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Early transition to near-zero emissions electricity and carbon dioxide removal is essential to achieve net-zero emissions at a low cost in Australia

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Achieving net-zero emissions requires major changes across a nation's economy, energy and land systems, particularly due to sectors where emissions are difficult to eliminate. Here we adapt two global scenarios from the International Energy Agency—the net-zero emissions by 2050 and the Stated Policies Scenario—using an integrated numerical economic-energy model tailored to Australia. We explore how emissions may evolve by sector and identify key technologies for decarbonisation. Our results show that a rapid shift to near-zero emissions electricity is central to reducing costs and enabling wider emissions reductions. From 2030 onwards, carbon removal through land management and engineered solutions such as direct air capture and bioenergy with carbon capture and storage becomes critical. Australia is also well-positioned to become a global supplier of clean energy, such as hydrogen made using renewable electricity, helping reduce emissions beyond its borders.

Australia's net-zero emissions (NZE) pathway faces major challenges such as decarbonisation of agriculture and hard-to-abate sectors (e.g. steel, cement and fertilisers manufacturing, chemicals manufacturing and transport)[1]. The country is also heavily dependent on fossil fuels; thus, phasing out fossil fuels while maintaining energy reliability and economic stability is a major hurdle. Coal and gas exports also remain major pillars of the economy, but Australia's exporters face growing pressure to decarbonise due to international climate polices. For example, the European Union (EU) and other regions are implementing policies that tax imports based on their carbon content, indicating that Australian exports with high embedded emissions could face tariffs or lose competitiveness. Major trading partners such as the EU, Japan, South Korea and China are also pursuing net-zero goals and prefer cleaner supply chains, pushing exporters to decarbonise or risk losing market access. In addition, Australia's large agricultural sector contributes substantially to methane and nitrous oxide emissions. Consequently, reducing emissions without harming productivity or food security is a delicate balance, as well as avoiding conflicting demands on land for food, biodiversity, carbon offsets and bioenergy.

Deployment of carbon dioxide removal (CDR) technologies is thus considered critical in counterbalancing hard-to-abate residual emissions so that Australia and other nations can achieve NZE[2,3]. Additional industries are expected to emerge and thrive through the advancement of low-emissions technologies, helping to offset emissions from hard-to-abate sectors. Transition to renewable resources in the power sector is another critical factor in reducing greenhouse gas (GHG) emissions[4–6], as electricity generation makes up over 40% of global energy-related carbon dioxide emissions from burning fossil fuels[7]. Emissions-free electricity generation would therefore reduce the otherwise substantial burden on CDR technologies, as well as related investment expenses. An early transition to emissions-free electricity generation would also reduce the economic costs for a country in mitigating high levels of GHG emissions[8,9]. A pathway to a NZE global economy would also require a major contribution by land use, land use change and forestry (LULUCF) activities[10–12]. Some areas may have high potential for decarbonisation from these activities. For instance, LULUCF currently removes around an annual amount of 50–60 Mt CO_2e in Australia[13], while it removes

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around 230 Mt CO_2e annually in the EU, equivalent to 7% of the annual EU's GHG emissions[14].

Recent work by the International Energy Agency (IEA) provides an authoritative global analysis of technological, energy and investment needs for a 1.5 °C scenario, though it does not identify individual country decarbonisation pathways[15]. Global analysis is important in highlighting broad targets and objectives that must be achieved to reach an NZE world economy. However, an NZE transition will affect the whole economy, impacting progress towards social, economic and environmental goals, presenting decision-makers with challenges of how to balance multiple objectives. Thus, country-specific analyses are needed to operationalise this transition and to assess the potential trade-offs of different national development strategies.

Here, we develop an integrated modelling framework to examine the implications of the IEA's modelling work on international climate action at a country scale. Two contrasting scenarios are evaluated. The first is the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Rapid Decarbonisation (CRD) scenario, which assumes Australia follows a rapid decarbonisation trajectory consistent with the IEA's NZE global 1.5 °C carbon budget (see Section 1 in the Supplementary Information for detailed assumptions). The second is the CSIRO Stated Policies (CSP) scenario, which reflects current domestic and international policy commitments and is projected to result in a global temperature rise of ~2.6 °C by 2100. In this framework, we apply the global emissions target over years with specific technological improvements, including productivity growth, power shares, negative emissions technologies following the IEA[15], LULUCF removals (global values calculated from GLOBIOM-G4M models data[16], while Australian values redrived from ref. 17), etc. Countries and industrial sectors will then calculate how much emissions levels can be cut along with changes in production levels, subject to marginal abatement costs induced by substitution possibilities for high-emissions intensive inputs, trade power and supply chain systems. These costs also decline with the development of negative emissions technologies and LULUCF removals. This framework, which could be applied to other countries, is developed for Australia, providing a comprehensive examination of how power sector transformation, negative emissions technologies and LULUCF activities may help a country achieve NZE.

Australia was selected as a case study due to the federal government's active engagement in net-zero initiatives across the economy, aimed at transforming the nation into a low-carbon and net-zero economy. Key actions include plans to phase out coal-fired power stations[18], the large-scale development of renewable energy[19] and substantial investments in negative emissions technologies[20]. Additionally, Australia shares many critical factors for decarbonisation with other countries worldwide. For example, while its power generation sector remains heavily reliant on fossil fuels, Australia possesses vast renewable energy resources, such as wind, solar, hydro and ocean thermal power, similar to regions like Europe, the United States and China. Australia's LULUCF sector also offers considerable potential, akin to regions such as Southeast Asia and South America, in offsetting emissions from hard-to-abate sectors. Furthermore, Australia is strongly focusing on deploying mature zero- and low-emissions technologies, providing valuable lessons for other nations striving to meet net-zero targets[21].

Australia, like many other nations, is increasingly exposed to international regulatory risks, as illustrated by the proposed European Carbon Border Adjustment Mechanism[22,23]. In addition to evolving regulatory frameworks, global markets and consumers are placing greater emphasis on value chain emissions and the decarbonisation of production processes. The capability to deliver goods and services with a reduced carbon footprint is emerging as a critical source of competitive advantage. Furthermore, the gap between current Nationally Determined Contributions and the temperature goals of the Paris Agreement highlights the growing likelihood of more stringent decarbonisation policies and the need for accelerated investment in low-emissions solutions[24–26]. Previous research by the Network for Greening the Financial System and CSIRO[9,27] has highlighted the risks of delaying the transition, including the need for faster and more costly decarbonisation efforts, the stranding of assets, heightened sovereign risk and negative impacts on Australia's long-term competitiveness. Therefore, analysing Australia's pathway to net zero, along with effective strategies and activities, can serve as a valuable example for other countries navigating similar challenges.

This study highlights several important advances in Australia's NZE pathway. First, it downscales the IEA global scenarios to the Australian context, providing a more detailed, sector-specific roadmap for decarbonisation. Second, power sector transformation emerges as a key enabler, with the rapid decarbonisation of electricity generation identified as a critical early step in achieving NZE at low cost. Third, LULUCF activities, along with negative emissions technologies, are crucial for reducing abatement costs—especially for a resource-rich country like Australia. Fourth, the development of a sustainable global zero-emissions energy market is vital for worldwide decarbonisation. In this context, Australia has the potential to become a key supplier of zero-emissions energy, particularly green hydrogen, supporting international net-zero efforts.

Results

Achieving near-zero emissions in electricity generation in the short term

Sectoral emissions analysis highlights the electricity sector as Australia's most important decarbonisation opportunity during the 2020s, positioning it as a cornerstone of the nation's broader emissions reduction pathway (Fig. 1). Between 2020 and 2035, the sector rapidly transitions from the largest emitter to contributing a relatively small volume of emissions. Annual GHG emissions from the electricity sector are projected to decline by over 50% between 2020 and 2025 (from 175 Mt CO_2e to 70 Mt CO_2e) compared to a decline to the level of 143 Mt in 2024 under the stated policy scenario, making it the third largest emitter—after transport and agriculture—by 2025. The electricity sector is expected to achieve net-zero GHG emissions by 2035. Given the magnitude of this transformation, its contribution is critical to meeting the 2050 emissions reduction target. Over the past decade, aging coal-fired power stations in Australia have faced rising operational costs and declining reliability, prompting early retirements driven by both economic and environmental considerations. At the same time, falling costs of renewable technologies have spurred substantial growth in renewable energy capacity, with continued expansion anticipated across solar, wind, hydro and battery storage systems[28]. Economic factors have played a key role in accelerating the adoption of rooftop solar photovoltaic systems, with installations now present in over one in four Australian households.

The modelling results also reflect the expectation that 85% of Australia's coal-fired generation capacity will close by 2030 (the remaining coal capacity by then generating just 6.7% of total electricity), and the remainder will be closed by 2035. Renewable energy is projected to make up more than 90% of the electricity mix by 2030. To achieve this, almost all additional capacity installed over the next decade would need to come from wind and solar, supported by increased storage capacity (Fig. 2). Total capacity installation is also higher in the CRD scenario, reaching 300 GW in 2050 compared to a capacity of 210 GW in the CSP scenario. Most of the additional capacity in the CRD scenario comes from solar and rooftop PV.

The transition away from fossil fuel-based electricity generation plays a pivotal role in reducing emissions intensity. In 2020, over 70% of electricity in the National Electricity Market was generated from fossil fuels, while wind and solar contributed ~20% (see Fig. 3). This energy mix resulted in an emissions intensity exceeding 600 kg CO_2/MWh. However, by 2030, a major shift occurs: wind and solar are projected to supply around 85% of NEM electricity, while fossil fuels account for only 10%. Rooftop solar PV generation is also expected to quadruple relative to 2020 levels. Consequently, the emissions intensity drops substantially—to below 15% of its 2020 level—reaching ~95 kg CO_2/MWh. With coal-fired power generation phased out by 2035, emissions intensity falls to around 40 kg CO_2/MWh and continues to decline, reaching net-zero by 2050.

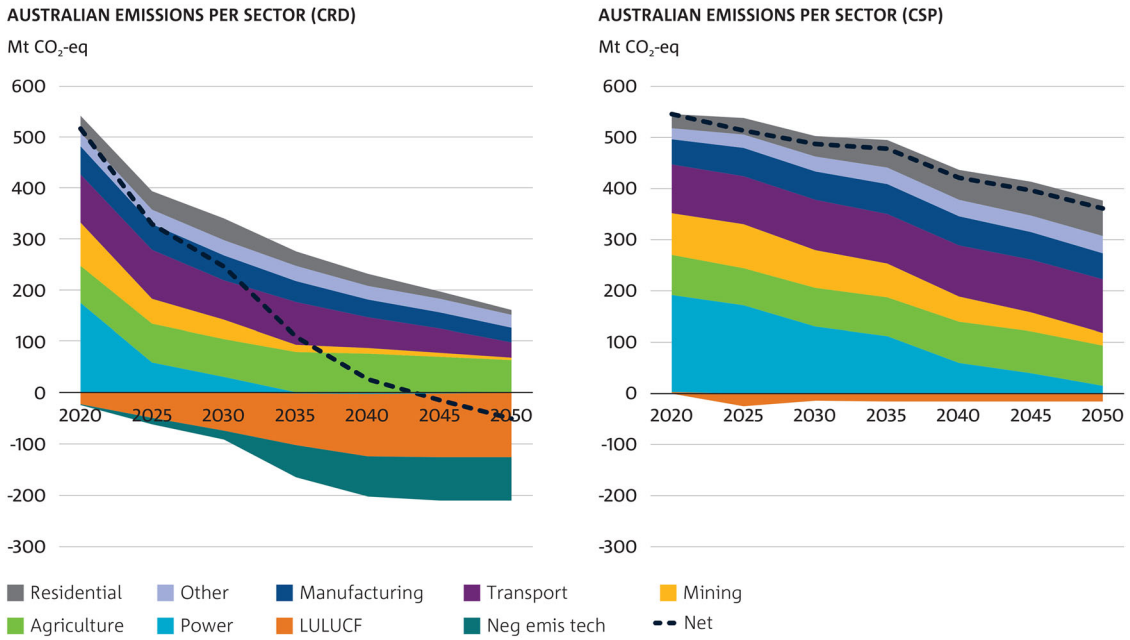

Fig. 1 | Australian gross emissions by sector[49]. Left panel indicates all greenhouse gas (CO_2e) emissions by sector in Australia in the CRD scenario (Mt CO_2e) over 2020–2050, while the right panel presents the corresponding values in the CSP scenario.

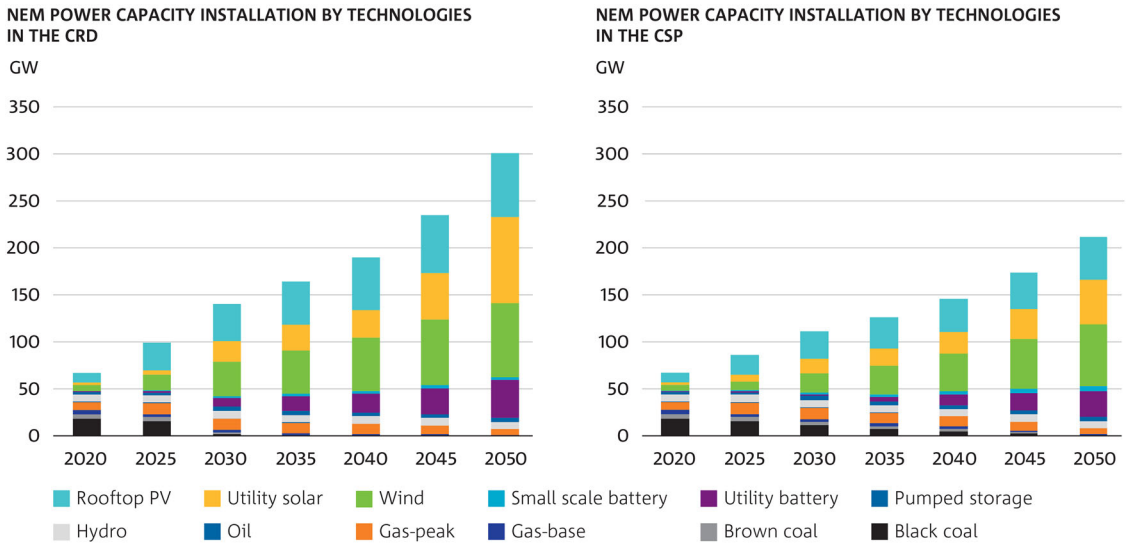

Fig. 2 | Installed power capacity by technology in Australia[49]. Left panel indicates the CSIRO Rapid Decarbonisation scenario, while the right panel shows the CSIRO Stated Policies scenario. Power capacity installation (GW) by technologies in the Australian National Energy Market (NEM) in 2020–2050. NEM covers New South Wales, the Australian Capital Territory, Queensland, South Australia, Victoria and Tasmania. Western Australia and the Northern Territory are not included in NEM.

Crucial CDR technologies in Australia's net-zero pathway

While many negative emissions technologies in Australia are still in the early stages of development, they are expected to play a vital role in achieving NZE. In the CRD scenario, modelling adopts a conservative approach to their contribution, aligning with IEA projections. By 2050, total global annual negative emissions are estimated at 7.2 gigatonnes (Gt) of CO_2—comprising 5.8 Gt from direct air capture with carbon storage (DACCS) and 1.4 Gt from bioenergy with carbon capture and storage (BECCS)[15]. That is, the projections for total global negative emissions technologies are based on those of the IEA, while the model allocates them across countries and regions according to relative market shares, costs and renewable energy availability. Australia aims to capture 84 million tonnes (Mt) of CO_2 by 2050, with 66 Mt expected from unspecified technologies including DACCS, and 18 Mt from BECCS (refer to Table 1). Additional measures could involve carbon capture and storage (CCS) to support emissions reduction in challenging sectors such as aluminium, cement and steel. While CCS helps lower emissions in these industries, it is not considered a source of negative emissions.

The global annual negative emissions assumed in this study differ slightly from the IEA's Net Zero Roadmap, which forecasts that 7.6 $GtCO_2$ per year will be captured worldwide by 2050, and 95% of that will be permanently stored[15] by DACCS and BECCS. Our study finds that BECCS plays a limited role in Australia, primarily due to its higher costs relative to other renewable energy options. Since BECCS serves as a source of power generation, its development also competes with the increasingly cost-effective solar and wind energy sources[29]. DACCS is gaining attention, and according to IEA analysis, it is expected to contribute to global decarbonisation efforts[30]. Preliminary research and feasibility studies are

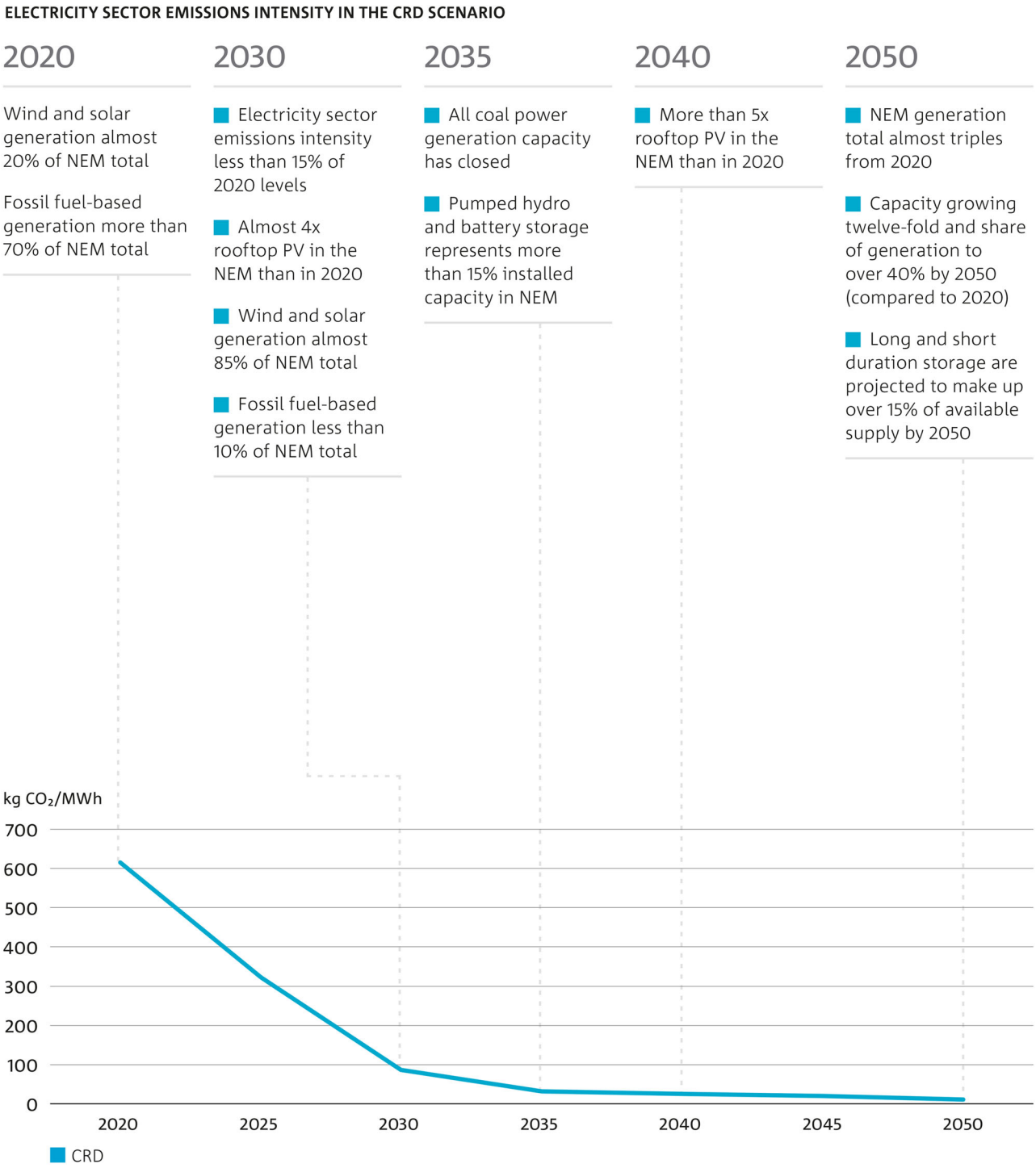

Fig. 3 | Key transition milestones for the electricity generation sector[49]. Australia's key energy transition milestones are associated with emissions intensities in the CSIRO Rapid Decarbonisation scenario. The upper part indicates milestones for key achievements in power technologies in 2020–2050. The lower part shows the corresponding emissions intensities in the electricity generation sector.

currently in progress, alongside the development of business cases. The IEA projects that DACCS costs could decrease to below $100/tCO$_2$, although the technology is anticipated to require substantial time before becoming fully established, with Australian projects still at an early phase[31]. The balance between permanent and temporary carbon removals depends on the relative costs of different technologies. In countries with abundant land, where temporary removals from LULUCF activities are relatively inexpensive,

Table 1 | Carbon removals by the negative emissions technologies in Australia by decade (Mt CO$_2$)[49]

Technology type	2020	2030	2040	2050
BECCS	0	−3	−17	−18
DACCS	0	−14	−63	−66

these methods tend to dominate over permanent removals from technologies like DAC and BECCS. This has been observed in Australia, where marginally productive lands provide ample opportunities for carbon sequestration[17]. However, Australia is projected to have a peak of land-based emissions removals by 2050 at 128 Mt per year due to land constraints[21] (Fig. 4). A portion of this increase stems from enhanced carbon sequestration in vegetation and soils. Activities such as tree planting and changes in agricultural practices are projected to remove ~3 $GtCO_2$-eq from the atmosphere between 2020 and 2050. However, forest fires could threaten this projected value, especially as climate change increases the extent and likelihood of fires in central Australia[32]. This, in turn, reduces forested land, negatively impacting carbon removals from LULUCF activities. Since most land-based removals in Australia occur on marginally productive lands, cropland and pastureland remain largely unaffected. As a result, GTEM (Global Trade and Environment Model) projects only a slight reduction in crop and livestock production, along with a modest decline in agricultural emissions (Fig. 1).

Discussion

In this study, we examine whether Australia has the capacity to develop negative emissions technologies and land-based carbon removals as part of its strategy to achieve NZE. Our model recognises that not all countries will be able to reach net-zero targets through these means alone, as the global allocation of resources for negative emissions technologies and land carbon removals depends on international cost competitiveness. We acknowledge that using land-based offsets to compensate for residual emissions may not deliver climate benefits equivalent to avoiding emissions altogether, as established in the broader literature[12,33]. Rather, our aim is to highlight that both land offsets and negative emissions technologies are likely to play a critical role in enabling Australia to reach NZE at economically viable costs, even though the climate impacts of emission avoidance and removal are not equivalent and must be carefully considered.

The findings indicate that decarbonising the electricity sector offers the greatest potential for emissions reductions in the near term. Total generation capacity expands substantially, with the proportion of electricity supplied by renewables tripling by 2030[34]. Battery storage capacity is expected to rise more than fivefold, surpassing 11 GW, while pumped hydro storage nearly doubles. The reliance on fossil fuels for electricity drops sharply—from over 70% today to under 10% by 2030—and is nearly eliminated by 2040, aside from limited gas-fired generation for peak demand. This transition in the electricity sector plays a critical role in lowering emissions across various areas, including homes, commercial buildings, resource extraction and processing, aluminium production, and eventually, transportation.

While fossil fuel exports are projected to decline sharply, the overall volume and value of Australia's mining exports are expected to rise. Coal production is anticipated to drop by 20% by 2030 and by as much as 80% by 2050, with the remaining output primarily consisting of metallurgical coal. These trends are driven by global adoption of NZE strategies, which substantially reduce demand for thermal coal. Oil and gas output may experience a modest increase—approximately 5%—by 2030, but both are forecast to fall by around 50% and 66%, respectively, by 2050. Conversely, production of iron ore is expected to grow by 73% compared to 2019 levels, and other mineral commodities may see an increase exceeding 40%. Rising global demand for solar photovoltaics and battery technologies is also projected to boost demand for critical minerals such as lithium, cobalt and rare earth elements—creating additional growth opportunities for Australia's mining sector. However, achieving net-zero targets will necessitate the decarbonisation of mining operations, requiring major advancements in technology and substantial capital investment to curb emissions from extraction, processing and transportation. Despite potential economic benefits, the fossil fuel segment of the mining industry faces mounting risks. Firms heavily reliant on fossil fuel revenue and reserves are under increasing pressure due to heightened legal scrutiny, shareholder activism[35] and stricter regulatory conditions[36]. Investors are demanding greater transparency on emissions, net-zero targets, and credible transition strategies[37]. Recent attempts by major firms, such as Origin[38] and BHP[39], to divest from fossil fuel assets have often been unsuccessful or resulted in financial losses, highlighting the sector's evolving challenges.

As Australia advances through the energy transition, sustained collaboration among governments, industry and communities will be essential to ensure that the shift is equitable and inclusive. Companies that continue to operate within the fossil fuel industry are increasingly looking to CCS and hydrogen technologies as strategies to maintain viability in a low-emissions economy. At the same time, Australia's pathway will be substantially shaped by the decarbonisation policies and trajectories of its international trading partners. Together, these dynamics present notable risks. Existing infrastructure for fossil fuel production, exploration and transport may face early obsolescence or become stranded assets. Moreover, our analysis indicates that alternatives to fossil fuels are unlikely to be deployed quickly or extensively enough to fully compensate for the declining role of conventional energy sources. This slow uptake may result in elevated energy costs for consumers and could severely impact regions whose economies are heavily reliant on fossil fuel industries. Without careful planning, these factors increase the likelihood of a disorderly transition. Addressing these risks will require a coordinated approach that includes recognition from stakeholders across the energy value chain, thoughtful policy and regulatory frameworks, and targeted public investment to catalyse private sector funding in emerging industries and technologies. Delaying the phase-out of fossil fuels will also place added pressure on other sectors to decarbonise more rapidly, making the overall transition to net zero even more complex and demanding.

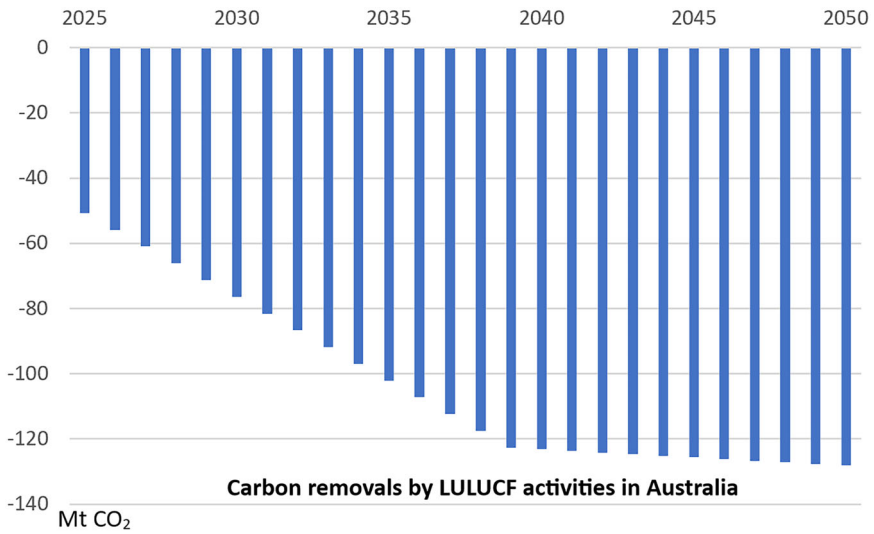

Fig. 4 | Carbon removals by LULUCF activities in Australia (Mt CO_2)[49]. The bar indicates the amount of carbon dioxide removals ($MtCO_2e$) by LULUCF activities in each year in 2025–2050 in Australia.

Although the modelling indicates a relatively orderly transition, there are several factors that could disrupt this trajectory. Companies operating in emissions-intensive sectors may depend heavily on CCS, hydrogen technologies, or offsets to extend their viability in a low-carbon economy. If the phase-out of fossil fuels proceeds more slowly than anticipated, the burden of deeper and faster emissions reductions will shift to other sectors, complicating the already demanding pathway to net zero. This creates a risk that existing high-emissions assets may be retired before sufficient low-emissions alternatives are in place, potentially leading to supply gaps or economic disruptions. To mitigate such risks and support a stable transition, carefully crafted policy and regulatory frameworks, along with targeted investments in emerging technologies and industries, will be essential.

To achieve NZE by 2050, technologies currently in early development must be widely deployed by 2030. By mid-century, approximately one-third of global emissions reductions are expected to rely on innovations still in prototype or demonstration phases today. Among the most critical of these are low- or zero-emissions hydrogen, carbon capture, utilisation and storage, and feedstocks and catalysts—particularly for emissions-intensive sectors like heavy industry and transport. Domestic uptake of green hydrogen is projected to drive substantial production growth, reaching an estimated 200 petajoules by 2050. However, achieving this scale of transformation will require sustained and substantial investment, both in emerging technologies and in supporting infrastructure. Model projections estimate that approximately AU$713 billion will be required between 2022 and 2050 to upgrade electricity infrastructure, primarily through replacing aging fossil fuel generation with renewable energy and storage solutions. This figure does not account for parallel investments needed to develop complementary technologies such as green hydrogen, carbon capture, utilisation and storage, and sustainable biofuels—each of which will require funding across the entire innovation pipeline, from research and development to commercial deployment. To support such a large-scale investment, public policy may need to go beyond direct funding. Removing barriers to private sector participation and enabling innovative financing mechanisms to distribute risk more effectively will be essential to unlocking capital and accelerating the transition.

Australia is well-positioned to capitalise on the rising global demand for zero-emissions fuels. As an early adopter, the nation benefits from expertise in the design, construction and operation of complex infrastructure, as well as in handling and processing volatile liquids and gases. These capabilities offer a competitive edge in establishing emerging export sectors that could eventually supplement and replace traditional fossil fuel exports. The development of a green hydrogen industry presents a strategic opportunity to maximise the use of Australia's abundant renewable energy resources—by absorbing surplus generation during periods of low demand and low prices. In addition, green hydrogen has the potential to support emissions reductions in hard-to-abate sectors such as aluminium smelting, cement production and steel manufacturing. However, realising this opportunity will require overcoming a range of technical and commercial challenges. These include improving production efficiency, reducing costs, building appropriate infrastructure and creating viable domestic and international markets for green hydrogen and its derivatives.

Currently, producing hydrogen from renewable energy sources remains considerably more expensive than conventional methods such as coal gasification or steam methane reforming. While it is technically feasible to blend small amounts of hydrogen (~10–20%) into existing natural gas networks, higher concentrations would necessitate the replacement of end-use appliances and the development of additional pipeline infrastructure[40]. Additionally, the process of generating hydrogen—especially when involving energy conversions at both the production and consumption ends—can lead to considerable energy losses. If hydrogen is produced through high-emissions pathways, these losses could actually result in a net increase in GHG emissions. Further obstacles include the limited infrastructure for hydrogen production, storage and distribution, as well as the underdeveloped state of domestic and international markets. Australia's ability to establish itself as a competitive player in the global hydrogen economy may also be challenged by rapidly advancing policy and investment shifts in other countries, such as the United States' Inflation Reduction Act[41]. To maintain a competitive edge and attract international capital and expertise, Australia must act swiftly to overcome these barriers and capitalise on its early-mover potential.

In developing a hydrogen industry, it is essential that policymakers, investors and stakeholders remain focused on the primary goal: supplying low- or zero-emissions energy to meet both domestic and global demand. As the industry takes shape, avoiding the risk of locking in high-emissions pathways will be critical. A comprehensive view of emissions across the entire hydrogen value chain is necessary, including efforts to minimise transport-related emissions—a particularly important consideration given Australia's geographic remoteness. To overcome existing barriers such as high production costs, limited infrastructure and uncertain demand, continued commercial investment and demonstration projects will be vital. Meanwhile, biofuels are expected to play a key role in decarbonising aviation and could also serve as alternatives to fossil fuels in sectors like heavy transport and industrial chemical production. However, increasing reliance on biofuels may intensify competition for land use, with implications for food production and carbon sequestration through vegetation and soils—both of which are projected to expand in a low-emissions future.

Research indicates that Australia is a global leader in leveraging land-based carbon removals to offset agricultural emissions. Although agriculture is projected to become one of the largest sources of residual emissions—rising from 14% of gross national emissions in 2020 to 39% by 2050—Australia's vast land area, including degraded and marginal lands, offers a great opportunity for mitigation through afforestation and reforestation. Generating carbon offsets from vegetation and soils could provide farmers with an additional revenue stream, often complementing existing practices, utilising underproductive land and enhancing natural capital.

However, achieving net-zero in the sector faces challenges related to measurement, traceability and carbon accounting. Moreover, while nature-based solutions like avoided deforestation offer considerable mitigation potential, their impact is constrained by temporal saturation (as forests cannot sequester carbon indefinitely), vulnerability to disturbances (such as wildfires and droughts) and land-use competition driven by economic pressures like agricultural expansion[42]. There are also considerable risks if nations, jurisdictions, or companies rely heavily on offset-based strategies at the expense of pursuing feasible decarbonisation pathways. Such an approach may delay progress toward zero—though not necessarily net-zero—emissions. Current land-based offset technologies, which provide only temporary carbon sequestration, are particularly vulnerable to reversal, as forested areas may be converted to cropland or pasture for agricultural use. Delaying decarbonisation increases the risk of a disorderly and globally fragmented transition, while also raising the future costs and pace of emissions reductions as offsets become scarcer and more expensive. This could heighten the risk of asset impairment or stranding, undermine Australia's long-term competitiveness, and elevate sovereign risk.

In summary, this study provides important quantitative insights, including yearly emissions breakdown across Australian sectors, particularly electricity, offering a data-driven framework for net-zero planning. Additionally, Australia can scale up NETs and LULUCF to over 200 $MtCO_2e$ by 2040, offsetting emissions from sectors that are difficult to decarbonise. The country also has the potential to become a major exporter of green hydrogen, contributing to emissions reductions both domestically and globally. Key qualitative message implies that early decarbonisation of electricity is both essential and cost-effective in reaching NZE. Negative emissions technologies and land-based removals play a critical role in offsetting residual emissions, enabling Australia to potentially reach NZE even earlier than 2050. With aggressive emissions reductions in the power sector and robust negative emissions strategies, Australia could achieve negative emissions by 2050, helping offset emissions from other regions and contributing to the global net-zero target.

To support a sustainable move toward an NZE economy, Australia needs to facilitate key concrete actions. First, Australia needs to expedite

infrastructure implementation by streamlining approvals and regulations (e.g. simplify and fast-track environmental and planning approvals for renewable energy projects, transmission networks and green hydrogen hubs), developing public-private partnerships to co-fund large scale infrastructure such as offshore wind farms, battery storage and electric vehicle charging networks, expanding strategic grid to accelerate transmission upgrades to connect renewable energy zones with major demand centres, and increasing domestic manufacturing support by developing local supply chains for wind turbines, solar panels, batteries and hydrogen electrolysers to reduce reliance on imports and ensure rapid deployment.

Second, Australia needs to attract more international capital and expertise by creating green investment incentives (e.g. introduce tax incentives, low-interest loans and government-backed guarantees to attract international investors in renewable energy, clean hydrogen and carbon capture technologies), creating fast-track foreign direct investment with reductions of bureaucratic hurdles for international firms looking to invest in clean energy projects, leverage skilled migration programs (e.g. expand visas for clean energy engineers, battery scientists, and hydrogen specialists to address skill shortages in the workforce), and establishing a government-backed green investment fund to co-finance major projects, leveraging private capital for rapid scale-up.

Third, transport is also a key sector requiring strong support. Australia can implement stronger fuel efficiency standards to encourage automakers to bring more electric vehicles into the Australian market and offer tax breaks and subsidies for electric vehicle purchases, and expand nationwide charging infrastructure. Australia should also develop public transport electrification by transitioning buses, trains, and ferries to electric and hydrogen-powered alternatives, especially in urban areas, and investing in high-speed rail along the east coast to reduce short-haul domestic flights. Development of green hydrogen for heavy transport is also needed by providing incentives for fleet operators to transition to hydrogen and battery-electric trucks, and supporting hydrogen refuelling stations and mandates for hydrogen-powered trucking, aviation and shipping. Australia should also develop urban planning for low-carbon mobility by expanding cycling lanes, pedestrian zones and public transport networks to reduce reliance on private cars and implementing congestion charges and low-emission zones in major cities.

Fourth, since carbon offsets from land use are abundant and relatively cheap sources to compensate for emissions from hard-to-abate sectors, Australia needs to expand these resources. Schemes might involve scaling up carbon farming by expanding incentives for soil carbon sequestration through regenerative agriculture and rotational grazing, and supporting biochar projects to lock carbon into soils and improve agricultural productivity. Australia can also foster indigenous land management programs by expanding funding for Indigenous-led fire management practices that reduce emissions while preserving ecosystems. In addition, Australia should also strengthen its participation in international carbon markets by exporting high-quality carbon credits from reforestation and soil carbon projects.

Results show that Australia provides valuable insights for other countries pursuing net-zero goals. First, since most nations rely heavily on fossil fuels, an early transition to renewable energy is critical to minimising the costs of achieving a net-zero economy. However, renewable energy may not expand quickly enough to fully replace fossil fuel-based power, potentially leading to energy insecurity. Therefore, it is essential to develop strategies that align the growth of renewable energy with the phased reduction of fossil fuels to meet rising energy demands.

For countries with substantial LULUCF potential, leveraging these activities is vital, as they often provide more cost-effective options for offsetting GHG emissions, lowering carbon prices and abatement costs. Additionally, the deployment of negative emissions technologies is indispensable for compensating for emissions from hard-to-abate sectors. Efforts must also address emissions across the full value chain, including minimising those associated with transport, which is particularly important for geographically isolated nations like Australia. Export-oriented countries should closely monitor and adapt to the decarbonisation policies of their trade partners, as these can considerably impact their economies.

Finally, international collaboration is crucial for sustainable decarbonisation and the maintenance of resilient value chain systems. Support from developed nations—whether through human, financial, or technical assistance—plays a key role in helping developing countries transition to a low-carbon economy.

The developed integrated modelling framework can also be applied to other countries, subject to key conditions such as data availability, policy relevance and structural flexibility. First, an applied country must have environmental and socioeconomic input-output data to serve as inputs for the models. Second, the framework requires comprehensive economic, emissions and climate data for projections and external shocks. Countries with well-established data collection systems, similar to Australia, can more easily implement such an integrated assessment modelling framework. Third, the models are designed for climate and energy policy analysis. In cases where a country lacks strong policy instruments (e.g. carbon pricing or renewable subsidies), alternative policy settings should be incorporated. Finally, the models account for global trade, capital flows and climate interactions. Therefore, countries that are highly dependent on imports or exports must ensure that trade linkages within the model accurately reflect real-world interdependencies.

It is also noted that the current framework does not account for changes in carbon emissions resulting from predicted forest fires. However, these emissions can be incorporated as exogenous shocks in future work when climate models are used to forecast emissions levels based on historical events and climate data. These will provide more comprehensive emissions pathways, particularly for Australia, which often experiences bushfires. Additionally, at this stage, the framework does not have detailed critical minerals resources due to data unavailability. If such data were available, there would be a more detailed analysis of the requirements in the transition. In addition, chronic and physical climate hazards are not included in the model, which may impose higher abatement costs and thus affect sectoral emissions pathways and the Australian NZE target.

Methods

This study employs a multi-model framework (Fig. 5) designed to downscale several IEA scenarios to the Australian context. The approach integrates three nested modelling layers—global, national and sectoral—to generate tailored Australian outputs:

- CSIRO's GTEM, a computable general equilibrium (CGE) model, assesses global macroeconomic impacts across scenarios and examines how these global dynamics affect Australia through trade and globalisation. Treatment of key variables in GTEM is provided in Table 2;
- KPMG's Energy and Environment model (KPMG-EE), another CGE model calibrated to Australia's industry sectors and international trade, translates the global influences into sector-specific impacts within the Australian economy. Treatment of key variables in KPMG-EE is provided in Table 3; and
- CSIRO and ClimateWorks' Australian TIMES (AusTIMES) model focuses on least-cost energy, emissions and technology pathways, providing detailed sectoral insights that complement KPMG-EE's economic analysis. Treatment of key variables in AusTIMES is provided in Table 4.

GTEM evaluates global transition risks and their effects on Australia via international linkages and trade[43]. Using KPMG-EE, the study examines how these global shifts translate into economic impacts across Australian sectors, focusing specifically on the economic transition without accounting for the financial consequences of physical climate hazards. Given that both chronic and acute climate-related risks are projected to rise—especially affecting agriculture, construction and carbon removal efforts like afforestation—future work should incorporate these factors more comprehensively.

Finally, AusTIMES explores technology pathways for six high-emission sectors: energy, transport, buildings, steel, aluminium and

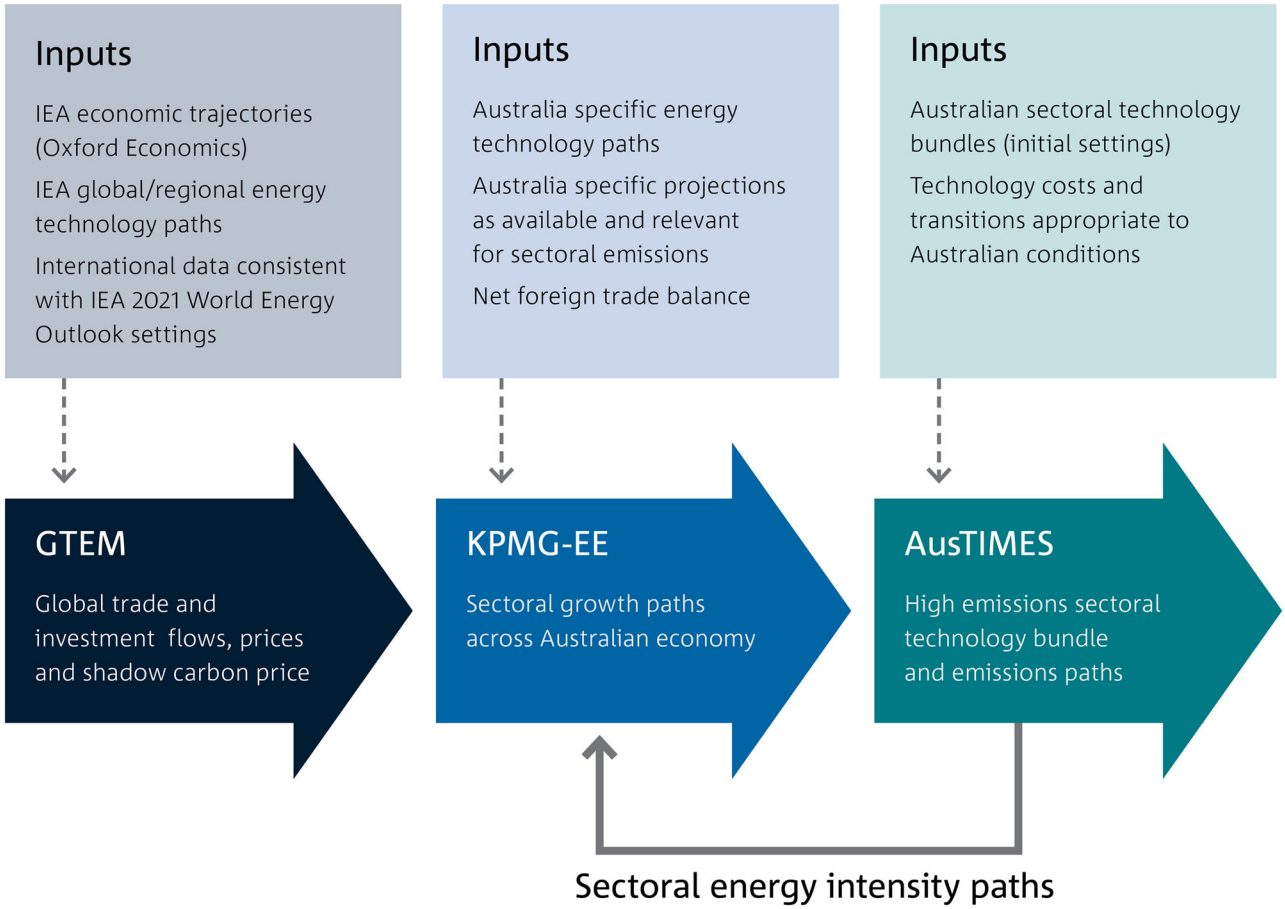

Fig. 5 | An overview of the interrelationship of input sources across the model suite[49]. The lower part shows the models used as well as connections with each other. The upper part highlights key inputs in each model, which are derived from different sources.

Table 2 | Treatment of key variables in GTEM[49]

Variable	CRD scenario	CSP scenario
Macroeconomic variables	Movements in regional population and regional debt-to-GDP ratios match the CSP scenario Movements in regional labour supply, regional GDP, regional employment and the global CPI are endogenously determined within GTEM	Movements in regional population, regional labour supply, regional GDP, regional employment and the global CPI are applied. These values are based on combining the latest NIGEM baseline with population and GDP forecasts from Oxford Economics as reported in the IEA's Net Zero by 2050 report Regional debt-to-GDP ratios are stabilised by 2050
GHG shadow price	Endogenously responds to emissions targets	US$10 in low-income regions and US$20 in high-income regions in 2021
Emissions	Global net CO_2 emissions budget of 500 Gt Global non-CO_2 emissions carbon budget of 326 Gt Global AFOLU CO_2 emissions budget of 40 Gt (included in net CO_2 emissions budget of 500 Gt)	Global and selected regional CO_2 emissions pathways via shifts in emission intensity Global and selected regional electricity CO_2 emissions pathways Global CO_2 emissions pathways for selected industries—basic chemicals, iron and steel, land transport, water transport and air transport Global and regional AFOLU CO_2-eq emissions pathways from GLOBIOM Source: IEA Stated Policies scenario
Electricity output and technology mix	Global electricity output pathway Global electricity technology mix pathway Source: IEA NZE scenario	Global and regional electricity output pathways Global electricity technology mix pathway Source: IEA Stated Policies scenario
Fossil fuel output	Global coal and gas output pathways from the IEA NZE scenario	Global coal, oil and gas output pathways from the IEA Stated Policies scenario
Energy efficiency	1.5% annual energy efficiency improvement for households and firms Extra 0.5% annual energy efficiency improvement for iron and steel, non-ferrous metals and all transport sectors Extra 0.5%–1% annual efficiency improvement in the use of fossil fuels	1.5% annual energy efficiency improvement for households and firms Extra 0.5% annual energy efficiency improvement for iron and steel, non-ferrous metals and all transport sectors

The CSP scenario also includes historical and projected Australian aggregate and sectoral emissions sourced from DISER[44].

Table 3 | Treatment of key variables in KPMG-EE[49]

Variable	CRD scenario	CSP scenario
Macroeconomic variables—real	GTEM CRD scenario results for Australia are applied to KPMG-EE. These are shifts in export demand, land supply and natural resource supply. The population moves with the CSP scenario. Net foreign liabilities-to-GDP ratio moves with the CSP scenario	GTEM CSP scenario results for Australia are applied to KPMG-EE. These are government consumption, shifts in export demand, shifts in investment, labour productivity, land supply, natural resource supply, population, employment and labour supply. Net foreign liabilities-to-GDP ratio stabilises by 2050
Macroeconomic variables—prices	GTEM CRD scenario results for Australia are applied to KPMG-EE. These are CIF import prices.	GTEM CSP scenario results for Australia are applied to KPMG-EE. These are shifts in FOB export prices, CIF import prices and the consumer price index.
GHG shadow price	GTEM CRD scenario results for Australia, representing the GHG shadow price, are applied to KPMG-EE. These are represented as ad valorem tax rates on output, intermediate inputs and household consumption	GTEM CSP scenario results for Australia, representing the GHG shadow price applied to KPMG-EE. These are represented as ad valorem tax rates on output, intermediate inputs and household consumption
Electricity output and technology mix	Endogenous	Consistent with GTEM CSP scenario results for Australia
Fossil fuel output	Endogenous	Endogenous
Energy efficiency	Consistent with GTEM CRD scenario results for Australia Selected sectoral energy intensities are made consistent with sectoral energy intensity changes in AusTIMES via an iterative process; the relevant sectors are iron ore, other mining, non-metallic mineral products, iron and steel, and other metal products.	Consistent with GTEM CSP scenario results for Australia

Table 4 | Treatment of key variables in AusTIMES[49]

Variable	CRD scenario	CSP scenario
Emissions	Shadow CO_2 price from GTEM reaches $38 by 2030 and $345 by 2050	Shadow CO_2 price from GTEM reaches $31 by 2030–2050
Industrial sectoral economic growth	Consistent with KPMG-EE. Lower growth in demand for steel, aluminium, alumina, bauxite	Higher growth in demand for steel, aluminium, alumina, bauxite
Coal retirements	Coal capacity in each NEM state is consistent with the 2022 ISP Progressive Change scenario	Coal capacity in each NEM state is consistent with the 2022 ISP Strong Electrification sensitivity scenario.
Global capital costs for power generation and battery storage	Derived from Graham et al. (2021): GenCost 2020–21, Net Zero by 2050 scenario.	Derived from Graham et al. (2021): GenCost 2020–21, Current Policies scenario.
Uptake of distributed energy (rooftop PV and customer batteries)	Consistent with the Export Superpower scenario in 2021 CSIRO projections	Consistent with the Current Trajectory scenario in the 2021 CSIRO projections
Transport Sector	1.5 degrees scenario (lower growth in transport demand)	Steady Progress scenario (higher growth in transport demand)
Building technology changes	High propensity for uptake of electrification and energy efficiency measures	Moderate propensity for uptake of electrification measures, high propensity for uptake of energy efficiency
Aluminium sector	Energy efficiency measures in Aluminium smelting reach 11 kWh/kg by 2050. Inert Anode technology implemented from 2040–50	Energy efficiency measures in Aluminium smelting reach 12.5 kWh/kg by 2050.

cement. Calibrated to Australia's existing sectoral technology base, AusTIMES identifies least-cost decarbonisation strategies consistent with emissions pricing and trading parameters from GTEM, alongside sector growth trajectories derived from KPMG-EE.

CSIRO Global Trade and Environment Model (GTEM)

GTEM combines a top-down macroeconomic CGE approach with detailed bottom-up energy production data and sector-level GHG emissions accounting (see Section 2 in the Supplementary Information for full model framework and structure). The model captures global energy flows within traded energy products, enabling an integrated analysis of the interactions between energy, carbon emissions and the environment. Below is a summary of the model's main components, with a comprehensive description provided in ref. 44.

In the GTEM model used for this analysis, adjustments to emissions pathways occur through two primary mechanisms. The first involves the pace at which technologies within the available mix can be substituted for one another, reflecting the elasticity of substitution across existing technologies. The second mechanism is the rate of technological innovation driven by price signals. Although GTEM includes a third mechanism—climate feedback effects from emissions pathways—this feature is not activated in the current analysis and is therefore not discussed here. The model's responses to emissions pathways are grounded in empirical data and can be adjusted or constrained as needed to align with outputs from other models, such as those from the IEA, or to incorporate updated information and anticipated future responses.

KPMG-EE energy and environment model of the Australian economy

Similar to GTEM, the KPMG-EE model integrates a top-down macroeconomic CGE framework with detailed bottom-up engineering data on energy production. In this study, KPMG-EE is employed to translate the global changes identified by GTEM into specific sectoral growth projections for the Australian economy. Unlike GTEM, KPMG-EE does not directly model GHG emissions by sector within Australia. To address this, the AusTIMES model (described below) is utilised to help calibrate GTEM's sector-level emissions and emissions intensity trajectories for key Australian industries. The foundational data, theoretical basis and parameters of KPMG-EE are derived from the model described in ref. 45. Below, we offer an overview of KPMG-EE, focusing specifically on elements not covered in ref. 45.

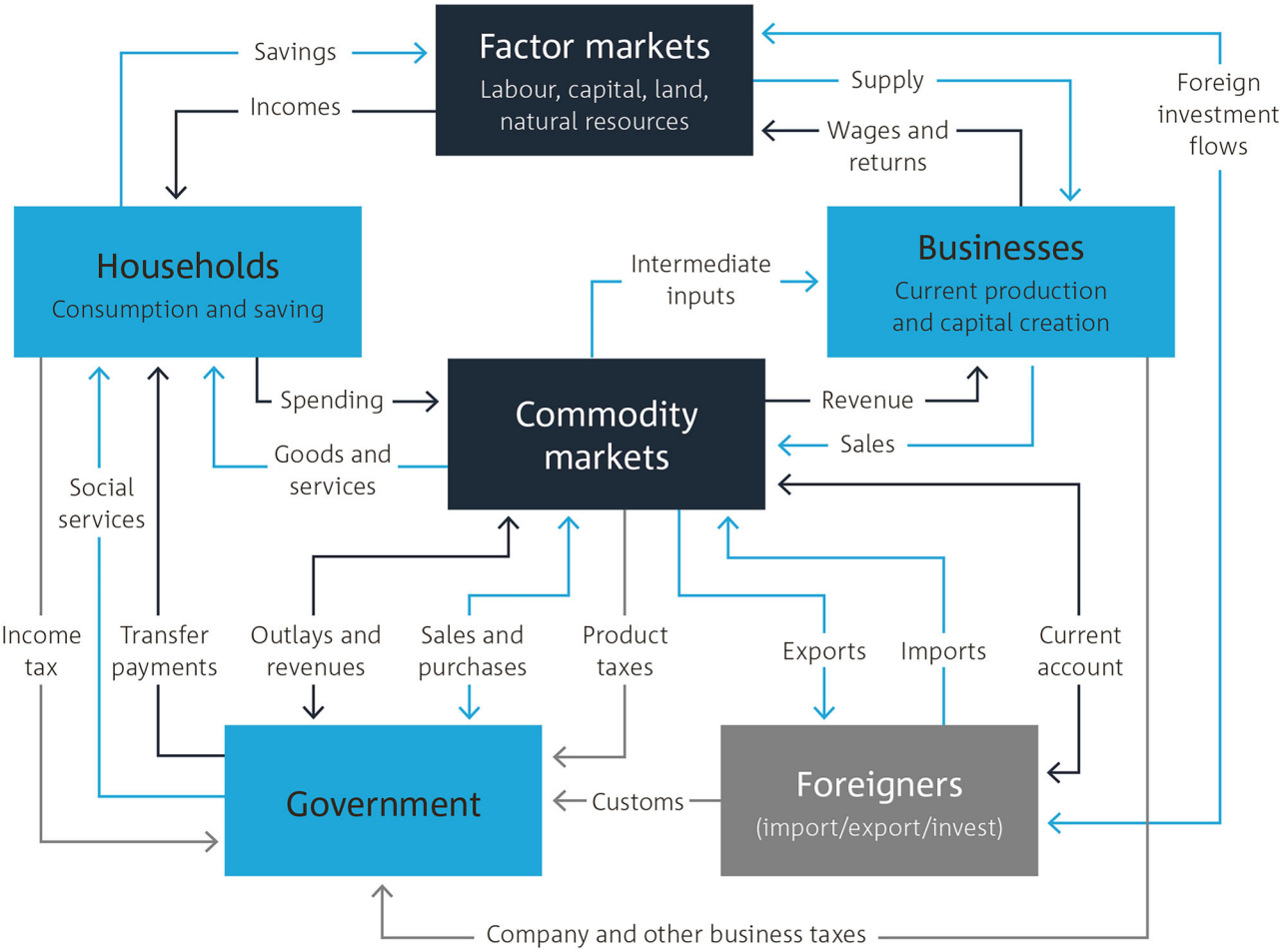

Fig. 6 | Interactions between agents within a given aggregate region in GTEM[9,49]. The resources drawn from the environment and the impact of the climate on economic activity are also incorporated in the CGE framework adopted in GTEM, as illustrated for a given aggregate region. Black arrows show the monetary flows. Grey arrows indicate taxation flows. Blue arrows indicate goods and services flows.

KPMG-EE represents the economy through a system of simultaneous equations that capture the interactions of interdependent economic agents functioning within competitive markets. The model is grounded in economic theory, detailing the behaviour and market dynamics of consumers, producers, investors and governments. These agents engage across domestic and international goods markets, as well as capital and labour markets, reflecting the relationships illustrated in (Fig. 6). Key characteristics of KPMG-EE's theoretical framework include:

- Households and businesses optimise their behaviour within competitive markets, subject to explicit resource and budget constraints (further details on agent behaviour are provided in Section 3, Supplementary Information).
- Prices adjust to clear both goods and primary factor markets.
- Marginal costs equal marginal revenues across all economic activities.

High-emission sectors' emission paths using AusTIMES

The Integrated MARKAL-EFOM System (TIMES) was developed collaboratively through the IEA's Energy Technology Systems Analysis Project (see Section 4, Supplementary Information for detailed structure and key features). As a contracting member of ETSAP, CSIRO has created an Australian adaptation of the TIMES model, known as AusTIMES, in partnership with ClimateWorks Australia, a key collaborator on this project.

The TIMES energy system modelling framework has been widely adopted in more than 20 countries and serves as the successor to the MARKAL model. It optimises the delivery of energy services by minimising total system costs while adhering to physical, technological and policy constraints. The model simultaneously determines technology investments, primary energy supply and energy trade. Comprehensive documentation for the TIMES model generator can be found on the ETSAP website (https://iea-etsap.org/index.php/documentation).

The TIMES model generator operates as a partial equilibrium model focused specifically on the energy sector. Partial equilibrium models in this context—often called 'bottom-up' models—were originally developed during the 1970s and 1980s to analyse energy systems in detail[45–47]. Partial equilibrium models are favoured in energy and environmental policy analysis because they allow for a detailed representation of technologies. The same end-use service—such as space heating or lighting—or fuel type—like electricity or transport fuels—can be supplied by multiple technologies. These technologies often rely on different primary energy sources and have varying emission levels, even if their costs are comparable[48].

Partial equilibrium modelling incorporates a range of technologies linked to each supply option and calculates market equilibrium without predetermined assumptions about which technologies or quantities will be adopted—some technologies may not be chosen at all. This approach offers analytical flexibility by allowing detailed representation of demand patterns, supply technologies and additional constraints, such as resource limits, industry scale-up, saturation effects and policy restrictions, to reflect their influence on market dynamics.

A key benefit of a system-level modelling approach, as opposed to focusing on individual fuels, technologies, or processes, is the explicit inclusion of infrastructure constraints. These include the lifespan of existing asset stocks (e.g. plants, buildings, vehicles, appliances) and consumer

adoption patterns for emission reduction options that may involve non-financial decision factors. This system perspective also enables capturing the combined effects of multiple abatement options when deployed together, rather than in isolation.

Compared to economy-wide CGE models, partial equilibrium models focus on a narrower subset of economic sectors, treating service demands, prices and elasticities in the rest of the economy as external inputs. However, they provide more detailed representations of investments in specific types of physical capital—such as industrial capacity, buildings, or transport fleets—which CGE models generally represent with less granularity.

Key scenario assumptions and inputs

We have created a comprehensive integrated framework to evaluate how the IEA's global climate action scenarios are reflected at the national scale. This study examines two distinct scenarios: (i) the CSP scenario, which incorporates current stated policies internationally and within Australia, and (ii) the CRD scenario, representing a swift pathway toward NZE worldwide and domestically. The tables below present the critical assumptions used within the GTEM, KPMG-EE and AusTIMES models for each scenario. A key focus in establishing these assumptions was to maintain coherence and consistency across all three modelling approaches whenever feasible.

Data availability

The data are available from CSIRO data centre https://doi.org/10.25919/s1m9-kh14 The data include greenhouse gas emissions by gas and by sector, electricity capacity installations by technology, electricity generation by technology, annual electricity investment, emissions intensity by sector, energy consumption by fuel, carbon prices, output by sector, fossil fuel exports by volume, and macroeconomic impact (e.g. GDP, employment, export, household consumption).

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Author contributions

Duy Nong led the design, analysis and writing of the article. George Verikios led and designed the project, carried out GTEM and KPMG-EE model simulations linking with AusTIMES, and helped write the article. Stuart Whitten led and designed the project and helped write the article. Thomas S Brinsmead did AusTIMES simulations linking with GTEM and KPMG-EE models, and helped write the article. Daniel Mason-D'Croz helped write the article. Shelley Rodriguez prepared figures and tables, helped manage the project and write the article. All authors helped with edits and comments.

Competing interests

The authors declare no competing interests.

Additional information

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