DISR, 2024). Australia's fossil fuel exports (mainly coal and LNG) account for around 35% of Australia's $686 billion total goods and services exports (ABS, 2023; DISR, 2024). When these fuels are burned by our export partners, they produce more than double Australia's domestic emissions (CCA, 2024).

The IPCC (2022) and IEA (2023) have concluded that, globally, new fossil fuel projects are incompatible with achieving the Paris Agreement goal of limiting warming to 1.5°C, and that global demand for fossil fuels will need to significantly decline over the period to 2050. According to the IPCC (2022), demand for natural gas and coal will need to reduce by as much as 62% and 99% respectively by 2050. The IEA (2023) has similarly identified reductions of 78% and 92% respectively in its net zero by 2050 scenario.

The demand for critical minerals and low emissions metals is expected to increase to enable the global net zero transition. The IEA estimates demand for critical minerals could nearly triple by 2030 and grow to over 3.5 times current levels by 2050 in a net zero by 2050 scenario (IEA, 2024). These shifts in demand underscore the significant changes required in global energy and resources markets to achieve the goals of the Paris Agreement.

For Australia's economy to thrive and grow, and also do its part to contribute to the goals of the Paris Agreement, it will need to adjust its export mix by ramping up exports that will be in demand in a net zero global economy and working with trade partners to manage an orderly transition away from fossil fuels.

> *'[Australia will see its] …fossil-fuel heavy export revenue decline. Australia's key trading partners have all committed to net-zero targets, and demand for Australia's fossil fuel commodities are expected to fall. Overall, this presents an unprecedented economic risk to the Australian economy that requires a proportionally adequate response to safeguard Australia's future and livelihoods… Endowed with world-leading renewable resources that are critical to powering competitive clean industries, Australia has the potential to grow its revenue from new clean exports to $333 billion by 2050. But it must move quickly, the global race is well underway in major economies such as China, the USA and Europe who are moving fast to attract investment and secure market share. Low cost solar and wind will be essential to capturing Australia's clean export opportunity'*
>
> Beyond Zero Emissions submission, 2024

'As one of the world's leading coal exporters, Australia is a trusted partner supporting the energy security of import-reliant economies like Japan and South Korea. However, with our major export destination countries committing to their own net zero targets, Australia will need to adapt and develop new export industries to retain our advantage. Critical minerals mining and processing and hydrogen production represent promising opportunities, and the policy attention they are attracting from federal and state governments is warranted'

Mining and Energy Union submission, 2024

'WWF-Australia through its Renewables Nation program has advocated for Australia to capture the jobs and growth opportunities presented by becoming a renewable energy superpower. The window of opportunity to realise these opportunities is small and narrowing.'

WWF Australia submission, 2024

To facilitate an orderly transition, working with trading partners to establish bilateral decarbonisation agreements will give Australia certainty about the timing of changes in demand for fossil fuels and low emissions exports, while also giving its trading partners certainty about their energy security as they transition their own economies to net zero. These agreements could also be used to facilitate an orderly transformation of global supply chains, which will require shifts in the location of production of energy intensive materials, like aluminium, iron and steel, to countries like Australia with abundant renewable energy. Participation in multilateral processes that are developing standards and definitions for low carbon products (e.g. steel and cement) – such as the Climate Club (2023) and the Inclusive Forum on Carbon Mitigation Approaches (OECD, 2024) – will also be important to ensure that global norms are compatible with the needs of Australian industry.

'In advising the Government on fossil fuel phase out, the CCA should consider… opportunities for Australia to cooperate with key trading partners to support wider fossil fuel phase out while ensuring energy security, including through exporting renewable resources and skills to support energy transition in developing export destination economies—noting such actions could achieve substantial emissions reductions compared to decarbonising Australia's economy alone.'

Carbon Market Institute submission, 2024

The Australian Government articulated its vision for maximising the economic and industrial benefits of the move to net zero and securing Australia's place in a changing global economic and strategic landscape through its Future Made in Australia plan announced in the 2024 Budget (see also section NP.5). Decisions under the plan about where to target significant public investment are subject to a 'National Interest Framework' that is currently before the parliament to provide additional rigour beyond existing government investment processes (Future Made in Australia Bill 2024, 2024). The framework has two streams under which an industry may warrant government intervention to attract private investment:

- The 'Net Zero Transformation Stream' is aimed at identifying industries that will make a significant contribution to the domestic and global net zero transformation and in which Australia is well placed to be competitive in global markets. The government has identified renewable hydrogen (referred to as electrolytic hydrogen in this report), green metals (referred to as low emissions metals in this report), and low carbon liquid fuels (referred to as renewable fuels in this report) as aligned with this stream.
- The 'Economic Resilience and Security Stream' is aimed at identifying industries that are critical to Australia's economic resilience, are vulnerable to supply disruptions and that require support to unlock sufficient private investment. The government has identified critical minerals processing and clean energy manufacturing, including in battery and solar panel supply chains, as aligned with this stream.

Australia has an opportunity to develop new industries that leverage its relatively small, high wage but highly skilled workforce to produce bulk exports from its abundant renewable energy sources and resources deposits. By investing in necessary infrastructure and skills development, and incentivising investment, Australia can create a new industrial base and build a stronger, more diversified and more resilient economy powered by renewable energy, in a way that creates secure, well-paid jobs and delivers benefits to communities across the country.

By investing in necessary infrastructure and skills development, and incentivising investment, Australia can create a new industrial base and build a stronger, more diversified and more resilient economy powered by renewable energy, in a way that creates secure, well-paid jobs and delivers benefits to communities across the country.

Australia is already a significant global producer of raw ores, such as iron ore, bauxite and lithium (DISR, 2024). Australia can reduce its domestic emissions by transitioning to net zero emissions mining practices (see Resources sector chapter). In addition, Australia's abundant sun and wind resources provide an opportunity to process more of these ores domestically into higher value products before they are exported. For example, large scale renewable energy installations with storage could power the processing of more iron ore into low emissions iron and steel, more bauxite into alumina and aluminium, and more lithium into lithium hydroxide. Iron, steel, alumina, aluminium and lithium are used in the production of transition technologies like wind turbines, solar panels, batteries and electric vehicles, and demand is likely to increase as the global net zero transition gathers pace (IEA, 2024).

Companies that use metals and critical minerals in their products, as well as their customers and financers, are increasingly demanding supplies that have been produced using high environmental, social and governance standards (PWC, 2024). Australia is well placed to capture a share of this growth in demand for high integrity, low emissions metals and critical minerals, but cannot ignore the need to be efficient and compete on cost to be competitive in global markets. Global market volatility and geopolitical influences will impact the opportunity for the Australian resources sector.

By doing more energy-intensive refining of ores before export and reducing the need for that processing to occur in other countries that use fossil fuels and produce emissions, Australia can also contribute to reducing global emissions. More domestic processing also means a lower volume of material is being exported, saving on emissions associated with shipping. In its submission, Tesla explained that by refining lithium ore into the lithium hydroxide used in batteries for electric vehicles and energy storage before exporting it, Australia could capture a much larger share of the electric vehicle value chain (2024). This would help reduce global emissions by ensuring renewable energy is used in the onshore refining process and by reducing transport emissions (and costs) tenfold by concentrating the ore down into a smaller volume.

> *'Specifically, value adding extraction and export supply chains through making 'green metals' is the next logical step in developing Australia's alternative to fossil fuel exports. Importantly, this has the dual benefit of not only affirming Australia's economic prosperity through establishing a profitable revenue stream, but it has also been said that it could offset global emissions by as much as 6-9 per cent. In the context of Australia's current contribution to global emissions of around one per cent, this is a substantial and profound opportunity.'*
>
> Engineers Australia submission, 2024

A number of organisations have attempted to quantify the value of the export opportunity. In its submission, Fortescue presented modelling results indicating Australia's current US$151 billion in annual fossil fuel export revenues could be replaced with new low emissions exports generating US$1.2 trillion in revenue per year by 2035 in an ambitious scenario or US$436 billion in a conservative scenario. Beyond Zero Emissions (2021) found that annual low emissions exports could grow to $333 billion by 2050, more than triple the value of Australia's fossil fuel exports at the time of the report. Accenture modelling for the Sunshot Alliance (2023a) found that five priority low emissions exports could result in an additional $314 billion of revenue per year by 2040. The EY Net Zero Centre (2023) conducted modelling indicating that if Australia capitalises on some of the business opportunities in low emissions iron and other energy transition minerals and metals, it could add more than $40 billion to national income and $65 billion to Australian economic activity by 2050, in a conservative scenario if around 10% of Australian iron ore production is used to make green iron for export.

Decarbonising Australia's exports at the same time as decarbonising its domestic economy will create challenges because the domestic and export transitions are tightly coupled. They will compete for access to infrastructure and supply chains, and for resources like land, water, electricity, and labour. The government will need to carefully plan and coordinate both transitions to manage these competing demands and maximise efficiency.

As set out in section NP.5 above, there is a global reorientation in trade and investment underway as governments, regulators, and markets around the world transition to net zero emissions and Australia needs to adapt to these changes or risk the economic opportunities flowing to other countries (CCA, 2021). The United States has committed substantial support through its *Inflation Reduction Act 2022*. Estimates of the total fiscal cost of the *Inflation Reduction Act 2022* over its 10 year life range between around US$800 billion (Credit Suisse, 2022) and US$1.2 trillion (Goldman Sachs, 2023). Other jurisdictions like the European Union, Canada, the Republic of Korea, Japan, India and Indonesia also have implemented policies to capture the opportunities of the global transition (Accenture, 2023b; King & Wood Mallesons, 2023). Companies are responding to these policies. In its submission, Tesla observed:

> *'As battery supply chains re-route and scale up in real time, Australian IP, jobs and potential investments are at risk of migrating overseas. Indeed, this is already happening. For example, Ioneer secured US$700m for its Nevada project, Novonix received US$240m for its Tennessee graphite plant, and Lynas was awarded US$120m to build its Heavy Rare Earths Facility in Texas. Pilbara Minerals is partnering with POSCO to build a lithium hydroxide refinery not in the Pilbara, but in South Korea. And Fortescue Future Industry has committed to building its Battery Hub in the US, citing incentives as a key factor'*
>
> Tesla submission, 2024

Australian iron ore exports face growing competition from jurisdictions like Africa, Brazil and the Middle East that have low emissions energy resources and magnetite ore deposits that are better suited to direct reduced iron processes using hydrogen than the hematite ore that makes up the bulk of Australia's current exports. Accelerating the development of a low emissions iron industry in Australia that uses locally produced electrolytic hydrogen to process Australian ore into low emissions iron could prevent Australian iron ore losing market share to other jurisdictions (IEEFA, 2023). Achieving this will require commercialising emerging low emissions technologies that are suited to Australia's hematite ores or increasing extraction from Australia's large magnetite deposits.

Table NP.2 below summarises potential new export opportunities beyond low emissions metals and minerals that draw on Australia's natural advantages.

Table NP.2: Potential new low emissions export opportunities beyond metals and minerals

Opportunity	Description
Hydrogen and its derivatives	· Electrolytic hydrogen is produced using renewable electricity and electrolysis. · Powering a hydrogen export industry would require a substantial increase in renewable electricity generation (AEMO, 2024). · Complexities and energy penalties associated with compressing, liquefying or chemically converting hydrogen gas into a transportable state (Hassan et al., 2023) are likely to limit its seaborne trade as an energy carrier. · More attractive opportunities are likely to lie in using domestically produced hydrogen close to its source to make products that are more readily transported, such as low emissions iron, alumina, fertiliser, explosives, petrochemicals and ammonia (EY Net Zero Centre, 2023). · Countries with high energy needs that are currently reliant on fossil fuels and have limited domestic energy resources like the Republic of Korea and Japan are likely to be demand centres for hydrogen and its derivatives (DCCEEW, 2022b). · The government's Guarantee of Origin scheme will enable Australia to verify the low emissions credentials of its hydrogen-based exports (DISR, 2021).
Storage of carbon dioxide	· CO_2 can be stored in onshore geological formations or beneath the seabed offshore. · Australia could leverage its science and engineering expertise and vast geological formations to establish a CO_2 storage and use industry. Partnering with other countries would help Australia to scale a geological storage industry. · Key trading partners of Australia are looking abroad for carbon management solutions to support their national net zero targets. Japan, the Republic of Korea and Singapore are all committed to CCS to support their emissions reduction targets (Australian Senate Environment and Communications Legislation Committee, 2023). · The Australian Government regulates storage of CO_2 offshore through a series of Commonwealth laws. A regulatory framework would need to be established to manage the importation, transportation and long-term storage of CO_2, ensure environmental and social safeguards are in place, manage risks such as leakage during transport, injection and storage, and address interactions with Article 6 of the Paris Agreement (trade of abatement between countries).
Energy intensive data centres	· Data centre capacity is expected to increase significantly due to the rise in artificial intelligence and cloud computing (Goldman Sachs, 2024). · The demand for low emissions data centres is increasing as organisations seek energy-efficient facilities to support their net zero commitments (ATIC, 2024). · Australia's direct subsea data connections to the Asia-Pacific region and renewable energy resources mean that Australia is emerging as a hub for low emissions data centres in the Asia-Pacific region (ATIC, 2024). · A reliable electricity system and opportunities to install back-up systems or microgrids are also important considerations for data centre owners because they require a continuous power supply with a steady voltage and frequency. · Australia is a lower cost location to build and operate data centres than competing Asian locations (Turner & Townsend, 2023). · The National Australian Built Environment Rating Scheme (NABERS) allows data centre providers to benchmark energy use and emissions, enabling credible sustainability claims to national and international customers. · GreenSquareDC is already developing low-emissions data centres in Australia, targeting international demand and using large-scale renewable energy and efficient liquid cooling systems.

The authority has identified five main barriers to establishing new low emissions industries:

1. Access to low-cost, firmed renewable electricity

Critical to Australia capitalising on the opportunities of the transition is certainty for investors about reliable access to renewable electricity at globally competitive costs. Metals and minerals extraction and processing are energy-intensive. To attract investment in these industries at the scale required to service their high energy needs and to make them major parts of Australia's economy, governments will need to coordinate with industry to dedicate vast amounts of new renewable electricity capacity to these facilities.

'It is important that critical minerals mining and processing has access to reliable, firmed, low-cost, and clean electricity. Grid connected facilities benefit from significant government incentives aimed at decarbonising the National Electricity Market (NEM), but off grid facilities do not. Off-grid electricity generation should not be penalised when compared to on-grid facilities that benefit from lower emissions generation being put in place to decarbonise the NEM.'

Minerals Council of Australia submission, 2024

'The greatest barrier to green energy projects today in Australia is the cost of power – not lack of demand for green products. Data from the International Energy Agency and CSIRO indicates that substantial scale up in renewable capacity can halve the cost of green energy generation in Australia by 2035… Investment in transmission and energy storage infrastructure must accelerate and policy settings must be put in place to enable significant reductions in the cost of green energy, enabling Australia's green industries to take off.'

Fortescue submission, 2024

2. Access to skilled workers at new mining and refining sites

Government coordination and assistance will be required to ensure skilled workers are attracted to likely locations of new industries. Wherever possible, coordinating the location and timing of new industries with the location and timing of declining fossil fuel industries will also help communities transition and make use of existing infrastructure (JSA, 2023b).

3. Site availability and approvals

Coordination of site availability and permitting will be crucial to new industries being able to scale rapidly (CEDA, 2024). By anticipating the areas best suited to new industries, identifying specific sites and approving developments in advance, governments can attract investors seeking speed and certainty

in approvals processes, without reducing the time needed to assess and manage environmental, cultural and community impacts.

> *Because the refining industry will need to scale rapidly, jurisdictions that can offer short and certain permitting for sites will be at a significant advantage. This need not reduce environmental outcomes if sites are identified and approved in advance, anticipating the unprecedented expansion required in coming years.*
>
> Tesla submission, 2024

4. Access to low-cost electrolytic hydrogen

Access to electrolytic hydrogen is a key enabler of new low emissions metals and minerals operations. Growing production and driving down costs in locations where low emissions metals and minerals will be processed will be crucial. The authority notes that as part of the 2024 Budget, the government announced a Hydrogen Production Tax Incentive to provide $2 per kilogram of renewable hydrogen to operate alongside the Hydrogen Headstart program, which supports early investments in the hydrogen industry (Australian Treasury, 2024d).

5. Capital and operating costs

The authority notes that as part of the 2024 Budget, the government announced a Critical Minerals Production Tax Incentive of 10% for eligible entities to support downstream refining and processing of Australia's 31 listed critical minerals to improve supply chain resilience (Australian Treasury, 2024b). This clear, targeted, production-linked credit will provide an incentive to value add to raw ores onshore and put Australia on a level playing field with other countries that have similar production incentives.

In addition to the Production Tax Incentive, which lowers operating costs for projects, the government is assisting project proponents to overcome the high up-front capital costs and risks associated with being a first-mover through the Critical Minerals Facility, the Critical Mineral Development Program and the Northern Australia Infrastructure Facility.

The government is investing in foundational initiatives to expedite the emergence of Australia's low emissions metals industry, including through enhanced industry and research collaboration, exploration of opportunities to improve the use of Australian scrap metal and undertaking of further consultation on incentives to support the production of green iron, steel, alumina and aluminium (Australian Treasury, 2024a).

As identified in the Treasury's Future Made in Australia National Interest Framework supporting paper (2024c) there may be sound economic resilience and security reasons to foster targeted domestic manufacturing capabilities in some areas, and others where there are not. For example, Australia's successful transition will rely on supply chains for solar PV and battery technologies, which are heavily concentrated in China and for which Australia does not have a meaningful sovereign manufacturing capability. Overwhelmingly, however, the commoditised equipment, appliances and vehicles Australia needs to decarbonise will be sourced from overseas manufacturers in countries with low-cost manufacturing.

Transition technologies like solar panels, wind turbines, electric vehicles, batteries, heat pumps, electrolysers and electrified industrial equipment need to be manufactured at scale to meet the global decarbonisation task. Other countries have a cost advantage over Australia. To make manufacturing in this higher cost environment viable, it makes sense for Australia to instead manufacture smaller-scale products that have unique quality, design or technology attributes that can attract a premium.

A heavy reliance on importing transition technologies from overseas means it will be essential for governments to work with industry and international partners to establish supply chains resilient to global economic, climate and geopolitical disruptions. This cannot be achieved by onshoring transition technology manufacturing in Australia alone. Australia will have the biggest impact and stand to benefit most by encouraging and working with trading partners who are better placed to become bulk manufacturers of commoditised transition technology to establish manufacturing operations and supply chains in their countries.

Australia has the existing heavy industry and skill base, renewable energy sources and resource deposits to become a dominant supplier of materials to its trading partners that are positioning themselves to become manufacturers of commoditised transition technologies. The extraction and processing of these metals and minerals is energy intensive and highly technical. The United States, the Republic of Korea, Japan, India, and Europe are already implementing incentives for transition technology manufacturing (Accenture, 2023b). The biggest contribution Australia can make to strengthening these supply chains is to expand its contribution as a supplier of key processed metals and minerals.

References: National Pathway

ABS (Australian Bureau of Statistics). (2022). *Childcare still largest barrier to female participation.* https://www.abs.gov.au/media-centre/media-releases/childcare-still-largest-barrier-female-participation

ABS. (2023). *International Trade: Supplementary Information, Financial Year.* https://www.abs.gov.au/statistics/economy/international-trade/international-trade-supplementary-information-financial-year/2022-23#key-statistics

Accenture. (2023a). *Sunshot: Achieving global leadership in clean exports.* https://assets.wwf.org.au/image/upload/Sunshot_-_Achieving_Global_Leadership_in_Clean_Exports_Final_Report?_a=ATO2Ba20

Accenture. (2023b). *Sunshot in 2023: Accelerating towards Australia's renewable exports opportunity.* https://assets.nationbuilder.com/auscon/pages/21744/attachments/original/1678743723/Sunshot_2023_-_Final_Report.pdf?1678743723

ACSI (Australian Council of Superannuation Investors). (2021). *ACSI Policy on Company Engagement With First Nations People.* https://acsi.org.au/wp-content/uploads/2021/12/ACSI-Policy-on-Company-Engagement-with-First-Nations-People.Dec21.pdf

AEMO (Australian Energy Market Operator). (2024). *2024 Integrated System Plan*. https://aemo.com.au/-/media/files/major-publications/isp/2024/2024-integrated-system-plan-isp.pdf?la=en

AFI (Australian Farm Institute). (2023). *Creating a sustainable, net-zero, food-secure Australia: Australian Farm Institute submission on the agriculture & land sector plan.* https://haveyoursay.agriculture.gov.au/agriculture-and-land-sectoral-plan

ASFI (Australian Sustainable Finance Institute). (2023). *Australian Sustainable Finance Progress Tracker 2023*. https://www.asfi.org.au/publications/australian-sustainable-finance-progress-tracker-2023

ASFI. (2024). *ASFI submission to NIAA Indigenous Procurement Policy (IPP)* reform. https://static1.squarespace.com/static/6182172c8c1fdb1d7425fd0d/t/65e7dacf6de35a617f6f5aeb/1709693648456/02020E~1.PDF

ASIC (Australian Securities & Investments Commission). (2014). *Digital Financial Reports.* https://asic.gov.au/regulatory-resources/financial-reporting-and-audit/preparers-of-financial-reports/digital-financial-reports/

ASIC. (2023). *ASIC's Indigenous Financial Services Framework - Driving change to support First Nations peoples to achieve and experience positive financial outcomes.* https://download.asic.gov.au/media/35wn0xyp/asic-indigenous-financial-services-framework-published-february-2023.pdf

ATIC (Australian Trade and Investment Commission). (2024). *Australia: APAC's rising regional hub for green data centres.* https://international.austrade.gov.au/en/news-and-analysis/news/australia-apacs-rising-regional-hub-for-green-data-centres

ATO (Australian Taxation Office). (2021). *Fuel tax credits - business*. https://www.ato.gov.au/businesses-and-organisations/income-deductions-and-concessions/incentives-and-concessions/fuel-schemes/fuel-tax-credits-business

Australian Senate Environment and Communications Legislation Committee. (2023). *Environment Protection (Sea Dumping) Amendment (Using New Technologies to Fight Climate Change) Bill 2023* [Provisions]. https://parlinfo.aph.gov.au/parlInfo/download/committees/reportsen/RB000184/toc_pdf/EnvironmentProtection(SeaDumping)Amendment(UsingNewTechnologiestoFightClimateChange)Bill2023[Provisions].pdf

Australian Treasury. (2023). *Intergenerational Report 2023: Australia's future to 2063.* https://treasury.gov.au/sites/default/files/2023-08/p2023-435150.pdf

Australian Treasury. (2024a). *Budget Measures Paper No. 2.* https://budget.gov.au/content/bp2/download/bp2_2024-25.pdf

Australian Treasury. (2024b). *Critical Minerals Production Tax Incentive - Consultation paper.* https://treasury.gov.au/sites/default/files/2024-06/c2024-541266-cp.pdf

Australian Treasury. (2024c). *Future Made In Australia National Interest Framework* . https://treasury.gov.au/sites/default/files/2024-05/p2024-526942-fmia-nif.pdf

Australian Treasury. (2024d). *Hydrogen Production Tax Incentive - Consultation paper.* https://treasury.gov.au/sites/default/files/2024-06/c2024-541265-cp.pdf

BCA (Business Council of Australia). (2023). *Seize the moment: A plan to secure Australia's economic future.* https://assets.nationbuilder.com/bca/pages/7307/attachments/original/1692333523/BCA_SEIZE_THE_MOMENT-FINAL-WEB.pdf?1692333523

Beasy, K., Emery, S., Pryor, K., & Vo, T. A. (2023). *Skilling the green hydrogen economy: A case study from Australia.* International Journal of Hydrogen Energy, 48(52), 19811–19820. https://doi.org/10.1016/j.ijhydene.2023.02.061

Beyond Zero Emissions. (2021). *Export Powerhouse: Australia's $333 billion opportunity*. https://www.bze.org.au/research/report/export-powerhouse

CCA (Climate Change Authority). (2020). *Prospering in a low-emissions world: an updated climate policy toolkit for Australia*. https://www.climatechangeauthority.gov.au/sites/default/files/2020-09/Prospering%20in%20a%20low-emissions%20world.pdf

CCA. (2021). *Paris Plus - Trade and investment trends in a decarbonising world.* https://www.climatechangeauthority.gov.au/news/paris-plus-trade-and-investment-trends-decarbonising-world

CCA. (2022). *2022 Review of International Offsets.* https://www.climatechangeauthority.gov.au/publications/2022-review-international-offsets

CCA. (2023a). *2023 Annual Progress Report.* https://www.climatechangeauthority.gov.au/sites/default/files/documents/2023-11/2023%20AnnualProgressReport_0.pdf

CCA. (2023b). *Reduce, remove and store: The role of carbon sequestration in accelerating Australia's decarbonisation*. https://www.climatechangeauthority.gov.au/publications/reduce-remove-and-store-role-carbon-sequestration-accelerating-australias-decarbonisation

CCA. (2024). *2024 Issues Paper: Targets, pathways and progress.* https://www.climatechangeauthority.gov.au/media-release-targets-pathways-and-progress-issues-paper-released-consultation

CEDA (Committee for Economic Development of Australia). (2024). *Clean Energy Precincts: How to seize the green export opportunity.* https://cedakenticomedia.blob.core.windows.net/cedamediatest/kentico/media/attachments/ceda-clean-energy-precincts-how-to-seize-the-green-export-opportunity.pdf

CER (Clean Energy Regulator). (2024). *Guarantee of Origin.* https://www.dcceew.gov.au/energy/renewable/guarantee-of-origin-scheme

CFFR (Council on Federal Financial Relations). (2020). *The Federation Funding Agreements Framework.* https://federalfinancialrelations.gov.au/federation-funding-agreements-framework

CIM (Clean Investment Monitor). (2024). *Q1 2024 Update.* https://www.cleaninvestmentmonitor.org/

Clean Energy Council. (2022). *Skilling the Energy Transition*. https://www.cleanenergycouncil.org.au/resources/resources-hub/skilling-the-energy-transition

Clean Energy Council and KPMG. (2024). *Leading Practice Principles: First Nations and Renewable Energy Projects.* https://assets.cleanenergycouncil.org.au/documents/resources/reports/Leading-Practice-Principles-First-Nations-and-Renewable-Energy-Projects.pdf

Climate Club. (2023). *Climate Club Work Programme 2024.* https://climate-club.org/wp-content/uploads/2023/11/CC-Work-Programme-2024_bf_final.pdf

CPI (Climate Policy Initiative). (2023). *Global Landscape of Climate Finance 2023.* https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2023/

Credit Suisse. (2022). *US Inflation Reduction Act: A tipping point in climate action*. https://www.credit-suisse.com/treeprintusinflationreductionact

CSIRO & BOM. (2022). *State of the Climate*. https://www.csiro.au/en/research/environmental-impacts/climate-change/state-of-the-climate

DAFF (Department of Agriculture, Fisheries and Forestry). (2022). *Australia's Indigenous land and forest estate (2020)*. https://www.agriculture.gov.au/abares/forestsaustralia/forest-data-maps-and-tools/spatial-data/indigenous-land-and-forest

DAFF. (2024a). *Catchment scale land use of Australia and commodities – Update December 2023.* https://www.agriculture.gov.au/abares/aclump/land-use/catchment-scale-land-use-and-commodities-update-2023#about-the-catchment-scale-land-use-of-australia--commodities--update-december-2023-spatial-dataset

DCCEEW (Department of Climate Change, Energy, the Environment and Water). (2022a). *Australia's 8th National Communication on Climate Change.* https://unfccc.int/sites/default/files/resource/NatComm8%20Biennial%20Statement_2022_v8%2021%20Dec.pdf

DCCEEW. (2022b). *State of Hydrogen 2022.* https://www.dcceew.gov.au/sites/default/files/documents/state-of-hydrogen-2022.pdf

DCCEEW. (2023a). *Annual Climate Change Statement 2023.* https://www.dcceew.gov.au/climate-change/strategies/annual-climate-change-statement-2023

DCCEEW. (2023b). *Carbon Leakage Review Consultation Paper*. https://www.dcceew.gov.au/climate-change/emissions-reduction/review-carbon-leakage

DCCEEW. (2024). *Australia's energy strategy and frameworks.* https://www.dcceew.gov.au/energy/strategies-and-frameworks

DCCEEW. (2024b). *Community Engagement Review.* https://www.dcceew.gov.au/energy/renewable/community-engagement-review

Department of Education. (2023). *Australian Universities Accord Final Report.* https://www.education.gov.au/download/17990/australian-universities-accord-final-report-document/36760/australian-universities-accord-final-report/pdf

DISR (Department of Industry, Science and Resources). (2021). *A Hydrogen Guarantee of Origin scheme for Australia - Discussion Paper.* https://consult.dcceew.gov.au/hydrogen-guarantee-of-origin-scheme

DISR. (2023). *Critical Minerals Strategy 2023–2030.* https://www.industry.gov.au/sites/default/files/2023-06/critical-minerals-strategy-2023-2030.pdf

DISR. (2024). *Resources and Energy Quarterly June 2024.* https://www.industry.gov.au/sites/default/files/2024-06/resources_and_energy_quarterly_june_2024_-_historical_tables.xlsx

DITRCA (Department of Infrastructure, Transport, Regional Development, Communications and the Arts). (2024). *State of Australia's Regions 2024.* https://www.infrastructure.gov.au/sites/default/files/documents/state-of-australias-regions-2024.pdf

Dumbrell, N. P., Robinson, C. J., Rickets, K. D., Urzedo, D., Walker, L., & Bong, A. J. (2024). Toward land restoration transitions: elevating regional voices and the provenance of co-benefits in Queensland rangelands. *The Rangeland Journal, 46(1)*. https://www.researchgate.net/publication/378372755_Toward_land_restoration_transitions_elevating_regional_voices_and_the_provenance_of_co-benefits_in_Queensland_rangelands

Energy Ministers. (2022). *National Energy Transformation Partnership*. https://www.energy.gov.au/sites/default/files/2022-08/National%20Energy%20Transformation%20Partnership.pdf

Engineers Australia. (2022). *Urgent need to address the lack of women in engineering.* https://www.engineersaustralia.org.au/news-and-media/2022/07/urgent-need-address-lack-women-engineering

Evans, M., & Polidano, C. (2022). *First Nations Businesses: Progress, Challenges and Opportunities| Bulletin–June 2022.* Reserve Bank of Australia. https://www.rba.gov.au/publications/bulletin/2022/jun/first-nations-businesses-progress-challenges-and-opportunities.html

Evans, M., Polidano, C., Dahmann, S. C., Kalera, Y., Ruiz, M., Moschion, J., & Blackman, M. (2024). *Indigenous Business and Corporation Snapshot Study 3.0. The University of Melbourne*. https://static1.squarespace.com/static/609c5b6fed6253178f23bdff/t/661c86c93796505e176452dc/1713145580800/Snapshot+3.0.pdf

EY Net Zero Centre. (2023). *Seizing Australia's energy superpower opportunities: Assessing the outlook for Australia in a net zero world.*

FNCEN (First Nations Clean Energy Network). (2024). *Response to the Hydrogen Headstart Consultation Paper.* https://www.firstnationscleanenergy.org.au/submissions

Future Made in Australia Bill 2024 (2024). https://parlinfo.aph.gov.au/parlInfo/download/legislation/bills/r7219_first-reps/toc_pdf/24084b01.pdf;fileType=application%2Fpdf

Gebbie, L., Miller, D., & Keenan, R. (2021). *Opportunities for Traditional Owners in the Carbon Economy.* In Pursuit, University of Melbourne. https://pursuit.unimelb.edu.au/articles/opportunities-for-traditional-owners-in-the-carbon-economy

Goldman Sachs. (2023). *Carbonomics: the third American energy revolution.* https://www.goldmansachs.com/intelligence/pages/gs-research/carbonomics-the-third-american-energy-revolution/report.pdf

Goldman Sachs. (2024). *GS SUSTAIN: Generational Growth — AI/data centers' global power surge and the sustainability impact.* https://www.goldmansachs.com/intelligence/pages/gs-research/ai-data-centers-global-power-surge-and-sustainability-impact/report.pdf

Grattan Institute. (2023). *Fuelling budget repair: how to reform fuel taxes for business.* https://grattan.edu.au/wp-content/uploads/2023/02/Fuelling-budget-repair-Grattan-report.pdf

Hammerle, M., & Phillips, T. (2023). *Making Our Way: Adaptive capacity and climate transition in Australia's regional economies .* https://cpd.org.au/work/making-our-way/

Hassan, Q., Algburi, S., Sameen, A. Z., Jaszczur, M., & Salman, H. M. (2023). *Hydrogen as an energy carrier: properties, storage methods, challenges, and future implications.* Environment Systems and Decisions. https://doi.org/10.1007/s10669-023-09932-z

Hellenic Competition Commission. (2024). *Sustainable Development Sandbox.* https://www.epant.gr/en/enimerosi/sandbox.html

ICIN (Indigenous Carbon Industry Network). (2024). *Industry Snapshot*. https://www.icin.org.au/latest_industry_snapshot

ICLEI Local Governments for Sustainability, & Ironbark Sustainability. (2021). *Australian Local Government Climate Review 2021.* https://ironbarksustainability.app.box.com/s/p6ylewyv92c6rkfh2k44vwjr9b6r9ltc

IEA (International Energy Agency). (2023). *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach - 2023 Update.* https://iea.blob.core.windows.net/assets/9a698da4-4002-4e53-8ef3-631d8971bf84/NetZeroRoadmap_AGlobalPathwaytoKeepthe1.5CGoalinReach-2023Update.pdf

IEA. (2024). *Global Critical Minerals Outlook 2024.* https://iea.blob.core.windows.net/assets/ee01701d-1d5c-4ba8-9df6-abeeac9de99a/GlobalCriticalMineralsOutlook2024.pdf

IEEFA (Institute for Energy Economics and Financial Analysis). (2023). *Australia faces growing green iron competition from overseas*. https://ieefa.org/sites/default/files/2023-08/Australia%20faces%20growing%20green%20iron%20competition%20from%20overseas_Sep23.pdf

ILSC (Indigenous Land and Sea Corporation). (2022). *Discussion paper: Indigenous participation in the carbon industry*. https://www.ilsc.gov.au/wp-content/uploads/2022/05/Indigenous-participation-in-the-carbon-industry.pdf

Infrastructure Australia. (2021). *A National Study of Infrastructure Risk.*

Infrastructure Australia. (2024). *Valuing emissions for economic analysis*. https://www.infrastructureaustralia.gov.au/publications/valuing-emissions-economic-analysis

IPCC (Intergovernmental Panel on Climate Change). (2022). *Climate Change 2022 - Mitigation of Climate Change* (Intergovernmental Panel on Climate Change (IPCC), Ed.). Cambridge University Press. https://doi.org/10.1017/9781009157926

Jobs Queensland. (2018). *Supporting workforces during industry transition: Key elements for success.* https://jobsqueensland.qld.gov.au/wp-content/uploads/2018/11/supporting-workforces-transition-report.pdf

Jobs Queensland. (2021). *Apprenticeship, women and workplace culture.* https://jobsqueensland.qld.gov.au/wp-content/uploads/2022/07/Apprenticeship-women-and-workplace-culture-Literature-review-October-2021-1.pdf

JSA (Jobs and Skills Australia). (2023a). *2023 Annual Jobs and Skills Report.* https://www.jobsandskills.gov.au/publications/towards-national-jobs-and-skills-roadmap

JSA. (2023b). *The Clean Energy Generation*. https://www.jobsandskills.gov.au/download/19313/clean-energy-generation/2385/clean-energy-generation/pdf

Kårtveit, B. (2021). *Green colonialism: The story of wind power in Sápmi.* In Stories of change and sustainability in the Arctic regions (pp. 157–177). Routledge.

King & Wood Mallesons. (2023). I*ndonesia's nickel rush - riding the waves of the EV battery revolution.* https://www.kwm.com/cn/en/insights/latest-thinking/indonesias-nickel-rush-riding-the-waves-of-the-ev-battery-revolution.html

Lee, D., Schelly, C., Gagnon, V. S., Smith, S., & Tiwari, S. (2023). *Preferences and perceived barriers to pursuing energy sovereignty and renewable energy: A tribal nations perspective.* Energy Research & Social Science, 97, 102967. https://doi.org/10.1016/j.erss.2023.102967

Lyons, P., Mynott, S., & Melbourne-Thomas, J. (2023). *Enabling Indigenous innovations to re-centre social licence to operate in the Blue Economy.* Marine Policy, 147, 105384. https://doi.org/https://doi.org/10.1016/j.marpol.2022.105384

McConnell, A., Janke, T., Cumpston, Z., & Cresswell, I. D. (2021). *Heritage: Indigenous heritage.* In Australia State of the environment 2021. Australian Government Department of Agriculture, Water and the Environment. https://doi.org/10.26194/7w85-3w50

Meckling, J., Aldy, J. E., Kotchen, M. J., Carley, S., Esty, D. C., Raymond, P. A., Tonkonogy, B., Harper, C., Sawyer, G., & Sweatman, J. (2022). *Busting the myths around public investment in clean energy.* Nature Energy. https://www.nature.com/articles/s41560-022-01081-y

NIAA (National Indigenous Australians Agency). (2022). *Commonwealth Closing the Gap - Annual Report 2022.* https://www.niaa.gov.au/sites/default/files/documents/inline/publications/niaa-closing-the-gap-annual-report-2022.pdf

NIAA. (2023). *2023 Commonwealth Closing the Gap Implementation Plan*. https://www.niaa.gov.au/2023-commonwealth-closing-gap-implementation-plan/copyright

NSW Government. (2023). *Technical note to NSW Government Guide to Cost-Benefit Analysis TPG23-08*. https://www.treasury.nsw.gov.au/sites/default/files/2023-03/20230302-technical-note-to-tpg23-08_carbon-value-to-use-for-cost-benefit-analysis.pdf

NZA (Net Zero Australia). (2023). *How to make net zero happen: Mobilisation report*. https://www.netzeroaustralia.net.au/wp-content/uploads/2023/07/Net-Zero-Australia-Mobilisation-How-to-make-net-zero-happen-12-July-23.pdf

OECD (Organisation for Economic Co-operation and Development). (2024). *Towards more accurate, timely, and granular product-level carbon intensity metrics.* https://doi.org/10.1787/4de3422f-en

Parliamentary Budget Office. (2023). *2023-24 Budget Snapshot.* https://www.pbo.gov.au/publications-and-data/publications /budget-charts/2023-24-budget-snapshot

Prime Minister and Cabinet. (2024). *Net Zero Economy Authority.* https://www.pmc.gov.au/netzero/net-zero-economy-authority

Productivity Commission. (2008). *Industry Policy for a Productive Australia*. https://www.pc.gov.au/media-speeches/speeches/cs20080806

Productivity Commission. (2023a). *5-year Productivity Inquiry: Advancing Prosperity.* https://www.pc.gov.au/inquiries/completed/productivity/report

Productivity Commission. (2023b). *5-year Productivity Inquiry: Managing the climate transition.* https://www.pc.gov.au/inquiries/completed/productivity/report/productivity-volume6-climate-transition.pdf

PWC. (2024). *Sustainability Reporting in Australia: A tipping point*. https://www.pwc.com.au/sustainability-reporting/sustainability-reporting-in-australia-a-tipping-point-2024.pdf

Queensland Government. (2024). *The Land Restoration Fund and Australia's carbon market.* https://www.qld.gov.au/environment/climate/climate-change/land-restoration-fund/about/australian-market

RBA (Reserve Bank of Australia). (2023). *The Extraordinary Decline in Australia's Net Foreign Liabilities.* https://www.rba.gov.au/speeches/2023/sp-so-2023-10-18.html

Romanello, M., Napoli, C. di, Green, C., Kennard, H., Lampard, P., Scamman, D., Walawender, M., Ali, Z., Ameli, N., Ayeb-Karlsson, S., Beggs, P. J., Belesova, K., Berrang Ford, L., Bowen, K., Cai, W., Callaghan, M., Campbell-Lendrum, D., Chambers, J., Cross, T. J., … Costello, A. (2023). *The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms*. In The Lancet (Vol. 402, Issue 10419, pp. 2346–2394). Elsevier B.V. https://doi.org/10.1016/S0140-6736(23)01859-7

Rutovitz, J., Visser, D., Sharpe, S., Taylor, H., Jennings, K., Atherton, A., Briggs, C., Mey, F., Niklas, S., Bos, A., Ferraro, S., Mahmoudi, F., Dwyer, S., Sharp, D., & Mortimer, G. (2021). *Developing the future energy workforce. Opportunity assessment for RACE for 2030.* https://www.racefor2030.com.au/wp-content/uploads/2021/10/RACE-E3-Opportunity-Assessment-FINAL-REPORT-October-2021.pdf

Turner & Townsend. (2023). Data centre cost trends. https://reports.turnerandtownsend.com/dcci-2023/data-centre-cost-trends

Tyler, M., & Dymock, D. (2021). *Attracting industry experts to become VET practitioners: a journey, not a destination.* https://www.ncver.edu.au/__data/assets/pdf_file/0039/9669603/Attracting_industry_experts_to_become_VET_practitioners_a_journey_not_a_destination.pdf

UN General Assembly. (2007). *United Nations declaration on the rights of indigenous peoples. In UN Wash (Vol. 12).* https://social.desa.un.org/issues/indigenous-peoples/united-nations-declaration-on-the-rights-of-indigenous-peoples

UNHRC (United Nations Human Rights Council). (2018). Free, prior and informed consent: a human rights-based approach. https://www.ohchr.org/en/documents/thematic-reports/free-prior-and-informed-consent-human-rights-based-approach-study-expert

United States Department of Energy. (2022). *Financial Incentives for Hydrogen and Fuel Cell Projects.* https://www.energy.gov/eere/fuelcells/financial-incentives-hydrogen-and-fuel-cell-projects

United States Department of Energy. (2023). *Biden-Harris Administration Announces $7 Billion For America's First Clean Hydrogen Hubs, Driving Clean Manufacturing and Delivering New Economic Opportunities Nationwide.* https://www.energy.gov/articles/biden-harris-administration-announces-7-billion-americas-first-clean-hydrogen-hubs-driving

Western Australian Government. (1979). *North West Gas Development (Woodside) Agreement.* https://www.legislation.wa.gov.au/legislation/prod/filestore.nsf/FileURL/mrdoc_8880.pdf/$FILE/North%20West%20Gas%20Development%20(Woodside)%20Agreement%20Act%201979%20-%20%5B00-00-00%5D.pdf?OpenElement

Woods, K., Markham, F., Smith, D., Taylor, J., Burbidge, B., & Dinku, Y. (2021). T*oward a perpetual funding model for Native Title Prescribed Bodies Corporate.* Canberra, ACT: Australian National University, Centre for Aboriginal …. https://openresearch-repository.anu.edu.au/items/4a065c69-f0d8-4ae6-8dd3-5462dafd577e

Yindjibarndi Energy. (2023). *Traditional Owners to lead large-scale renewable energy development in WA's Pilbara region.* Media Release. https://acenrenewables.com.au/2023/07/traditional-owners-to-lead-large-scale-renewable-energy-development-in-was-pilbara-region/

Appendices

APPENDIX

Appendix A Parliamentary referral to undertake this review

On 11 September 2023, the Australian Parliament agreed the following matter be referred to the Climate Change Authority for review, in accordance with section 59(1)(a)(ii) of the *Climate Change Authority Act 2011.*

1. The potential technology transition and emission pathways that best support Australia's transition to net zero emissions by 2050 for the following sectors:

    (i) electricity and energy;

    (ii) transport;

    (iii) industry and waste;

    (iv) agriculture and land;

    (v) resources; and

    (vi) built environment.

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

3. The review must take into consideration:
    a) the principles for the Climate Change Authority set out in section 12 of the *Climate Change Authority Act 2011*, including the global goals in Article 2 of the Paris Agreement and boosting economic, employment and social benefits; and
    b) the range of emissions reductions achievable through the deployment of available and prospective technologies;

4. The Climate Change Authority must give the report of the review to the Climate Change Minister, in accordance with section 60(1)(b) of the Climate *Change Authority Act 2011*, by 1 August 2024 to assist the Government in developing a national net zero by 2050 plan.

APPENDIX

Appendix B Methodology

How the authority has addressed the referral

The authority used six key questions in considering the requirements of the referral and the authority's legislative responsibilities. These questions were:

1. What is the scope of emissions considered in the report?
2. What are the emissions for the six sectors?
3. What are the potential technologies for decarbonising the emissions sources?
4. Which technologies should be focused on?
5. What is the trajectory for sectoral emissions and technology adoption that best supports each sector's contribution to Australia achieving net zero by 2050?
6. What are the relevant barriers, opportunities and enablers for each sector?

The authority engaged Boston Consulting Group (BCG) to assist the authority to develop a methodology to address these questions, drawing on BCG's experience advising on sector pathways for Germany, South Africa and others.

What is the scope of the emissions considered in the report?

The authority's quantitative analysis of emissions focused on scope 1 (direct greenhouse gas emissions) in each of the 6 sectors in the referral. These emissions account for all emissions Australia reports in its National Greenhouse Gas Inventory.

Emissions from electricity use (scope 2) were examined in the analysis of the built environment sectoral pathway, in the context of the to reduce that sector's scope 2 emissions through energy efficiency and distributed renewable energy. Enhancing energy efficiency is an opportunity in all sectors.

Potential process and technology changes to address scope 3 emissions were considered in 'user sectors' where it made sense to do so. For example, process and technology changes in the built environment sector could play an important role in addressing that sector's upstream Scope 3 emissions from cement and steel.

The authority analysed emissions that occur in the countries that consume Australia's exports, focusing on fossil fuel and green economy exports such as clean energy, green materials, and critical minerals. This was to inform our assessment of what global decarbonisation means for the Australian economy and people.

What are the emissions for the six sectors?

Sector pathways emissions mapping

To understand the current emissions and sources of emissions, the authority calculated the emissions for each of the six sectors named in the referral. The Australian Government does not publicly report emissions for these sectors on an individual basis. The authority calculated each of the sectors' emissions by aggregating from relevant sources of emissions data.

For most emissions sources, the authority allocated emissions from sources reported in Australia's inventory submission to the United Nations Framework Convention on Climate Change (UNFCCC) to one of the six sectors. This is based on 2022 emissions data, the most recent at the time of this report's publication.

Table B.1: Emissions and underlying sources for the six sectors

Sector	2022 emissions, Mt CO_2-e	Emissions sources
Electricity and Energy	153	The Electricity and energy sector contains emissions relating to the production of electricity (excepted 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.
Transport	90	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	64	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.
Agriculture and Land	-3	UNFCCC sectors (agriculture and land-use, land use change and forestry) plus fuel combustion associated with machinery use.
Resources	99	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.
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.
Total	433	

Source: Sector totals from authority national sectoral pathways emissions mapping based on Australia's National Greenhouse Accounts and emissions reported under the National Greenhouse and Energy Reporting Scheme. See the sector chapters in Part 1 for more infomation about the breakdown of emissions within sectors.

Note: sector emissions may not sum to the total emissions due to rounding.

Emissions mapping for AusTIMES model results

Emissions in AusTIMES are grouped into sectors, some of which are further broken down into subsectors (see the CSIRO's Sectoral Pathways Report's Appendix). The CSIRO calibrate emissions for these sectors to a base year of 2021, based on the Australian National Greenhouse Account's National Inventory by Economic Sector.

For its analysis, the authority has aggregated emissions from the AusTIMES subsectors to the six sectors used in this report (Table B.2). The authority has assigned the AusTIMES subsectors to match as closely as possible to the emissions sources in the sectoral pathways emissions mapping.

The authority's sector pathways emissions mapping and the AusTIMES emissions classification differ. This is partly because the authority's emissions mapping is based on Australia's 2022 inventory which includes revisions to emissions data that are not reflected in AusTIMES. Also, the UNFCCC inventory is more detailed and includes categories that are not represented in the AusTIMES model. Therefore, the AusTIMES classification is not able to allocate all sources of emissions to the report's six sectors as precisely as the sector pathways emissions mapping.

Table B.2: Emissions and the underlying AusTIMES subsectors assigned to the six sector pathways sectors

Sector	2025 emissions, Mt CO_2-e	AusTIMES sectors/subsectors
Electricity and Energy	150	Power (including off-site generation), Petroleum Refinery, Gas Supply, Hydrogen
Transport	92	Transport
Industry and Waste	73	Chemicals, Iron and Steel, Manufacturing (excluding Petroleum Refinery), Waste, Water Supply
Agriculture and Land	34	Agriculture, LULUCF, Land sequestration, Forestry and Logging
Resources	74	Mining and Gas extraction
Built Environment	23	Buildings, Construction, Refrigeration and aircon
Total	446	

What is the economic contribution of the six sectors?

To provide an indication of the economic contribution of each of the six sectors discussed in this report, the authority has compiled indicators of economic activity associated with each sector. These indicators are referenced throughout the report.

The authority is focusing on each sector's Gross Value Added (GVA) and employment numbers. GVA is the value of a sector's output less its intermediate consumption. It is a measure of an industry's contribution to Gross Domestic Product (GDP) (OECD, 2008). The authority's calculation of these economic statistics is shown in Table B.3 and referenced throughout this report.

Table B.3: Economic statistics for emissions sectors, 2022-23

Sector	GVA ($ millions)	GVA (% of GDP)	Employees ('000s)	Female employees ('000s)	Female employees (% of sector's employees)
Electricity & Energy	29,777	1%	91	22	24%
Transport	124,556	5%	861	188	22%
Industry and waste	140,588	5%	916	255	28%
Agriculture and Land	61,044	2%	299	93	31%
Resources	344,351	13%	288	56	19%
Built Environment (Commercial)	1,328,227	52%	10,149	5,828	57%
Built Environment (Construction)	170,488	7%	1,300	176	14%

Note: GVA for the six sectors does not sum to Australia's total GDP as GDP also includes ownership of dwellings and an adjustment for taxes and subsidies on products.
Source: Authority analysis of ABS (2023a, 2023b, 2023c, 2024).

Concordance to emissions sectors

Economic data are often grouped into industries that are defined using official industrial classifications (Box B.1). Employment data are reported in the Australian Bureau of Statistics' (ABS') Labour Force Survey in Australian and New Zealand Standard Industrial Classification (ANZSIC) groups, while GVA is reported using ANZSIC divisions, Input-Output Industry Groups (IOIGs) and the Supply-Use Industrial Classification (SUIC).

As economic data are not explicitly reported for the six sectors referred to in this report, the authority has aggregated official data from the underlying detailed industrial classifications to the six sectors. This aggregation is done using a "concordance table" which describes which detailed industries the 6 sectors are comprised of (Figure B.1).

The authority produced a concordance table that defines how Input-Output Industry Groups (IOIGs) and ANZSIC groups can be aggregated to the sectors used in this report. IOIGs and ANZSIC groups were used as the basis because the ABS commonly reports data for these classifications. IOIG industries and ANZSIC groups are comprised of one or more ANZSIC classes. Therefore, the concordance table was developed based on the authority's assessment of the sector to which the underlying ANSIC classes' emissions were predominantly allocated.

Box B.1: Industrial classifications used in economic statistics

There is often interest in understanding economic indicators for various industries. To do this, data from individual business entities, which include any organisation undertaking productive activities, can be aggregated using an 'industrial classification'. An industrial classification is a standard framework for grouping similar business entities into industries (ABS, 2013). In compiling its economic indicators, the authority uses different industrial classifications.

The Australian and New Zealand Industrial Classification (ANZSIC)

The ANZSIC is a widely used industrial classification, jointly developed by the ABS and Statistics New Zealand. It was most recently updated in 2006 (ABS, 2013). The ANZSIC structure includes industrial categories at 4 levels of detail: classes (most detailed), groups, subdivisions and divisions (least detailed).

A wide range of data is reported using the ANZSIC classification. This includes employment data from the ABS' Labour Force Survey (ABS, 2023c), emissions data from DCCEEW's National Inventory by Economic Sector (DCCEEW, 2024), and economic activity data from the ABS' System of National Accounts (ABS, 2023b).

Industrial classifications used in the Australian System of National Accounts (ASNA)

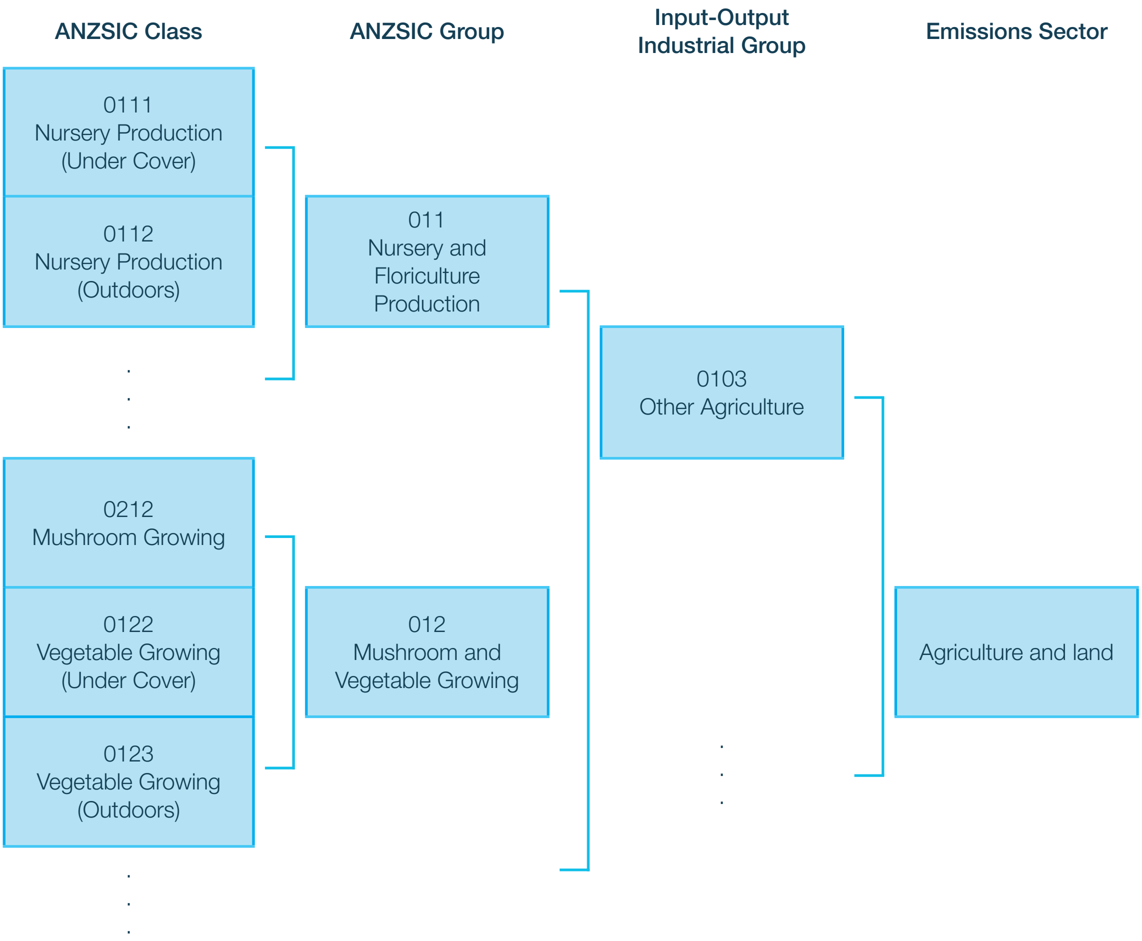
The ASNA uses a number of industrial classifications to report economic statistics (ABS, 2021). The authority uses GVA statistics from the ASNA. In the national accounts, GVA is reported by

- ANZSIC division. Used for reporting GVA in the annual and quarterly Australian System of National Accounts releases.
- Input-Output Industry Groups (IOIG). IOIGs are used for reporting industries in the ASNA's Input—Output Tables. They are comprised of one or more ANZSIC classes and are the most detailed classification that GVA is reported at.
- Supply-Use Industry Classification (SUIC). Used for reporting GVA in the Supply—Use Tables. A SUIC is comprised of one or more IOIGs.

In a limited number of cases, an IOIG may naturally map to more than one sector. In these cases, the authority made an assessment about the most appropriate sector.

To reflect the fact that economic activity in the built environment sector is significantly different depending on whether someone works in a services industry or construction industry, the authority has separated the built environment sector into the built environment (commercial) and built environment (construction) subsectors.

Figure B.1: Illustration of concordance from ANZSIC class to Agriculture and Land



Gross Value Added

GVA is reported by the ABS in its annual and quarterly Australian System of National Accounts (ASNA) at the ANZSIC division level. GVA is also reported at a more detailed level in the ABS' Supply Use Tables and Input—Output Tables, although this data is released after the annual and quarterly ASNA releases (ABS, 2021).

To aggregate the GVA, the authority apportioned the most data at the ANZSIC division into more detailed industrial classifications. This was done by:

- using the current-price GVA from the 2022-23 Australian System of National Accounts for each ANZSIC division (ABS, 2023b)
- apportioning the ANZSIC division-level GVA data into SUIC industries using the share of GVA for each SUIC industry from the 2021-22 Supply Use Tables (ABS, 2023a)
- apportioning the GVA from SUIC industries to IOIGs using the 2021-22 Input-Output Tables (ABS, 2024)
- aggregating GVA by IOIG to this report's 6 sectors, using the authority's concordance table.

Employment

To calculate the total employment by emissions sector, the authority aggregated data from the ABS Labour Force Survey. The total employment by sector was determined by:

- using the average total employment for 2022-23, by ANZSIC group, from the ABS' Detailed November 2023 Labour Force, Detailed release (ABS, 2023c)
- apportioning employed people in not further defined classifications into the underlying classifications, based on the share of employment of the underlying classifications
- aggregating employment from ANZSIC groups to this report's sectors using the authority's concordance table.

What are the potential technologies for the emissions sources?

The authority identified the technologies under the following categories:

Existing technologies are technologies or operational changes currently in use or available to be deployed (mature and demonstrated).

Prospective technologies are emerging technologies or operational changes which are at an early stage of development that could play an important role in future emissions reductions if rapid scaling and commercialisation can be achieved.

Which technologies should be focused on?

The authority used a principles-based assessment of readiness, abatement potential and cost to determine which technologies to focus on in the report. This means the report is not an exhaustive list of emissions reduction activities, but instead evaluates barriers and enablers for the most impactful prospective technologies.

The authority acknowledges the inherent uncertainty in 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, technologies were initially grouped into three phases based on technical and commercial readiness: 'Research and Development' (early-stage), 'Demonstration' and 'Deployment' (mature).

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 term emissions reductions were an area of focus in the review.

Abatement potential

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

Where possible, the authority 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 were a greater area of focus in the report.

To determine maximum feasible emissions reductions potential, the authority:

- analysed where top-down outputs (modelling results) show technology being adopted prior to attaining technical maturity or more rapidly than practically possible.
- considered by working back from net zero at a given date, what are the key milestones for transitioning an asset base.
- assessed the challenges of the least cost pathway.

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. Nonetheless, 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.

Additional technologies

The authority also made 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' technologies with low readiness today but that have breakthrough potential to deliver significant emissions reductions in the longer-term.

What is the trajectory for sectoral emissions and technology adoption that best supports each sector's contribution to Australia achieving net zero by 2050?

To determine the trajectory for sectoral emissions, the authority used a combination of 'top-down' and 'ground-up' analysis

Top-down analysis

Whole-of-economy ('top-down') and sector modelling provided estimated sector-level technology adoption and emissions under a least cost decarbonisation pathway.

The authority used a combination of the CSIRO's GTEM, AusTIMES and LUTO models. GTEM models whole of economy and global effects, while AusTIMES and LUTO provides 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 authority focused its analysis in this report on two emissions reduction scenarios (Australia in a 1.5°C world and 2°C world) representing potential Australian and global ambition. The modelling scenarios provided insights about possible developments in each sector and across the economy under different emissions pathways.

For further information on the authority's modelling, please see **Appendix C.**

Ground-up analysis

The authority also examined each sector from a more granular, sector-specific and technology-specific perspective ('ground-up') by drawing on diverse inputs from research, analysis and consultation. Ground-up analysis outputs included granular examination of technology adoption over time by sector or abatement potential by technology.

What are the barriers, opportunities and enablers relevant for each sector?

The authority considered the barriers to and enablers of implementing the technologies and operational changes at a sector and whole of economy level. Barriers included cost, workforce shortages, social licence, planning and approval delays, supply chain constraints and data gaps, as well as other matters. Enablers included a supportive policy and regulatory environment, cost incentives as well as other matters.

The authority has had regard to its legislated principles as part of this analysis of barriers, opportunities and enablers of the sector pathway.

Inputs to the authority's advice

Consultation

A review under section 59 of the *Climate Change Authority Act 2011* must make provision for public consultation.

Since May 2023, the authority has released three issues papers to inform our sector pathways and other reports. These were:

- 2023 Issues Paper: Setting, tracking and achieving Australia's emissions reduction target (received 595 submissions)
- Economic modelling of Australia's potential emissions reduction pathways (received 22 submissions)
- 2024 Issues Paper – Targets, Pathways and Progress (received 220 submissions)

The authority met with over 175 stakeholders to inform the authority's sector pathways and 2035 targets advice. These stakeholders included industry, state and territory government agencies, community groups, unions, jobs and skills councils, First Nations experts and youth.

References: Appendices A and B

ABS (Australian Bureau of Statistics). (2013). *Australian and New Zealand Standard Industrial Classification (ANZSIC).* https://www.abs.gov.au/statistics/classifications/australian-and-new-zealand-standard-industrial-classification-anzsic/latest-release

ABS. (2021). *Australian System of National Accounts: Concepts, Sources and Methods.* https://www.abs.gov.au/statistics/detailed-methodology-information/concepts-sources-methods/australian-system-national-accounts-concepts-sources-and-methods/2020-21

ABS. (2023a). *Australian National Accounts: Supply Use Tables 2021-22: Table 3. Primary Inputs Table*. https://www.abs.gov.au/statistics/economy/national-accounts/australian-national-accounts-supply-use-tables/latest-release

ABS. (2023b). *Australian System of National Accounts 2022-23: Table 5. Gross Value Added (GVA) by Industry.* https://www.abs.gov.au/statistics/economy/national-accounts/australian-system-national-accounts/2022-23

ABS. (2023c). *Labour Force, Australia, Detailed: EQ06 - Employed persons by Industry group of main job (ANZSIC), Sex, State and Territory, November 1984 onwards (Pivot Table)*. https://www.abs.gov.au/statistics/labour/employment-and-unemployment/labour-force-australia-detailed/nov-2023

ABS. (2024). *Australian National Accounts: Input-Output Tables 2021-22: Table 2. Input by industry and final use category and Australian production and imports by product group.* https://www.abs.gov.au/statistics/economy/national-accounts/australian-national-accounts-input-output-tables/2021-22

DCCEEW (Department of Climate Change, Energy, the Environment and Water). (2024). *National Inventory by Economic Sector 2022.* https://www.dcceew.gov.au/climate-change/publications/national-greenhouse-accounts-2022/national-inventory-by-economic-sector-2022

OECD (Organisation for Economic Co-operation and Development). (2008). *OECD Glossary of Statistical Terms.* OECD Publishing. https://doi.org/10.1787/9789264055087-en

APPENDIX

Appendix C Modelling

Modelling background and scope

One source of information that the authority drew upon for this report was whole-of-economy and sector modelling that the authority commissioned from the CSIRO. This modelling project also serves a broader purpose as a source of information to inform the 2035 Targets Advice that the authority will deliver later in 2024.

Purpose and limitations of the modelling

Modelling of emissions in the Australian economy is an analytical approach that can indicate, given certain sets of assumptions, how different sectors could contribute to emissions reductions, and provide insights into interactions and interdependencies across sectors.

All modelling exercises have limitations and are very simplified versions of the techno-economic interactions that occur in the economy. The authority has used the modelling to provide broad indications of trends and interactions; however, the modelling project commissioned by the authority, or any other modelling project, does not provide definitive or conclusive evidence of how the Australian economy would transition to net zero emissions.

In the sectoral pathways report, the CSIRO's modelling is intended to complement the ground-up analysis by providing:

- insights into how abatement could be achieved across different sectors of the economy
- insights into which technologies are taken up in different sectors under modelled least-cost pathways, given the model assumptions
- an economic context under which the net zero transition may occur, including projections of global demand for emissions intensive products.

Modelling approach

Modelling framework

The authority commissioned modelling from the CSIRO using a best-practice suite of models (Table C.1). The models are the CSIRO's Global Trade and Environment Model (GTEM)[1], the Australian implementation of the International Energy Agency's (IEA) energy technology systems model TIMES (AusTIMES)[2], and the CSIRO's Land Use Trade Offs (LUTO)[3] model.

1 The data and theory behind GTEM are outlined in detail in Cai et al. (2015).

2 The TIMES model brings together the Integrated Market Allocation (MARKAL)-Energy Flow Optimisation Model (EFOM) System, and was jointly developed under the IEA's Energy Technology Systems Analysis Project. Documentation of the TIMES model generator is available from the ETSAP website.

3 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.

GTEM provides Australia's economic context, including activity in different sectors, given global decarbonisation ambition. AusTIMES and LUTO provide greater detail at the sector level, including possible sectoral decarbonisation pathways. Each of these models is well-established and has been used in other significant modelling exercises (Australian Government 2021; Reedman et al. 2022).

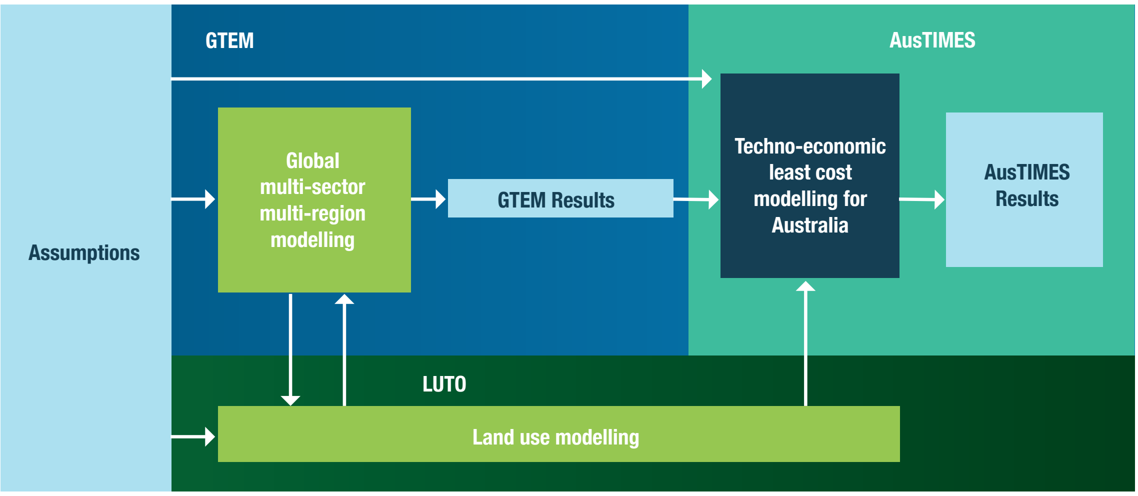
Table C.1: Summary of models used in the sector pathways report

Model	Summary of model	How is it used in this report?
GTEM	GTEM is a global multi-sector multi-region model that combines the top-down macroeconomic representation of a computable general equilibrium (CGE) model with the bottom-up engineering details of energy production and greenhouse gas emissions and abatement. The model features detailed accounting for global energy flows that are embedded in traded energy goods and offers a unified framework to analyse the energy-carbon-environment nexus. It provides projections of economic activity, energy and resource use, and emissions by sector. The global economic structure in GTEM is informed by the Global Trade Analysis Project database (Aguiar et al., 2019). The calibration of emissions by sector for Australia was updated for this exercise using Australia's National Inventory Report 2021 (DCCEEW, 2023a) and the accompanying 2021 National Inventory by economic sector.	GTEM models the global economy, with the Australian economy represented as a single region. This establishes the Australian economic context, given different levels of Australian and global ambition, including the economic activity of different sectors.
AusTIMES	AusTIMES is a techno-economic model covering Australian energy supply and demand and the other sources of emissions within Australia. The model determines least-cost decarbonisation pathways for Australia consistent with the sector activity projections from GTEM.	AusTIMES provides projections of emissions by sector[4] and the uptake of technologies. It provides insights into the relative contributions of sectors and technologies to cost-effective abatement.
LUTO	LUTO is a model of Australian intensive agricultural land use that combines data on existing land use, production functions, input and output prices, and physical variables (including climate) to calculate the relative profitability of a wide range of potential land uses.	LUTO provides projections of land-based carbon sequestration, based on incentive prices from GTEM.

For the sector pathways report the authority used the outputs provided from the CSIRO's operation of the AusTIMES model as this model provides greater sectoral detail. The AusTIMES outputs presented in the sectoral pathways report are consistent with GTEM projections of economic activity in end-use sectors (final energy consumers) and LUTO projections of land sector sequestration for each of the scenarios.

4 AusTIMES native sectors do not directly correspond to the sectors outlined in the referral to the Climate Change Authority for the Sector Pathways Review (Electricity and energy, Transport, Industry and waste, Agriculture and land, Resources, and Built Environment). For the purposes of the authority's analysis, some interpretation has been necessary to imperfectly align AusTIMES sectors with corresponding sectors in the referral.

Figure C.1: Modelling framework and interactions



Consultation on modelling

The authority released a consultation paper on the authority's proposed modelling approach in August 2023 and received 34 submissions. The authority also released an Issues paper in April 2024 that outlined the authority's thinking on its three major projects, the Sector Pathways Review, 2035 Targets Advice and 2024 Annual Progress Report. A number of submissions that the authority received in response to the Issues paper included commentary on the modelling approach.

Some stakeholders have commented on the authority's choice of models. Some were supportive of the choice of models: the Australia Institute noted that 'more recent information about GTEM is available … suggesting the model is a good choice to answer the CCA's questions, provided the modelling is done in an open and transparent manner', while the Energy Efficiency Council indicated '[t]he modelling framework is mainly appropriate'. Some stakeholders suggested alternative or additional models. The CSIRO's GTEM, AusTIMES and LUTO models were chosen to provide whole-of-economy interactions and technology-informed sectoral pathways and have been used in similar exercises previously (BHP, Centre for Policy Development, the Energy Efficiency Council, and the Institute for Energy Economics and Financial Analysis, submissions, 2023). The authority recognises that regional and distributional modelling at a domestic level could provide useful insights that are not produced by the current modelling ensemble.

Due to limited time the authority did not commission additional sector specific modelling, such as an electricity sector or a building stock model. The authority recognises the results for some sectors may not capture 'lumpy' investment decisions and sectoral tipping points (such as when previous infrastructure needs to retire at scale). However, the CSIRO's AusTIMES results will still provide insights about the relative trade-offs between abatement in different sectors.

Some stakeholders also highlighted the need for assumptions to be up-to-date and consistent (the Urban Transformations Research Centre and the Investor Group on Climate Change, submissions, 2023). The CSIRO maintains its models on an ongoing basis and has updated model inputs to the latest release where it has been practical to do so in the time available. The CSIRO, supported by the authority, has reviewed model outputs for alignment and consistency with other modelling exercises. Key assumptions are outlined in this appendix.

Several stakeholders highlighted the importance of learning rates. Learning rates have not been varied across the scenarios (the Centre for Policy Development, the Energy Efficiency Council, submissions, 2023). However, learning rates are considered in several sources of assumptions used in the modelling, such as the CSIRO's GenCost publication. Learning rates are also considered in the authority's ground-up analysis.

Some stakeholders have commented on the breadth of scenarios and the decision not to model a 'business as usual' scenario (The Australia Institute, Beyond Zero Emissions, the Centre for Policy Development, the Insurance Council of Australia, the Lock the Gate Alliance, the Investor Group on Climate Change, Ampol, submissions, 2023). The authority chose not to ask the CSIRO to model a scenario where Australia does not meet its current emissions targets, where the transition is disorderly or a world with a greater than 2°C temperature rise. Modelling a 'business as usual' or a 'no further action' scenario was not the authority's main priority for this modelling exercise. The authority has asked the CSIRO to model scenarios for 1.5°C and 2°C degree worlds to provide the necessary information for the authority to develop its advice.

Many stakeholders recommended considering the impacts of climate change on economic prosperity when comparing global scenarios. The authority intends to account for climate damages through additional analysis in its forthcoming 2035 Targets Advice.

Several stakeholders have identified benefits associated with decarbonisation, such as health benefits (Climate Action Network, Beyond Zero Emissions, the Institute for Energy Economics and Financial Analysis, submissions, 2023), the emergence of new industries (the Investor Group on Climate Change submission, 2023), and reduced risk of major weather events (Beyond Zero Emissions, Climate Action Network, the Insurance Council of Australia, submissions, 2023). Stakeholders generally preferred that the authority integrate these benefits into the economic modelling directly. However, due to limited time, the authority intends to consider these benefits primarily through ground-up analysis.

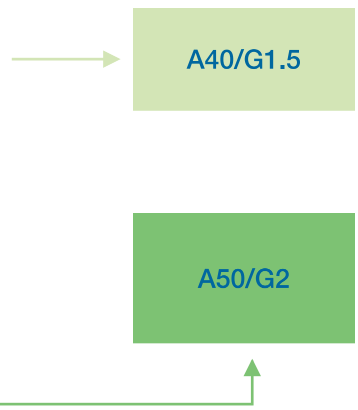
Scenarios

The scenarios the authority requested the CSIRO model were designed to indicate the effects of various levels of emissions reduction ambition within a broad range that the authority could consider in forming its advice.

It is not possible to explore all possible futures and the scenarios requested by the authority are stylised and indicative, with a focus on different emissions trajectories in Australia and different global emissions reduction ambition. Globally, the modelling considers a '1.5°C world' (broadly consistent with 1.5°C with no or limited overshoot with 50% probability) and a 'less than 2°C world' (broadly consistent with less than 2°C with 67% probability).

Figure C.2: Diagram of modelled scenarios

		Global ambition	
Australian ambition		<2°C (67% chance) Moderate ambition	1.5°C (50% chance) High ambition
Net Zero Year	2035 net emissions relative to 2005		
2035	-100%	*Not modelled*	***Modelled scenario:*** A35/G1.5
2040	-75%	***Modelled scenario:*** A40/G2	***Modelled scenario:*** A40/G1.5
2045	-62%	***Modelled scenario:*** A45/G2	*Not modelled*
2050	-57%	***Modelled 'Reference' scenario:*** A50/G2	***Modelled 'Reference' scenario:*** A50/G1.5

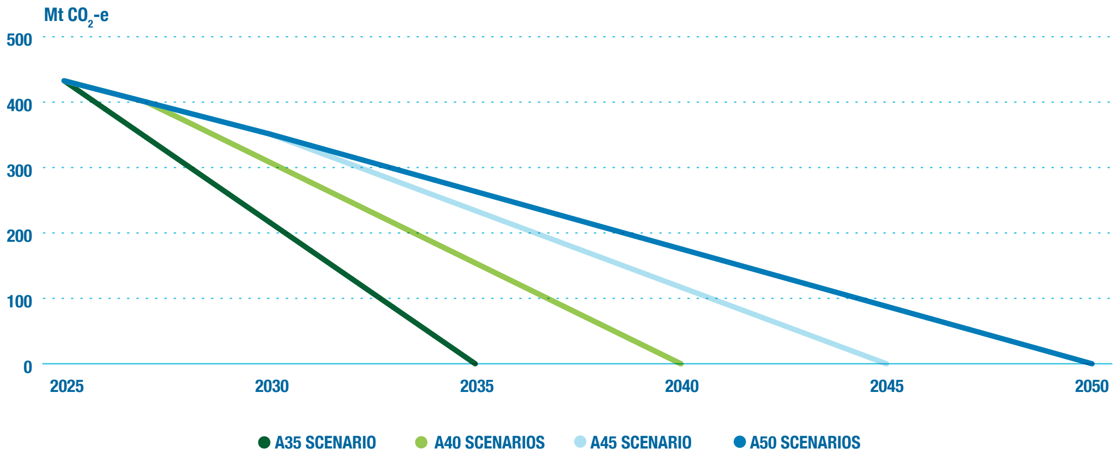


The CSIRO modelled these scenarios as straight-line trajectories to net zero in four different years: 2035, 2040, 2045 and 2050. The trajectories to net zero in 2045 and 2050 pass through the government's emissions reduction target for 2030 (a 43% reduction on 2005 levels), while the trajectories to net zero in 2035 and 2040 overachieve on the 43% target.[5]

These trajectories result in an array of emissions outcomes in 2035 that will be relevant when considering the authority's 2035 Targets Advice later this year. Scenarios are given a name based on a combination of their net zero year (e.g. A50 scenarios reach net zero in 2050), and the 'world' in which they exist (G1.5 scenarios are consistent with 1.5°C with no or limited overshoot, while G2 scenarios are consistent with limiting warming to below 2°C)

This report focuses on the CSIRO's modelling results from the A50/G2 and A40/G1.5 scenarios.

Figure C.3: Net emissions trajectories of modelled scenarios



Modelling different global contexts provides a comparison of the impacts of the level of global decarbonisation on Australia's decarbonisation pathways. These impacts include differing global demands for Australian exports (including fossil fuels and mineral resources), global trends in technology availability and costs, and the availability and deployment of engineered carbon dioxide removals.

These global contexts would likely be associated with different physical climate impacts, particularly beyond 2050, but these are not explicitly represented or accounted for in the models that the authority has asked the CSIRO to work with, other than through productivity impacts that are considered in the LUTO model when determining land sector sequestration. Instead, these impacts will be considered through additional analysis in the forthcoming 2035 targets advice.

The modelling assumptions applied by the CSIRO are consistent with a neutral view of Australia's relative economic positioning and technology deployment in a low emissions world. In most cases, technology cost and availability assumptions are similar across all scenarios, although there are some differences between the 1.5°C and less than 2°C worlds (see the assumptions relating to technology costs in the 'Modelling assumptions for this exercise' section below).

5 Due to the timing of the modelling exercise, emissions trajectories were calibrated to Australia's National Inventory Report 2021 (DCCEEW, 2023a). The more recent National Inventory Report 2022 revises the starting point downward and may imply other slight changes to the modelled trajectories, but was not published in time for incorporation in this modelling exercise.

Focus scenarios for sectoral pathways analysis

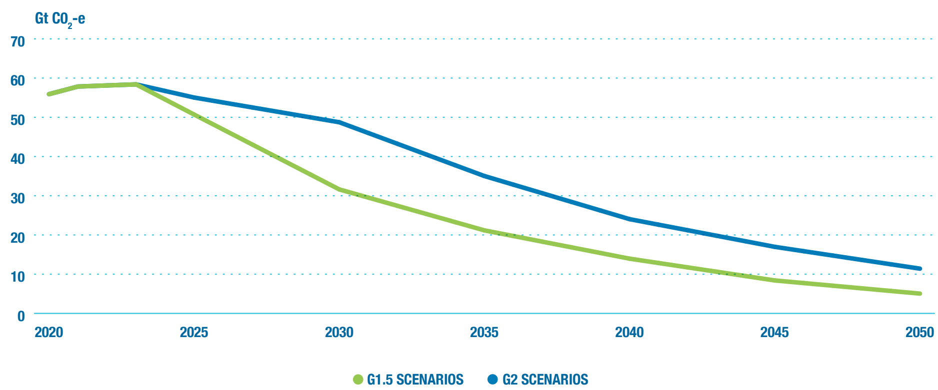
Although all the CSIRO's modelled scenarios inform the sectoral pathways analysis, two illustrative scenarios have been identified to facilitate comparison between possible pathways for sectors.

- The **A50/G2** scenario is consistent with achieving Australia's current emissions reduction targets in a less than 2°C world. Although these targets are challenging, Australia is not a leader in decarbonisation in this world and reaches net zero in 2050, while many other developed nations reach net zero in 2040 or 2045. The global energy mix retains more fossil fuel demand than the 1.5°C world, and Australia's fossil fuel production declines gradually. There is a strong global investment in negative emissions (land-based and technology-based emissions removals) to support the achievement of this goal.
- The **A40/G1.5** scenario is consistent with a 75% reduction on 2005 levels in 2035 and net zero by 2040, reflecting greater ambition and more rapid emissions reductions. Australian targets are consistent with greater ambition from other developed nations as the world cooperates to limit warming to 1.5°C. Fossil fuel demand falls more rapidly globally and in Australia, and there is even stronger investment in negative emissions technologies.

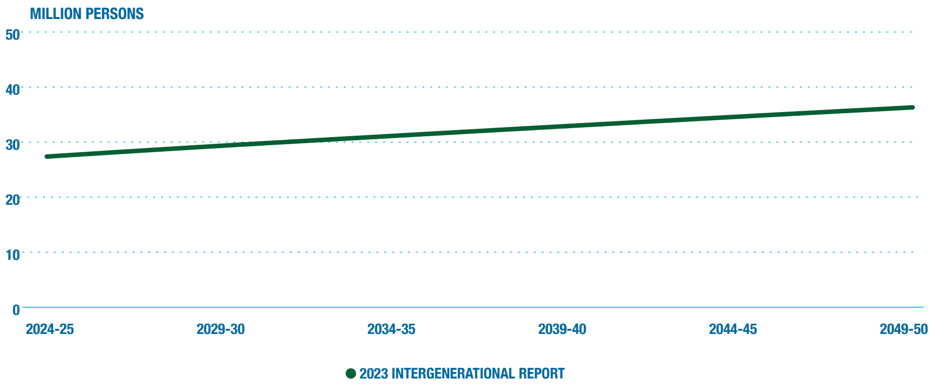
Modelling assumptions for this exercise

The CSIRO maintains and operates the models used for this modelling exercise (alongside Monash University's Climateworks Centre, which jointly maintains and operates the AusTIMES model with the CSIRO). The authority reviewed and provided input into some macro assumptions for each of these models. The models used include thousands if not more than one million assumptions and these have been paramaterised by the CSIRO. A list of significant assumptions is below, with some qualitative analysis of the implications of these assumptions.

Table C.2: GTEM assumptions

Global net emissions trajectory	*Source: Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report Illustrative Mitigation Pathways: IMP-GS (applied to the less than 2°C world) and IMP-Ren (applied to the 1.5°C world) (Byers et al., 2022) – with adjustments to account for historical emissions* IPCC 'Illustrative Mitigation Pathways' were chosen because they reflect a credible established benchmark, with a clearly described underlying narrative. In IMP-GS, mitigation action is gradually strengthened over time, and this is from the IPCC's 'C3' suite of scenarios that limit warming to 2°C with >67% probability. In IMP-Ren, emissions reduction efforts focus on rapid deployment of renewables, and this is from the IPCC's 'C1' suite of scenarios that limit warming to 1.5°C with no or limited overshoot with >50% probability. The authority requested the CSIRO impose versions of these trajectories that were adjusted for historical emissions. Total cumulative emissions up to 2050 are retained as well as the general shape of IPCC trajectories. Other global trajectories with different narratives would be legitimate alternatives. Figure C.4: Global net emissions trajectories 
Global energy mix	*Source: International Energy Agency (IEA) World Energy Outlook (IEA, 2021b) Announced Pledges Scenario (APS) applied to the less than 2°C world, and Net Zero Emissions by 2050 Scenario (NZE) applied to the 1.5°C world.* The IEA 2021 APS reflects a world that is relatively slower to phase out fossil fuels than the NZE scenario.

Global and domestic engineered removals	*Source: IEA's 2021 NZE scenario (IEA, 2021a) was used as the source for the amount of global engineered removals in a 2°C world, with adjustments to align with the GTEM model structure (resulting in about 2 Gt CO_2-e of engineered removals worldwide in 2050). Engineered removals are slightly higher in the 1.5°C (around 2.1 Gt CO_2-e). The CSIRO downscaled these global assumptions for Australia, resulting in engineered removals between 20 Mt CO_2-e and 25 Mt CO_2-e in 2050, with no engineered removals assumed to occur in Australia before 2030.* The cost and potential scale of deployment for engineered emissions removals are highly uncertain. These are emerging technologies but they will need to be developed rapidly to support global emissions reduction efforts. The authority considers these assumptions are consistent with other modelling of below 2°C and 1.5°C scenarios but notes they will not be achieved without significant global investments.
Australia's population	*Source: 2023 Intergenerational Report (Australian Treasury, 2023)* Consistent with this source, Australia's population reaches about 36.3 million people by 2050. Figure C.5: Australia's population

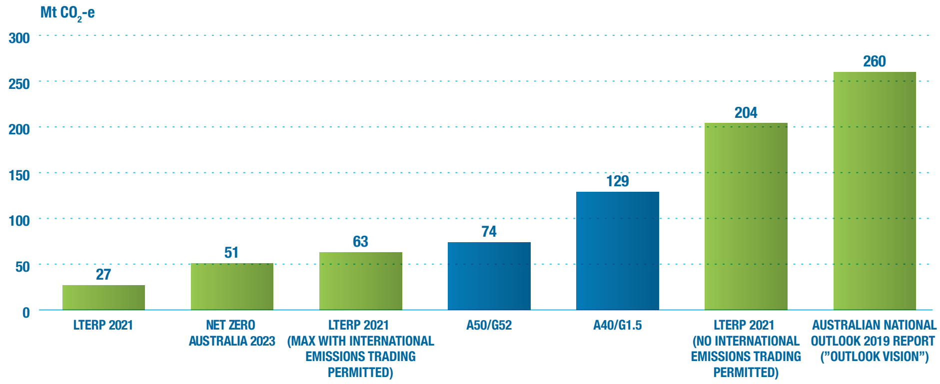


Domestic LULUCF emissions and sequestration	See the LUTO assumptions section below for more details.
Agriculture	Agricultural production and commodity exports were modelled in GTEM. There were two sets of broad assumptions that the authority discussed with the CSIRO: · Crop production – Modelled using GTEM assumptions of ongoing improvements in productivity over time · Livestock production – As described in the Issues paper that the authority released in April 2024 that the authority would include the assumption that cattle numbers would remain relatively stable over time, consistent with the long run historical trend (ABARES, 2022) and ABARES projections (ABARES, 2023a).
Participation in international emissions trading	Assumption: Australia does not engage in international trade of emissions units, either as a buyer or as a seller. Other global regions are not similarly restricted. Due to uncertainty about the future role of international trade of emissions units, the authority has chosen to reflect current policy by asking the CSIRO to impose an assumption that Australia does not engage in international emissions trading. This assumption means Australia cannot purchase lower-cost international abatement (which could disincentivise domestic abatement) or provide emissions units to the international market (which could incentivise Australia to sell land-based offsets to the global market that it may wish to reserve for domestic use in the future).
Global Warming Potential	*Source: All analysis in the CSIRO's GTEM and other models for this modelling exercise relies on estimates for the 100-year global warming potential of gases (GWP 100) from the IPCC's fifth Assessment Report (IPCC, 2013).*

Table C.3: LUTO assumptions

<table>
<tr><td>Sequestration from new plantings</td><td>
Modelled annual land sequestration from new plantings in LUTO as applied in AusTIMES (distinct from the existing LULUCF sink) reaches about 74 Mt CO_2-e in the A50/G2 scenario in 2050, increasing to around 129 Mt CO_2-e in the A40/G1.5 scenario. The chart below compares this to some examples of annual sequestration from new plantings in other modelling exercises.

Figure C.6: Comparison of sequestration achieved from new plantings in 2050 across different exercises. (Australian Government, 2021; CSIRO, 2019; Davis et al., 2023)



Note: The LUTO sequestration rates in this figure are the rates that are applied in the corresponding AusTIMES scenarios.

This is a modelled outcome in LUTO. The amount of land sequestration from new plantings is used as an input to GTEM and AusTIMES modelling. LTERP is Australia's Long-Term Emissions Reduction Plan.
</td></tr>
<tr><td>Profitability threshold</td><td>
Assumption: The authority has requested that land use does not change to an alternative use until the financial return on the alternative land use is five times the return on the current land use on a net present value basis.

For reforestation land uses, LUTO is operated on the assumption that landholders make decisions as if they will receive an annuity payment over 100 years based on the present value of carbon sequestration at a discount rate of 7%.
</td></tr>
<tr><td>Planting rate constraint</td><td>
Assumption: Initial constraint of 22,500 ha per year in 2025. Once the initial constraint is met the planting rate grows to a final cap of 260,000 ha per year.

The initial constraint reflects a balance of considerations, including the historically achieved planting rates in the mid-1990s and time needed to upscale a plantation industry that has planted less than 10,000 ha in every year since 2009-10 (ABARES, 2023b).

The upper limit is informed by the previous maximum planting area achieved of around 130,000 ha in 1999-2000 with the upper limit set at two times this to reflect future potential financial incentives (such as ACCUs).
</td></tr>
<tr><td>Biodiversity plantings</td><td>
Assumption: Up to 30 per cent of plantings are ‘environmental plantings’ that support biodiversity in addition to carbon sequestration.

The authority’s view is that there would need to be a balance of environmental and carbon plantings to reflect the diverse goals under a just transition. This reflects emerging policy approaches such as Australia’s commitment to contribute to the goals of the Kunming-Montreal Global Biodiversity Framework through conserving 30 per cent of land and oceans by 2030, and the government’s Nature Positive Plan. The LUTO model is calibrated to keep environmental plantings at approximately 30% of total plantings cumulative to 2050.
</td></tr>
<tr><td>Water use</td><td>
Assumption: All plantings in class C and D water stressed catchments are required to account for water entitlements or allocations, in line with managing competing water uses.
</td></tr>
</table>

Table C.4: AusTIMES assumptions

GTEM and LUTO outputs used as inputs in AusTIMES	
AusTIMES targets the gross value added for each sector from GTEM modelling results, as well as mirroring GTEM assumptions about population growth and the amount of engineered removals. For land sector emissions and sequestration AusTIMES uses LUTO model outputs in combination with the 2023 Emissions Projections (DCCEEW, 2023b).	
Electricity	
Transmission	Transmission options and costs are drawn from the Draft 2024 ISP (AEMO, 2023). Generators are mapped to transmission zones. Interconnector limits apply to interstate trade of electricity. Where new transmission is needed, for example to support new renewable generators, this is factored in as the model solves to minimise total discounted system costs over the projection period.
Technology costs	Electricity technology costs are based on the CSIRO's 2023-24 GenCost consultation draft (P. Graham et al., 2023) rather than the final 2023-24 GenCost report released in May 2024 (P. Graham et al., 2024). The final version of this report was not available when the CSIRO finalised the assumptions to be used for this modelling exercise. The final report features several revisions, including upward revisions to the outlook for onshore wind and large-scale solar capital costs.
Renewable energy policies	AusTIMES represents a range of state or territory and national renewable energy targets and objectives, including Australia's 82% renewable energy target for 2030 (assumed to apply to major grids) , the New South Wales Electricity Infrastructure Roadmap, the Northern Territory, Queensland, Tasmania and Victoria Renewable Energy Targets, and the Victorian Offshore Wind Target. While the CSIRO modelling achieves the 82% renewable energy target for the major grids where it applies, when examining the Australia-wide share (which includes off-grid generation) it is slightly less than that target.

Scenario	Renewable energy share in 2030
A50/G2	77%
A40/G1.5	79%

Transport	
Technology costs	Road vehicle costs are aligned with the CSIRO's EV Projections (P. Graham, 2023) for the 'Step Change' scenario. Cost assumptions have not been varied across scenarios.
Fleet turnover	For road transport, existing vehicle stock (20.1 million registered motor vehicles with various characteristics as at 31 January 2021) is based on the ABS Motor Vehicle Census (ABS, 2021) and AusTIMES models the change in vehicle stock over time. Changes to the mix of vehicles and other assets in shipping, rail and aviation are not explicitly modelled in AusTIMES.
New Vehicle Efficiency Standard (NVES)	A simplified implementation of the NVES is used in AusTIMES, with headline targets for emissions intensity applied to sales of passenger vehicles and light commercial vehicles from 2025 to 2029.

Maximum emissions intensity of light vehicle sales (g CO_2/km)		
Year	**New passenger vehicles**	**New light commercial vehicles**
2025	141	210
2026	117	180
2027	92	150
2028	68	122
2029	58	110

Industry and Resources	
Technology costs and options	Technology options for emissions reductions in the industry and resources sector are consistent with the analysis undertaken for Climateworks' Industry Energy Transition Initiative (ETI) (Climateworks Centre & CSIRO, 2023). Hydrogen production costs are based on the same source as electricity technology costs (the 2023-24 GenCost consultation draft). Where data on technology costs was not available, the authority has relied on advice from the CSIRO and Climateworks, with additional advice from EY on abatement of fugitive emissions from coal mining.
Built Environment	
Technology costs and options	Assumptions about the technologies available to reduce emissions from buildings are consistent with those used in other AusTIMES modelling exercises – see the Climateworks Centre Decarbonisation Scenarios 2023 report (T. Graham et al., 2023). No explicit technologies are included for the built environment sector outside of residential and commercial buildings. The authority has relied on the expertise of the Climateworks Centre and the CSIRO for plausible assumptions for the costs and options of technologies to decarbonise buildings.
Agriculture	
Technology costs and options	Assumptions about the technologies available to reduce emissions from the agriculture sector are consistent with those outlined in the Climateworks Decarbonisation Scenarios 2023 report (T. Graham et al., 2023).

Key uncertainties to consider alongside the modelling

There are a range of reasons why modelled outcomes may not be achieved in the real world. The issues below have been identified as some (but by no means all) of the key uncertainties that should be considered when evaluating the likelihood of the different modelling results.

Supply chains

As outlined in many of the sector chapters, supply chain risks exist for many of the key technologies to support decarbonisation in Australia and globally. This includes not just the relevant materials for production, but also the necessary public and private investment, and the workforce required to deliver the transition.

Global coordination

All the scenarios assume orderly global action to achieve a global emissions trajectory consistent with the relevant long term global temperature outcome. In practice, differences in policy settings across different countries could well impact on the commercial viability of deploying available abatement technologies in Australian energy and emissions-intensive trade-exposed industry sectors.

Smooth uptake of new technologies

Some parts of Australia's economy are made up of only a few facilities throughout Australia. Both GTEM and AusTIMES often represent smooth changes in production or gradual transitions to a new technology. In reality, capital turnover in these sectors is likely to be more 'lumpy' as a small number of facilities are established, or switch to a new production or abatement technology.

Electricity mix and renewables buildout

The modelling exercise shows a plausible electricity capacity and generation mix, but does not fully capture all aspects of the technical requirements of the system, commercial viability of generation assets, impacts on electricity prices, or potential restrictions on the rate of expansion of renewable electricity. Any of these factors could influence real-world outcomes in the electricity sector, and slower buildout of renewables in particular could make rapid decarbonisation of the economy more challenging.

Competition for land use

There may be increasing competition for land use as demand grows over time for renewable energy, biofuels and biomass, agricultural commodities and land sector sequestration. Some of this competition may be offset by improving agricultural efficiency, co-benefits (e.g. shelterbelts), and co-use (e.g. co-location of renewable energy generation and grazing).

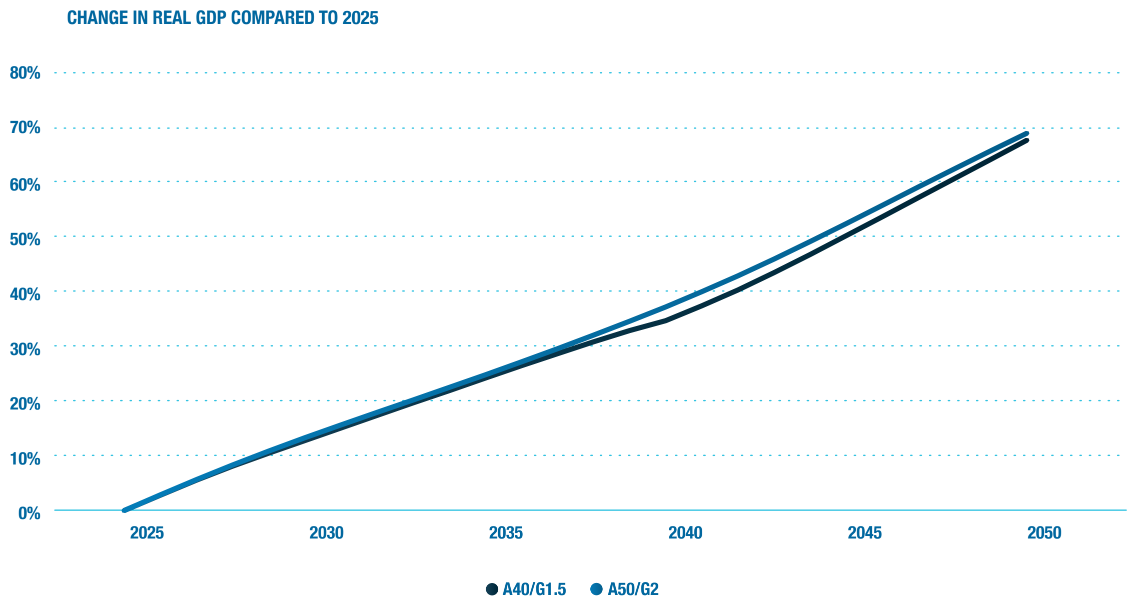
GTEM – High level GDP results and marginal cost of abatement

Gross Domestic Product

In the A40/G1.5 and A50/G2 scenarios modelled by the CSIRO for the authority, Australia continues to experience economic growth that is broadly in line with recent Treasury projections. In both scenarios, the Australian economy grows in real terms by an average of 2.1% per year between 2025 and 2050 (Figure C.7). The Australian Treasury's 2023 Intergenerational Report projects an average growth rate of 2.2% per year over the next 40 years (Australian Treasury, 2023).

The modelling undertaken for the authority does not the incorporate the potential impacts of climate change on Australia's economy. It also takes a neutral view of the extent to which Australia takes advantage of the economic opportunities in international trade of the global transition to net zero. It does not, for example, incorporate assumptions and policies reflected in the modelling undertaken to support the forthcoming update to the National Hydrogen Strategy, or in the measures in the 2024 Budget to support the government's Future Made in Australia agenda.

Figure C.7: Change in gross domestic product, 2025 to 2050



Source: CSIRO modelling in GTEM commissioned by the Climate Change Authority

Marginal cost of abatement

GTEM solves for the marginal cost of abatement necessary to meet the net emissions constraint that it is given under each scenario modelled, based on the suite of technologies and technology cost assumptions that are included in the model. The marginal cost of abatement motivates the avoidance or reduction of emissions, or an increase in removals, across the economy.

Although this is sometimes described as a 'shadow carbon price', it is an abstract modelling mechanism and does not imply a true carbon price. It may require producers in the model to switch to higher cost (lower emissions) production methods, but it is not a carbon tax, where revenue would be collected (and potentially redistributed by government), nor is it necessarily enforced through a cap-and-trade or baseline-and-credit mechanism (see section NP.6 for a discussion of ways to signal the cost of carbon across the economy).

The table below compares the marginal cost of abatement from GTEM in the year 2050 under the A40/G1.5 and A50/G2 scenarios with estimates of the values of emissions reductions that have been developed for different purposes (see Table C.5, notes). The comparisons are provided for general, illustrative purposes only and should be interpreted with caution, given the different approaches used to develop the estimates and the different purposes for which they have been prepared.

Table C.5: Marginal cost of abatement / value of emissions reductions in 2050

Source	Scenario	$ (2023 Australian dollars)
Climate Change Authority /CSIRO GTEM results	A40/G1.5	477
	A50/G2	518
Australian Energy Market Commission[1]		420
Infrastructure Australia[2]	Central	377
	High	469
	Low	287

Notes:

1 From Australian Energy Market Commission (2024). Value of emissions reductions to be used by a government or regulatory entity where quantitative analysis is required of costs and benefits of projects relating to emissions reduction in the National Electricity Market. This interim value was calculated based on the methodology approved by the Ministerial Council on Energy and will remain in force until 2025 unless superseded by an updated instrument, rule or regulation.

2 From Infrastructure Australia (2024). This Infrastructure Australia Guidance Note sets out the monetised value of GHG emissions for use in economic analysis of a new proposal, including cost-benefit analysis (CBA) and cost effectiveness analysis (CEA). The values are based on the estimated future costs of abatement necessary for the Australian economy to meet national emissions reduction targets and international commitments. The 'High' and 'Low' cases are for use in sensitivity analysis.

Further information on the GTEM modelling results will be provided in the report of the authority's 2035 targets advice.

References: Appendix C

ABARES (Australian Bureau of Agricultural and Resource Economics and Sciences). (2022). *Rural commodities - meat - beef and veal.* https://www.agriculture.gov.au/abares/research-topics/agricultural-outlook/data#_2022

ABARES. (2023a). *Agricultural commodities: March quarter 2023 - Outlook tables - data tables.* https://www.agriculture.gov.au/abares/research-topics/agriculturaloutlook/data#agricultural-commodities

ABARES. (2023b). *Australian plantation statistics 2023 update*. https://doi.org/10.25814/hhk8-4x26

ABS (Australian Bureau of Statistics). (2021). *Motor Vehicle Census, Australia.* https://www.abs.gov.au/statistics/industry/tourism-and-transport/motor-vehicle-census-australia/31-jan-2021

AEMC (Australian Energy Market Commission). (2024). *How the national energy objectives shape our decisions.* https://www.aemc.gov.au/market-reviews-advice/aemc-guide-applying-emissions-component-national-energy-objectives

AEMO (Australian Energy Market Operator). (2023). *Draft 2024 Integrated System Plan Inputs and Assumptions Workbook.* https://aemo.com.au/consultations/current-and-closed-consultations/draft-2024-isp-consultation

Aguiar, A., Chepeliev, M., Corong, E. L., McDougall, R., & van der Mensbrugghe, D. (2019). *The GTAP Data Base: Version 10. Journal of Global Economic Analysis, 4(1),* 1–27. https://doi.org/10.21642/JGEA.040101AF

Australian Government. (2021). *Australia's Long-Term Emissions Reduction Plan: Modelling and Analysis.* https://www.dcceew.gov.au/climate-change/publications/australias-long-term-emissions-reduction-plan

Australian Treasury. (2023). *Intergenerational Report 2023.* https://treasury.gov.au/publication/2023-intergenerational-report

Byers, E., Krey, V., Kriegler, E., Riahi, K., Schaeffer, R., Kikstra, J., Lamboll, R., Nicholls, Z., Sanstad, M., Smith, C., van der Wijst, K.-I., Al Khourdajie, A., Lecocq, F., Portugal-Pereira, J., Saheb, Y., Strømann, A., Winkler, H., Auer, C., Brutschin, E., … van Vuuren, D. (2022). *AR6 Scenarios Database hosted by IIASA.* https://doi.org/10.5281/zenodo.5886911

Cai, Y., Newth, D., Finnigan, J., & Gunasekera, D. (2015). *A hybrid energy-economy model for global integrated assessment of climate change, carbon mitigation and energy transformation.* Applied Energy, 148, 381–395. https://doi.org/10.1016/j.apenergy.2015.03.106

Climateworks Centre & CSIRO (Commonwealth Scientific and Industrial Research Organisation). (2023). *Australian Industry Energy Transitions Initiative: Pathways to industrial decarbonisation Phase 3 technical report.* https://energytransitionsinitiative.org/

CSIRO (Commonwealth Scientific and Industrial Research Organisation). (2019). *Australian National Outlook 2019.* https://www.csiro.au/en/work-with-us/services/consultancy-strategic-advice-services/csiro-futures/innovation-business-growth/australian-national-outlook

Davis, D., Pascale, A., Vecchi, A., Bharadwaj, B., Jones, R., Strawhorn, T., Tabatabaei, M., Lopez Peralta, M., Zhang, Y., Beiraghi, J., Kiri, U., Vosshage, Finch, B., Batterham, R., Bolt, R., Brear, M., Cullen, B., Domansky, K., Eckard, R., … Smart, S. (2023). *Modelling Summary Report.* https://www.netzeroaustralia.net.au/

DCCEEW (Department of Climate Change Energy the Environment and Water). (2023a). *National Inventory Report 2021*. https://www.dcceew.gov.au/climate-change/publications/national-inventory-report-2021

DCCEEW. (2023b). Australia's emissions projections 2023. *Barrington Stoke.* https://www.dcceew.gov.au/climate-change/publications/australias-emissions-projections-2023

Graham, P. (2023). *Electric vehicle projections 2023: Update to the 2022 projections report.* https://aemo.com.au/-/media/files/stakeholder_consultation/consultations/nem-consultations/2023/2024-forecasting-assumptions-update-consultation-page/csiro---2023-electric-vehicle-projections-report.pdf

Graham, P., Hayward, J., & Foster, J. (2023). *GenCost 2023-24 Consultation draft.* https://www.csiro.au/en/research/technology-space/energy/Energy-data-modelling/GenCost

Graham, P., Hayward, J., & Foster, J. (2024). *GenCost 2023-24 Final report.* https://www.csiro.au/en/research/technology-space/energy/GenCost

Graham, T., Li, M., Whelan, J., Maxwell, R., Murugesan, M., Croser, L., Sue, W., & Reedman, L. (2023). *Climateworks Centre Decarbonisation Scenarios 2023: AusTIMES Modelling Assumptions and Methodology Technical report.* https://www.climateworkscentre.org/resource/climateworkscentre-decarbonisation-scenarios-2023-australia-can-still-meet-the-paris-agreement/

IEA (International Energy Agency). (2021a). *Net Zero by 2050 - A Roadmap for the Global Energy Sector.* https://www.iea.org/reports/net-zero-by-2050

IEA. (2021b). World Energy Outlook 2021. https://www.iea.org/reports/world-energy-outlook-2021

Infrastructure Australia. (2024). *Valuing emissions for economic analysis: Guidance note*. https://www.infrastructureaustralia.gov.au/publications/valuing-emissions-economic-analysis

IPCC (Intergovernmental Panel on Climate Change). (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* https://www.ipcc.ch/report/ar5/wg1/

Reedman, L., Gordon, J., Murugesan, M., Croser, L., Li, M., Hayward, J., Khandoker, T., Brinsmead, T., & Havas, L. (2022). *Multi-sector energy modelling 2022: Methodology and results Final report.* https://doi.org/10.25919/2x25-vd38

Acronyms and abbreviations

#

3-NOP	3-Nitrooxypropanol

A

A40/G1.5	Scenario modelled for the authority by the CSIRO. See Appendix C for details.
A50/G2	Scenario modelled for the authority by the CSIRO. See Appendix C for details.
ABARES	Australian Bureau of Agricultural and Resource Economics and Sciences
ABCB	Australian Building Codes Board
ABS	Australian Bureau of Statistics
ACCU	Australian Carbon Credit Unit
ACOSS	Australian Council of Social Service
ACSI	Australian Council of Superannuation Investors
ACT	Australian Capital Territory
AEIC	Australian Energy Infrastructure Commissioner
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
AFI	Australian Farm Institute
ANU	Australian National University
ANZSIC	Australia and New Zealand Standard Industrial Classification
APR	Annual Progress Report
APRA	Australian Prudential Regulation Authority
APS	Announced Pledges Scenario
ARENA	Australian Renewable Energy Agency
ASX	Australian Securities Exchange
ASBEC	Australian Sustainable Built Environment Council
ATIC	Australian Trade and Investment Commission
ATO	Australian Taxation Office
AusTIMES	Australian implementation of The Integrated MARKAL-EFOM System

B

BCA	Business Council of Australia
BCG	Boston Consulting Group
BESS	Battery and Energy Storage Systems
BITRE	Bureau of Infrastructure and Transport Research Economics
BNEF	Bloomberg New Energy Finance

C

CAPEX	Capital Expenditure
CBA	Cost-Benefit Analysis
CBAM	Carbon Border Adjustment Mechanism
CCA	Climate Change Authority
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CDR	Carbon Dioxide Removal
CDU	Collie Delivery Unit
CEA	Cost-Effectiveness Analysis
CEC	Clean Energy Council
CEDA	Committee for Economic Development of Australia
CEFC	Clean Energy Finance Corporation
CEIG	Clean Energy Investor Group
CER	Clean Energy Regulator
CFFR	Council on Federal Financial Relations
CFI	Carbon Farming Initiative
CGE	Computable General Equilibrium
CIM	Clean Investment Monitor
CIS	Capacity Investment Scheme
CO_2	Carbon Dioxide
CO_2-e	Carbon Dioxide equivalent
COP	Conference of the Parties
CPI	Climate Policy Initiative
CSIRO	Commonwealth Scientific and Industrial Research Organisation

D

DAC	Direct Air Capture
DAFF	Department of Agriculture, Fisheries and Forestry
DAT	Act Data Availability and Transparency Act 2022
DCCEEW	Department of Climate Change, Energy, the Environment and Water

DISR	Department of Industry, Science and Resources

E

E3	Equipment Energy Efficiency program
EPBC	Environment Protection and Biodiversity Conservation Act 1999
ESG	Environmental, Social, and Governance
ETI	Energy Transitions Initiative
ETSAP	Energy Technology Systems Analysis Program
EU	European Union
EVs	Electric Vehicles

F

FNCEN	First Nations Clean Energy Network
FPIC	Free, Prior, and Informed Consent
FY	Financial year

G

GBCA	Green Building Council of Australia
GDP	Gross Domestic Product
GEMS	Greenhouse and Energy Minimum Standards
GLaWAC	Gunaikurnai Land and Waters Aboriginal Corporation
GO	Guarantee of Origin
GRDC	Grains Research and Development Corporation
Gt	Gigatonne
GTEM	Global Trade and Environment Model
GVA	Gross Value Added
GW	Gigawatt
GWP	Global Warming Potential

H

HFC	Hydrofluorocarbons
HTS	High Temperature Superconductors

I

IA	Infrastructure Australia
ICCPR	International Covenant on Civil and Political Rights
ICE	Internal Combustion Engine
ICIN	Indigenous Carbon Industry Network
IEA	International Energy Agency
IEEFA	Institute for Energy Economics and Financial Analysis
IGCC	Investor Group on Climate Change
ILSC	Indigenous Land and Sea Corporation
IMP	Illustrative Mitigation Pathway
IMP-GS	Illustrative Mitigation Pathway ('Gradual Strengthening')
IMP-Ren	Illustrative Mitigation Pathway ('Renewables')
IOIG	Input-Output Industry Group
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use
IRA	Inflation Reduction Act 2022 (United States)
ISP	Integrated System Plan
ITMO	Internationally Transferred Mitigation Outcome
IUCN	International Union for Conservation of Nature

J

JSA	Jobs and Skills Australia

L

LNG	Liquified Natural Gas
LPG	Liquid Petroleum Gas
LULUCF	Land Use, Land-Use Change and Forestry
LUTO	Land Use Trade Offs (model)
LVA	La Trobe Valley Authority

M

MARKAL-EFOM	Market Allocation-Energy Flow Optimisation Model
MERiL	Methane Emissions Reduction in Livestock
MERNAP	Maritime Emissions Reduction National Action Plan
MLA	Meat & Livestock Australia
MRV	Measurement, Reporting and Verification
Mt	Megatonne

MW	Megawatt

N

NABERS	National Built Environment Rating System
NatHERS	Nationwide House Energy Rating Scheme
NCC	National Construction Code
NDC	Nationally Determined Contribution
NEM	National Electricity Market
NEPS	National Energy Performance Strategy
NFF	National Farmers' Federation
NGER	National Greenhouse and Energy Reporting
NGFS	Network for Greening the Financial System
NIAA	National Indigenous Australians Agency
NRF	National Reconstruction Fund
NSW	New South Wales
NVES	New Vehicle Efficiency Standard
NZA	Net Zero Australia
NZE	Net Zero Emissions by 2050 Scenario

O

OCGT	Open Cycle Gas Turbines
ODP	Optimal Development Path
OECD	Organisation for Economic Cooperation and Development
OPEX	Operating Expenses

P

PBC	Prescribed Body Corporate
PCA	Property Council of Australia
PHES	Pumped Hydro Energy StoragePFAS Perfluoroalkyl and Polyfluoroalkyl Substances
PM&C	Prime Minister & Cabinet
PV	Photovoltaic

Q

QFF	Queensland Farmers' Federation
QNI	Connect Queensland New South Wales Interconnector Connect

R

R&D	Research and Development
RBA	Reserve Bank of Australia
RD&D	Research, Development and Demonstration
REZ	Renewable Energy Zones
RIT-T	Regulatory Investment Test for Transmission

S

SAF	Sustainable Aviation Fuel
SBTi	Science Based Targets initiative
SCM	Supplementary Cementitious Materials
SMCs	Safeguard Mechanism Credits
SRES	Small-scale Renewable Energy Scheme
STEM	Science, Technology, Engineering, and Mathematics
SUIC	Supply-Use Industry Classification

T

TAFE	Technical and Further Education
TCO	Total Cost of Ownership
TNFD	Taskforce for Nature-related Financial Disclosures

U

UDIA	Urban Development Institute of Australia
UNDRIP	United Nations Declaration on the Rights of Indigenous Peoples
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNHRC	United Nations Human Rights Committee
UQ	The University of Queensland
USD	US Dollar

V

VET	Vocational Education and Training
VNI	West Victoria New South Wales Interconnector West

W

WEM	Wholesale Electricity Market